Producibility analysis using analytical and empirical process models

by

Lakshmikantan Balasubramaniam

B.Tech, Indian Institute of Technology, Madras (1988)
M.Eng, Carnegie Mellon University (1990)

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Signature of Author ....
Department of Mechanical Engineering
August 17, 1993

Certified by ....
Karl T. Ulrich
Associate Professor, Sloan School of Management
Thesis Supervisor

Accepted by ....
Ain A. Sonin
Chairman, Departmental Committee on Graduate Students

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Abstract

This thesis is about *How to analyze producibility of designs and provide useful feedback to designers.* It deals with producibility problems that arise because of part shape and that lead to high scrap, excessive rework or extensive tool trials. I first present a classification of production processes and then focus on processes such as extrusion and injection molding in which shaped tools are used to form similarly shaped parts. I call such processes *process-physics dominated.* I propose process-model based metrics as an alternative to representing producibility constraints as examples or as localized geometric features. I decompose the problem of producibility evaluation in terms of the different failure modes of the process rather than in terms of geometrical features of the part. Metrics based on process-models are used to predict the severity of the different failure modes. In the absence of rigorous analytical process-models to analyze the complicated shapes designed in practice, approximate models are used to define the metrics. I present a methodology to identify, validate, and refine such metrics. Aluminum extrusion has been used as an example to illustrate the details of the methodology. Evidence to validate the aluminum extrusion metrics has been obtained from expert opinions, experimental results, direct measurements on tooling and by constructing arguments from first principles. I also propose an activity-based costing framework that uses metrics to estimate the cost impact of producibility problems.

The main contribution of this thesis is to show that *metrics based on approximate models of process-physics can be used to make useful predictions about producibility problems.* Data to establish the value of the method, and to validate the metrics has been obtained by collaboration with Boeing Commercial Airplane Group and their aluminum extrusion vendors.

Thesis Supervisor: Karl T. Ulrich
Title: Associate Professor, Sloan School of Management

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Chapter 1

Introduction

1.1 What is this thesis about?

Very broadly speaking this thesis is about *How to analyze producibility of designs and provide useful feedback to designers.* It deals with producibility problems that arise because of part shape and cause high scrap, excessive rework or extensive tool trials. I focus on processes in which shaped tools are used to form similarly shaped parts. I call these *process-physics* dominated as the physics of the process determines the extent to which the part will conform to the tool shape. (More on this in Chapter 3.) Unfortunately, rigorous models that predict the physical behavior of machines and materials often do not exist for this class of processes. In the absence of rigorous technical models, I propose the use of approximate models. The essence of the thesis is that *metrics based on approximate models of process physics can be used to make useful predictions about producibility problems.* In this section, I describe why and where such producibility information is useful. In a later section, I describe the industrial context for this project and motivate it from that angle.

1.1.1 Design in the small and in the large

The classical view of design is that it is an creative activity pursued by a gifted individual who comes up with marvelously clever solutions to practical problems seemingly out of thin air. This view of design as an act of invention is reflected in its definition in many dictionaries. The designer is an inventor or an artist, a la Thomas Alva Edison[1].

Researchers in Artificial Intelligence think of design as an example of a problem solving activity. They see a designer as *systematically* generating and exploring different alternatives till one is found that *satisfices* the desired and pre-determined specifications. This view is exemplified in the book by Herbert Simon ([Sim81]) in which he describes design as an activity concerned with devising artifacts to meet goals. [Whi90] calls such individual activity as design in the small.

Researchers who study design as practiced in companies report a very different picture. In the place of one individual systematically sifting through different alternatives. they find teams of engineers feverishly trying to work together in the face of conflicting goals, ever changing constraints, extreme time pressures and different working styles. The scope for creativity and the necessity to invent is limited. The search for solutions is anything but systematic. The constraints on any individual designer are constantly changing as a result of the activities of the other designers. Designers seldom have complete information on all aspects of the design. Conflicts are common and must be resolved. Design in this view is more akin to a thousand blind men trying to assemble the Pharaoh's pyramid. Design as a collaborative effort constrained heavily by issues of communication and coordination has been referred to by [Whi90] as design in the large.

The best companies attempt to introduce some order into this chaotic state by trying to develop efficient ways to communicate and coordinate the different designers. Difficulties in achieving this increase rapidly with the size of the team. Table 1.1 from [Whi92] lists the size of design teams for several different industrial products designed in Japan[2]. The industrial context for this thesis is the development of the

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[1] A genius in the practical application of scientific principles, Edison was one of the greatest and productive inventors of his time with the phonograph, the first commercially viable incandescent lamp and more than 1300 other US and foreign patents to his credit.- The New Columbia Encyclopedia

[2] One of the points made in [Whi92] is that product development teams in Japanese companies tend to be much smaller than product developments teams in comparable US companies.

777 airplane by the Boeing Commercial Airplane Group. The development team in this large project consisted of about 7000 personnel.

Product	*Team size*
Machine tool	5 – 10
VCR mechanism	10
Dot matrix printer	10 – 15
Washing machine	15
Videocamera	20
Auto focus camera	20 – 30
Copier	30
PC hard drive	30
Auto alternator	20 – 40
Construction crane	30 – 40
Auto engine	30 – 80
Car styling and body design	200 – 400

(1.1)

With small design teams communication and coordination problems can be overcome by regular face-to-face meetings and phone-calls. Engineers working in small teams are more likely to have multiple responsibilities and see their goals more in terms of the overall success of the product. In very large design organizations, however, designers tend to have focused responsibilities and much narrower and sometimes conflicting goals. In large complex products, the necessary technical knowledge is distributed among many different engineers. Designers may simply not be knowledgeable enough to make decisions that are optimal with regard to all the important criteria. Effective and early communication is very desirable but difficult to realize in practice due to the size of the organization. Sub-optimal decisions made at one point in time are often locked in, because other designers have proceeded with their work taking those decisions for granted. Researchers and companies have observed that such communication gaps often arise between the product design engineers and the process design (manufacturing) engineers especially in large industrial projects.

This communication gap has resulted in products that could have been designed to be less costly to produce. Design for manufacturing (DFM) has been proposed as a solution to this problem.

1.1.2 What is design for producibility?

Design for manufacturing is a design philosophy that says that the design of a product and that of the process to produce it must be coordinated. This basic philosophy has spawned two main branches, one focuses on assembly and the other on fabrication of individual parts. The latter has been referred to as design for producibility or design for fabrication. In practice, design for producibility translates to making the designer aware of the constraints imposed by what is practical on the production side. This may be done by identifying problematic designs, ordering or prioritizing design alternatives, making suggestions for improving producibility and ultimately giving the designer an intuitive feel for producibility issues. It is hoped that a designer who is so aware will make design decisions that necessitate high cost production steps only when they are absolutely unavoidable.

1.1.3 What are the implications of poor producibility?

The implication of poor producibility are:

- High cost/low yield. A design that pushes the limits of producibility is likely to be expensive to make. It is likely that only a few vendors possess the technical expertise necessary to produce the design and they may expect a premium price for their services. Without a sufficient degree of control the process may result in low yields necessitating much rework or large amounts of scrap.

- Long lead times. It takes more trials to get the process good enough to begin production. This would result in long lead times for designs which suffer from poor producibility.

- Downstream processing difficulties/quality loss. With poor control on the process, the output may vary significantly around the desired nominal. Even when these variations are within tolerance, *quality loss* results [Pha89]. For example, extrusions used in the assembly of aircraft frames will distort heavily during heat treatment if there is much variation in section thickness. When cold worked to remove the shape distortion they will develop significant residual stresses. These residual stress would cause the extrusion to distort on finish machining and necessitate shims during final assembly.

1.2 Motivation and industrial context for this thesis

The industrial context for the research described in this thesis is design and manufacture of aluminum structural parts for use in Boeing's new 777 airplane. In this section I motivate my research by describing this context in some detail.

1.2.1 Use of aluminum extrusion for structural applications in aircraft

A modern day jetliner such as the Boeing 777 has a large number of aluminum extruded parts providing structural support. At Boeing, these extrusion shapes have been classified into various shape categories such as angles, tees, channels and minor modifications of these shapes. Shapes that cannot be classified easily are lumped into a miscellaneous category. For instance of the 1200 new extrusions designed for the 777 project approximately 42% belong to one of the standard shape categories. Another 53% are minor modifications and about 5% are classified under the miscellaneous category. Finished parts made from these 1200 different extrusions add up to approximately 23,000 lbs and make up about 15% of the weight of the airplane. The fraction of structural parts that are extrusions has been increasing with each generation of aircraft. In order to reduce part count, more and more parts originally

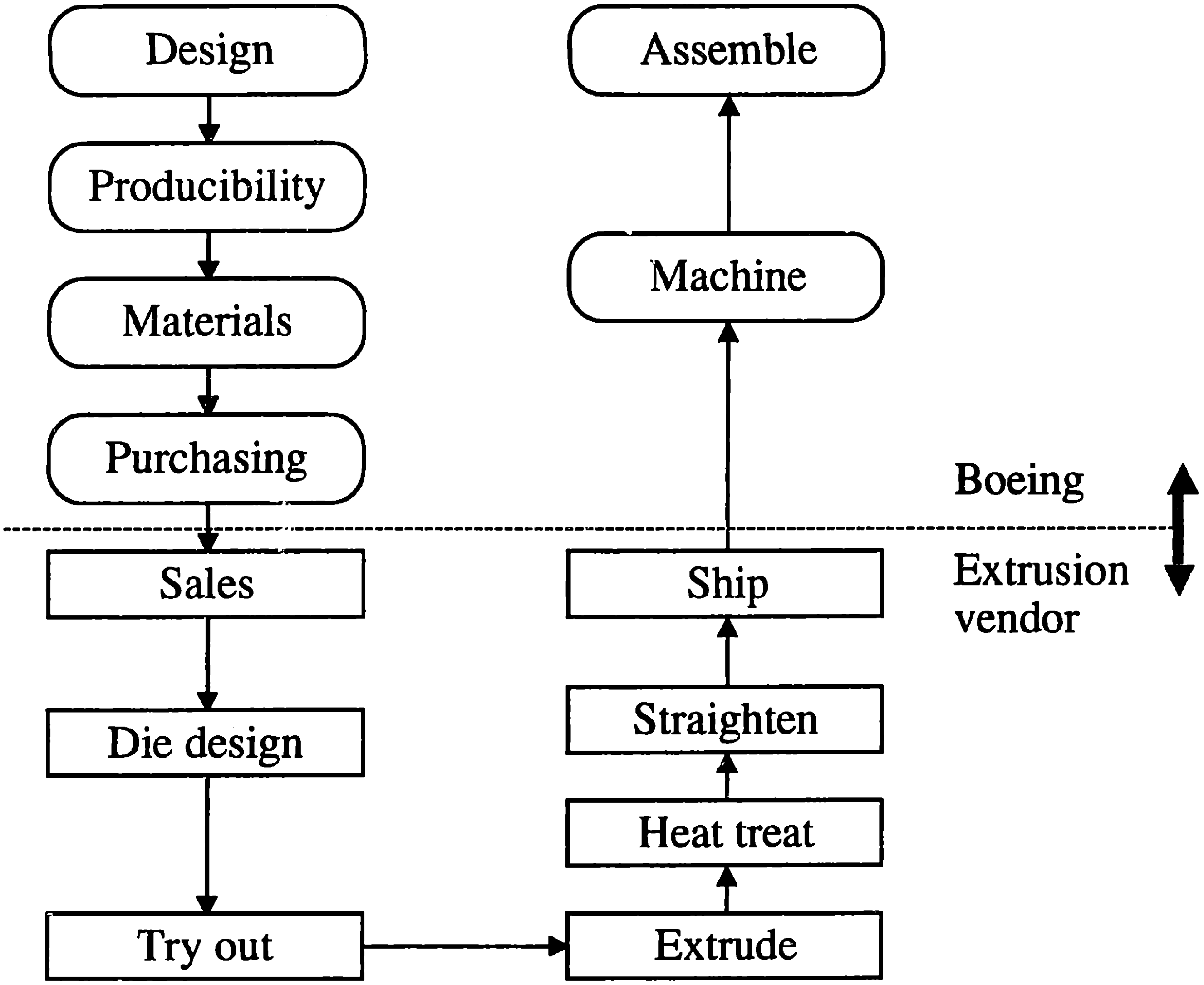

Figure 1-1: Steps in extrusion design and production

assembled from rolled-sections are being replaced by extruded and finish-machined parts. An informal estimate comparing the 777 with the 747 suggested that around 65% of the structural parts in the 777 start off as extrusions up from around 35% for the 747. Boeing does not manufacture extrusions internally but relies on a number of extrusion vendors to meet its needs. Figure 1-1 illustrates the important steps in the design and use of extrusions at Boeing.

1.2.2 Potential benefits from improving producibility of aluminum extrusions

I visualize at least two important and quantifiable benefits of improving the producibility of aluminum extrusions:

Potential for lower cost extrusions The price of hard alloy aluminum extrusions[3] for aircraft applications ranges from about \$5/lb to about \$20/lb. Assuming that 10% of the material is removed during finish machining, 23000 lbs of finished parts translates to about 25,000 lbs of raw extrusion per airplane. From the spread of \$15/lb between the least expensive and the most expensive extrusion, an upper bound on savings from vendor quotations is estimated to be about \$375,000 per airplane[4]. Boeing expects to build over a thousand 777s and hence potential savings from producibility improvements are significant.

Potential for better control of operations From the data in [LS81], I estimated that a single 8 inch (200 mm), 2000 ton (16 MN) extrusion press can produce 25,000 lbs of one hard alloy extrusion shape in 38 hours. [LS81] also estimates the average die-change time to be 8 minutes. So ideally, 25000 lbs of 1200 different extrusions could be produced by 3 presses in 9 shifts. Since Boeing currently produces a 747 (similar in size to the 777) once in about 4 days (12 shifts), 3 extrusion presses could *theoretically* meet the entire demand for the 777 airplane. Unfortunately this is far from reality. At the present time Boeing deals directly with about four or five extrusion vendors and, through intermediary stocking companies, with several more. Dependence on such a diverse vendor base may be necessary because of the long lead times involved in die development. Perhaps because of the numerous bottlenecks in the process (die trials and rework), extrusion vendors ask for a lead time of 8 to 32 weeks[5]

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[3] The price of raw aluminum alloys in billet form is about 1-2\$/lb

[4] I wish to emphasize that this is an upper bound figure. More exact estimates can be obtained from statistical analysis of actual vendor quotations. Unfortunately, such data is regarded as confidential and is not easily available.

[5] Some smaller vendors undertake to deliver a new shape in about 3 weeks

for a new extrusion. With hard deadlines on delivery of airplanes, Boeing needs parallel processing to shorten the overall time to develop 1200 different dies. *Thus the start-up/lead time rather than the steady-state output rate determines the number of extrusion presses (vendors) required.* Better producibility may allow the vendors to decrease the lead-time for new shapes and Boeing to feed its operations from a smaller number of presses. This has obvious strategic advantages.

1.2.3 How extrusions are designed at Boeing

Four internal organizations at Boeing are closely linked with the design of aluminum extrusions.

- Project engineering or more specifically the different design groups in the **Boeing Structures** organization are responsible for designing shapes to meet load and geometric specifications.
- **Boeing Material Technology** and **Boeing Producibility** function as internal producibility consultants.
- **Boeing Standards** maintains the original drawings and supplies copies on demand to vendors, designers, airline maintenance crews etc. Standards also interfaces with the vendors and acts as a focal point for flow of engineering information between the various design groups inside Boeing and the extrusion vendors.

Decisions were made at the highest levels within Boeing to utilize concepts from concurrent engineering and design-build teams to design the 777 airplane. The design-build process was a commitment for Engineering and Manufacturing to work together to develop a more producible, more error free design. Engineering was to be responsible for the design but was expected to incorporate Manufacturing's producibility knowledge into the design to the maximum extent possible. About 222 Design-Build Teams (DBTs) were formed in the Structures and Systems groups. A DBT averaged about 20 people drawn from Engineering (Designers and Analysts), Manufacturing engineering, Tool design, NC programming, Quality Control, Materiel (Purchasing) and other internal organizations depending on the specifics of the design. Extrusion vendors were not generally members of DBTs. Boeing Material (BMT) functioned as the stand-in for the vendors. These groups met about once a week during the early stages. The frequency of meetings gradually decreased as the release date drew closer as more of the design was completed.

The most time consuming task in the design of airplane structures is the determination of the loads and the geometric constraints on the structural parts. This is a highly coupled task involving many different groups within the structures organization and takes many months to complete. Once the specifications converge to a stable value, the designers and the analysts define the shapes and the minimum cross-section of the extrusions necessary to carry the loads and satisfy the geometric constraints. They then add a machining allowance to the shape of the extrusions where necessary. The process of shape design and refinement takes about 2 person weeks for each extrusion. The engineering drawings prepared by the designers are sent to the Boeing producibility experts for signature a few days before they have to be sent to the vendor for design and fabrication of dies.

A small fraction of these drawings have been incorporated into a design standards handbook to facilitate re-use of old designs. More recently, a computer tool that uses group technology techniques has been developed and is being used to facilitate access and searching through this huge database of parts.

Boeing Standards recently studied the extrusion design process within the company and documented various statistics. According to their report, the rate of drawing releases in the 777 project reached a peak of about 230 new shapes per week. They report that on average a drawing spends 1.25 days with Boeing Material (BMT) which finds about 90 to 95% of the shapes "pretty good" from the point of view of producibility. The drawings are further checked by Standards personnel for drafting errors and missing drawing notes. On an average, a drawing spends about 4.2 days in Standards. Drafting errors were noticed in about 32% of the drawings. After correction the drawings are archived and released for distribution. Boeing Standards is also responsible for reviewing the die drawings[6] sent by the extrusion vendor. Errors are noticed in about .3% of the die drawings which then have to be sent back to the vendor for correction.

Almost all of the 500 structural designers in the 777 project are involved in the design of extrusions at one time or another. The size of the organization and number of designers involved make it difficult for producibility experts to work beside every designer on a day to day basis. On the other hand, by the time the design reaches the vendor or the in-house producibility experts, the amount of time and effort committed to the design warrant that only the most severe problems merit redesign. Also any changes suggested by the different in-house producibility experts or the vendor at this stage would delay the release date imposing an additional cost on manufacturing.

This study conducted by Boeing Standards has suggested several changes to improve the current process of extrusion design. The report recognizes the potential in the use of design tools such as expert systems to provide feedback to designers. Because Boeing has to maintain drawings and physical inventory for every part on an airplane model for long periods of time there is a substantial cost associated with proliferation of similar extrusions. On the other hand, parts are never exactly identical and the philosophy of net shape manufacturing argues against unnecessary machining. There is also a practical problem of archiving and retrieving a "similar" shape from a database of 30,000 shapes. The report identifies this problem and suggests investigating some potential solutions such as group technology based classification, and artificial intelligence techniques for shape recognition.

1.3 Research Methodology

Much of the data that underly this thesis were gathered during informal interviews with many different people at Boeing as well as at various extrusion vendors. Specif-

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[6] Extrusion vendors redraw the extrusion section sometimes changing the dimensioning to make it more suitable for die cutting. See Section 4.2.1 for more details

ically, I conducted interviews with

- Personnel from Boeing Structures (5), Boeing Materials (2), Boeing Producibility (2), Boeing Standards (4), Boeing Materiel/Purchasing (2).
- Plant managers, production managers, quality control engineers, die correctors, cost estimators, and extrusion press operators at six different vendors:
  - Alcoa, Vernon, California.
  - Alcoa, Tifton, Georgia.
  - Easco Aluminum, Ohio.
  - Minolex, New Jersey.
  - TDA, Portland, Oregon.
  - Universal Alloys, Ananheim, California.
- Plant visits to Alcoa (Vernon), Universal (Anaheim) and TDA (Portland).
- Tool and die designer (Garbell Tool and Die Company, Florida)
- Academic and industrial researchers. (MIT, Purdue, Ohio State, Alcoa Tech Center)

I talked to most people more than once. In many cases, my interaction with these sources stretched over several months. Practical problems faced in the industry often stretch over very broad domains (compared to a PhD thesis). Much of initial discussions stemmed from my desire to focus on a narrow but interesting segment of the problem. In the latter part of my work, my sources helped me validate my ideas.

Additional data to validate my ideas was obtained from actual measurements of extrusion dies and a simple experiment conducted at MIT. Published literature and numerous texts were useful to come up to speed on the state of the art.

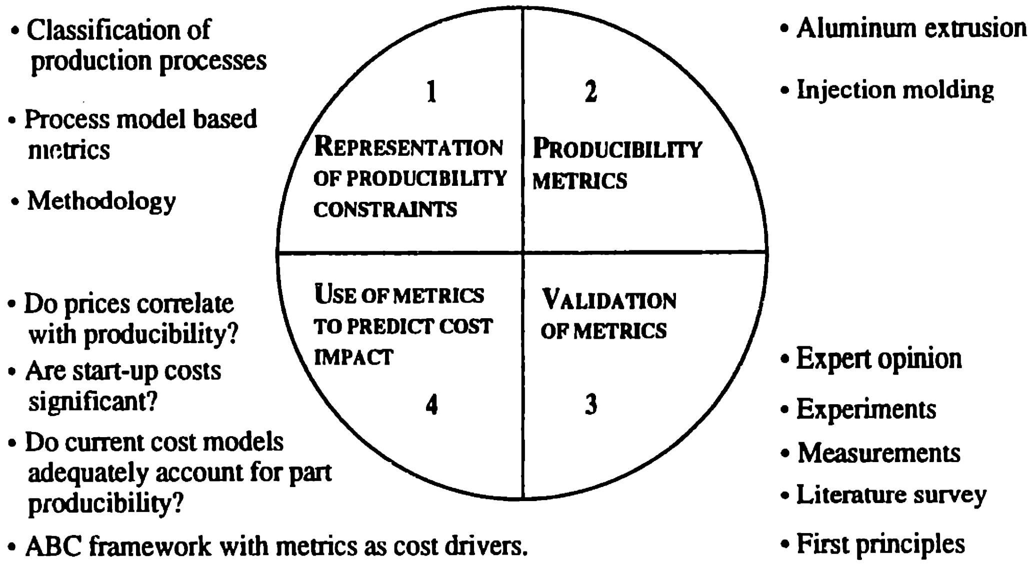

Figure 1-2: Overview of key thesis chapters

1.4 A road map to this thesis

In the next chapter (Chapter 2) I review a number of publications in related areas of research. The bulk of this thesis consists of the next four chapters whose contents and the main ideas are summarized below: (Fig 1-2 summarizes the key ideas in each of the four chapters)

1.4.1 Chapter 3: Representation of producibility constraints

The core theme of this chapter is *How should producibility constraints be represented?* Some of the other question that are explored are:

- Are certain representations more suitable for some processes than others?
- Is there a hierarchy of importance among the different issues that contribute to producibility or lack thereof? Is it possible to classify the different issues into primary or core issues and secondary or peripheral issues? To what extent is the relative importance of different issues influenced by our understanding of and control over the process?

The key ideas presented in this chapter are a classification of production processes, a classification of issues in producibility analysis, approximate process model based metrics to represent producibility information, and a methodology to identify, validate and refine these metrics.

1.4.2 Chapter 4: Process-model based producibility metrics

In Chapter 4, I illustrate how process-model based metrics can be developed using aluminum extrusion as an example. First I describe the process in some detail, then I list the various producibility problems encountered in practice, and finally I propose a set of metrics to predict these problems.

1.4.3 Chapter 5: Validation of metrics

In Chapter 5, I describe the various approaches used to validate the metrics and also the evidence gathered from such efforts. To validate the metrics, I collected evidence based on opinion of experts, direct measurements and experiments, and review of available literature. The results indicate that process-model based metrics, though approximate, can yield useful predictions.

1.4.4 Chapter 6: Use of metrics in cost model

In Chapter 6, I propose a frame-work that extends activity-based costing using metrics to estimate the cost impact of producibility.

1.4.5 Appendices

Appendix A recasts injection molding research done elsewhere into the framework of metrics to provide another example in which approximate models of process physics have been used to define metrics to make useful predictions of producibility problems.

1.5 Summary of key contributions

I believe that four contributions result from this thesis:

- Metrics have been identified as an alternative to geometric features to represent and evaluate producibility.
- A methodology to identify and validate metrics has been proposed.
- A set of metrics for aluminum extrusion have been identified and validated.
- It has been established that metrics based on approximate models of process physics can yield useful predictions.

Chapter 2

Review of related literature

In this chapter I review a selection of books and papers from the following eight areas of related interest:

- Strategies for new product development.
- Heuristics for good design practice.
- Structured methods for producibility analysis.
- Expert systems and feature recognition.
- Feature based design.
- Approximate process simulation
- Aluminum extrusion process modeling
- Role of cost modeling in design.

and conclude with the last section on where this thesis fits in.

2.1 Strategies for new product development

Recognition that

- product design has a major impact on the life-cycle costs of a product

- and that sequential or *over-the-wall* design process increases development lead time, lowers product quality and increases product cost

has led many researchers to advocate and companies to implement alternative models for product development (See for instance [NW89, CF91, CDMP91, ES90]).

Some researchers have proposed organizational strategies to create multi and cross-functional product development teams (See for example [TN86].) They argue that no single designer can have all knowledge necessary to do product and process design alone and that present-day design tools cannot substitute for human expertise. Hence as a practical matter, companies must rely on teams of specialists pooling their knowledge to create better products and manufacturing systems [NW89]. This team approach is however not without its own problems. Two major obstacles to successful implementation are :

- Engineering or technical limitations may dictate that certain decisions cannot be made until others have been made. Manufacturing engineers do not like to comment or give price quotations on incomplete designs.
- Institutional barriers to team design arise from the ingrained habit of design and manufacturing engineers, even within the same company, to see each other as belonging to opposing or warring groups. In other cases geographical distances may make effective team work difficult. Institutional barriers become even more difficult to overcome when manufacturing is contracted out to independent vendors.

Other researchers have proposed techniques to guide individual designers in making their designs more *down-stream friendly.* The essential theme of all these techniques is to try and identify features or aspects of the design that could potentially cause producibility problems. The hope is that identification of these features at an early stage in the design process will make it easier for the designer to modify them suitably. Design principles such as Design for Assembly(DFA) [GP87, NW89] and DFx (where the x stands for different production processes such as Casting, Forging, Injection Molding) fall in this category. DFx has been alternately given other names, such as Design for Fabrication and Design for Producibility. Researchers have proposed many different approaches to DFx and these techniques are described in following sections.

2.2 Heuristics for good design practice

Heuristics and recommendations for good design can be found in texts on production technology [Tru87] or in handbooks [Bra86]. Such design rules are commonly expressed in terms of features either by giving specific examples or broad guidelines. Figure 2-1 shows some typical examples for the extrusion process[1].

There are several barriers to the use of guidelines such as shown in Figure 2-1. Because the shape in question is unlikely to be exactly similar to the examples shown, the designer has to decide which and to what extent the recommendations are applicable to his situation. Secondly, the examples show one possible solution. For instance, would flatness improve if the leg in the figure were made thicker. Short of having a symmetrical shape, is there any way of achieving a balanced section? What can you do if the function of the part necessitates unbalanced voids? Finally, without dimensions on the drawings, the designer has no way of telling whether the design guideline applies to his case even if the shape were to be similar. How much imbalance can be tolerated?

[Tru87] specifies seven factors which should be within limits for an extrusion to be producible:

- Extrusion ratio. This is the ratio of the billet cross-sectional area to the cross-sectional area of the extruded part. Common extrusion ratios for aluminum range between 15:1 and 50:1. However extrusions dies may have more than one opening and this is often used to bring the effective extrusion ratio within range.

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[1] Readers unfamiliar with the basics of aluminum extrusion may wish to read through Section 4.1 where I explain some of the standard terminology used in this section and in Section 2.7.

- Part size. This is measured by the diameter of the smallest circle that can circumscribe the extrusion section. This is often limited by press capacities. Different vendors will specify different constraints on this number depending on their press size. The most common limit for aluminum extrusion is between 7 and 9 inches. However presses with much larger capacities (up to 27 inches) are in operation.

- Length. Aluminum extrusions are usually made in lengths of about 20 to 60 feet depending on the size of the cross-section and the length of the run-out table.

- Minimum size. According to [Tru87] the minimum cross-section for aluminum extrusion is about $0.1 in^2$.

- Thickness. The larger the size of the extrusion the thicker the walls have to be. Wall thicknesses for aluminum extrusions are generally greater than 0.050 inches.

- Corner and fillet radii. According to [Tru87], corners can be sharp in aluminum extrusions. However [Bra86] cautions against sharp corners and knife edges (probably because these increase die wear). As a practical matter, corners can only be as sharp as the diameter of wire on the EDM machine used to cut the die, unless special measures are taken. Fillets should be 0.030 at the minimum.

- Indents. According to [Tru87] the depth of indents should be no greater than their width. According to [Bra86], for aluminum extrusions the depth can be upto three times the width of the indent. In the extrusion industry, the ratio of indent depth to indent width is referred to as the *gap ratio*.

These factors differentiate feasible from completely infeasible shapes. Most shapes designed in practice ofcourse fall in the feasible space. However they vary widely in complexity. [Tru87] describes the industry practice of measuring the complexity of an extrusion section in terms of a shape classification and the shape factor.

Extrusion shapes are classified into six different categories. In the order of increasing production and die cost, they are:

- Solid. Any extruded shape other than semihollow or hollow.
- Semihollow-Class 1. Any semi-hollow shape with one or two voids placed symmetrically.
- Semihollow-Class 2. Any semi-hollow shape other than the class 1 shapes.
- Hollow-Class 1. A hollow shape whose void is round, one inch or more in diameter and placed symmetrically.
- Hollow-Class 2. A hollow shape other than class 1, whose circumscribing circle does not exceed 5 inches and whose void diameter is not less that 0.375 inches.
- Hollow-Class 3. Any hollow shape that is not class 1 or class 2.

There are definite differences between solid, semi-hollow and hollow sections in extrusion die design and construction. In order to produce a hollow section, the extruded metal must flow around the support that holds the mandrel and weld on the other side. A semi-hollow section needs a die tongue which must be adequately supported to prevent deflection or breakage. However further classification in classes of semi-hollow and hollow shapes seems ad hoc and too general to be of any real help to extrusion shape designers.

The shape factor is defined as the ratio of the perimeter of section in inches to the weight of extrusion per lineal foot in pounds. According to [Tru87], the cost of an extrusion is generally expected to increase as the shape factor increases. However, in Section 6.1 I present some preliminary data that indicates that in current practice pricing of custom-shape aluminum extrusions is driven more by competitive market forces than by technical factors such as the shape factor.

Commercially achievable tolerances for aluminum extrusion are listed in [Ass90]. In practice, extrusion vendors claim to be able to achieve upto three-quarters of these standard tolerances without much problem.

2.3 Structured methods for producibility analysis

The effort in this area of research is to develop systematic methods for engineers evaluating the producibility of designs.

[JSP91] proposes a framework for manufacturability evaluation that is based on three principles:

- Designers should be provided with a number of *quantitative* measures of manufacturability in order to evaluate designs.
- Each of the above measures should be explicitly linked to the variables that characterize the designs.
- The measures should be generalized so that the methodology can be applied to any manufacturing domain.

[JSP91] defines six *general manufacturability indices* to evaluate the manufacturability of any design: Compatibility, Bug index, Availability, Complexity, Standardization, Efficiency. Each index is further split into a number of contributing factors. To evaluate producibility, an engineer uses a check-list to ask a series of questions. The answers determine the rating of the design with respect to each index.

The framework presented in [JSP91] covers a wide range of manufacturability issues. The manufacturability indices are general enough to be applicable for many different manufacturing processes. In its essence, this framework is intended to systematize manufacturability evaluation by providing a checklist of potential concerns.

However, correctly evaluating the contributing factors is not simple. To evaluate *Compatibility*, for instance, the engineer has to decide if the overall shape of the part is compatible with the manufacturing process. It is clear that this question hides much of the complexity of producibility analysis. It calls for a high degree of human expertise and decision making.

In defining measures of manufacturability, there is a clear trade-off between generalizability and accuracy of prediction. To ensure accuracy, the measures have to be based on deep process knowledge. Such measures are however likely to be process-specific. The measures proposed in [JSP91] are in accordance with their basic objective of defining measures that are generalized enough to be applicable for a wide range of processes. The level of abstraction of these measures is much higher that the level at which experts with deep process knowledge evaluate design producibility. In order to be useful, the measures for manufacturability evaluation must capture a significant portion of the expert's knowledge base. It is not clear that loss in detail and accuracy is worth the gains obtained from generalizability. Industrial product designers seem to develop strong preferences for certain production process. Often this is the case because new parts evolve from other pre-existing parts that perform a similar function in a related product. Structural support parts in Polaroid cameras are most often injection molded parts. Xerox copiers on the other hand have lots of bent sheet metal parts and Boeing airplanes have aluminum extrusions. In an environment where product development proceeds in an evolutionary manner, designers may not have the option of jumping to a totally different process. Under such circumstances designers are likely to value accuracy over generalizability in manufacturability evaluation.

[PDM91, PMDG93] describe a group technology (GT) based framework to evaluate producibility of stampings by estimating relative cost of producing the part. The GT indices are the different part features and these are used to evaluate the tooling and processing costs. In its essence, this approach of linking part features to producibility is similar to that used in the Boothroyd Dewhurst method for evaluation of assembleability.

The tool manufacturing cost is estimated to be about 80% of the tooling cost. The choice of die material determines the remaining 20%. Processing cost is given to be the product of cycle time and machine rent. The size of press is estimated by adding up estimates for forces necessary to stamp the part. Machine rent is determined as a function of press tonnage. Cycle time is computed from estimates of set-up time and productive up-time for the press. Material cost is a product of part volume and cost of rolled sheet metal.

The framework presented in [PDM91, PMDG93] is detailed enough to be used by product design engineers to evaluate design alternatives. The framework has been developed by interviewing cost estimators and producibility experts at sheet metal stamping companies. While that in itself lends some credibility to the framework, product designers may wish to see more evidence validating the framework before they can apply this method with confidence.

2.4 Expert systems and feature recognition

[BNA78] describes a set of computer programs that were developed for the design and manufacture of aluminum extrusion dies. The programs assist the die designer in determining:

- The optimum number and location of die openings.
- Stresses in die and support tools.
- Compensation of die openings for deflection under load.
- Bearing dimensions for metal flow.
- Thermal shrinkage of extrusion and thinning during stretching.

The programs were validated by designing a die for a T section which was used to extrude 7075 aluminum alloy on a 700-ton hydraulic press at Battelle laboratories. According to the authors, the extrusion came out straight and within dimensional tolerances.

Some researchers [GGH$^+$91] have developed expert systems which use design guidelines such as given by [Tru87, Bra86] to check for constraint violation and suggest design modifications. Since design guidelines are usually expressed in terms of geometric features, the expert system must first be able to identify the features in the part geometry database and match them with the features specified in its rule-base. This is the problem of feature-recognition. A number of papers have been published describing various approaches to feature-recognition [GP91, PFP89]. [PFP89] describes shape features using a graph grammar. Because the design is an element in the language generated by this grammar, shape features can be recognized by parsing the feature against the graph of the object. [PFP89] has implemented a restricted version of the grammar for the domain of injection molding. [GP91] presents an approach to use silhouette information to recognize protrusions and depressions in a part. This approach, called the differential depth perception filter, can be used to recognize certain types of features while avoiding the combinatorially explosive problem of graph matching. [GP91] also the discusses the use of medial axis transformation to reduce a 3 dimensional object to a 2 dimensional skeleton. Recognition of certain types of features would be much easier in this reduced model of the object.

Though much progress has been made, certain critical issues remain subjects of research at the present time. Are real experts available for different domains? Is it possible to effectively capture their real world producibility knowledge in terms of rules based on a relatively small set of geometric features? Can these features be recognized with reasonable effort? What happens when features interact?

2.5 Feature based design

Feature-based CAD tools have been proposed as a more convenient way to create CAD models[DD88]. Macros are provided for commonly occurring geometric patterns. The user can create a CAD model with less effort than would be required if he were start with raw geometric primitives such as lines and arcs. It is also possible to attach additional attributes pertaining to issues such as manufacturing. For instance, the diameter of holes could be restricted to certain preferred numbers. Because the part geometry is now described in terms of features, the need to recognize and extract features is reduced but not eliminated. The reason is that manufacturing constraints are often described in terms of features that are different from the vocabulary of features that designers use when designing parts.

Some researchers feel that forcing designers to work with manufacturing features will hamper them. [CT90] however argues that designers will not be unduly hampered as long as manufacturing features are represented at the right level of abstraction.

[CT90] starts with the basic premise of concurrent engineering: Manufacturability is best assured by simultaneously designing a part or assembly and the process used to manufacture it. The central hypothesis in this paper is that a tool that will allow designing in *manufacturing mode* will enable designers to achieve this concurrency. The authors describe a prototype CAD system, First-Cut, in which the designer creates a part by specifying the manufacturable features on the part. These are then promptly translated into process plans. In effect, a part is specified by drawing out a process-plan to manufacture it. Producibility is evaluated by ensuring that the geometric parameters of each feature lies within permissible limits. However the authors caution that "we would have to be careful about suggesting too strongly what is better or worse in terms of manufacturability. Feedback in First Cut is largely based on what is feasible, not optimal." The manufacturing plan that is created incrementally may not be the most optimal plan for machining the part. Hence it cannot be used to compare the relative manufacturability of two feasible designs. Finally the authors argue that attention to manufacturing processes will not reduce creativity, but will actually enhance creativity by providing "an intuitive feel for materials and processes".

[LDS86] describes a feature-based CAD tool for extrusion design and analysis. Three feature-types are defined: walls, intersection of walls, and fillets between intersecting walls. The major benefit of this system is the convenient user-interface it provides for specifying designs in a compact manner. The feature-based design specification is used as a data-base for automatic computation of section properties and for input to a FEM package. The issue of producibility analysis has not been explored much by the authors.

[WTG+92] describes a stamping die cost evaluation system which is an extension of the approach described in [PDM91]. The GT techniques of [PDM91] have been coupled with a methodology for converting the initial component design-with-features representation into a representation suitable for producibility evaluation.

2.6 Approximate process simulation

[TOHY85] describes an approach to evaluation of sheet-metal dies that is similar to the approach proposed in this thesis in two ways:

- The problem of producibility evaluation is decomposed in terms of different failure-modes of the process rather than in terms of geometrical features.
- Approximations and simplified models of the process are utilized.

[TOHY85] classifies sheet metal defects into surface deflection / wrinkles and fracture. The process of sheet metal forming is itself broken down into six steps:

- Blank holding
- Punch contact
- Forming progress
- Counter die forming
- Bottoming of punch.
- Elastic recovery after take-off of punch.

Surface deflection and wrinkles may appear during any of the above six stages. Fracture of the sheet is further sub-classified into fracture due to total enlongation, fracture due to local enlongation and fracture due to stretch flanging. [TOHY85] then proposes seven "evaluation functions of press forming severity".

- Blank shape in die cavity
- Spreading behavior of punch contact
- Shape change of section lines
- Generating behavior of ridge lines
- Movement of sheet

- Mean section length ratio
- Local enlongation ratio

The first five of these seven "evaluation functions" are created by process-simulations based on simplified models of the sheet-metal forming process. They are intended to be used as visual aids by the die designer. Mean section length ratio and the local enlongation ratio are metrics based on approximate models of process-physics. [TOHY85] report that this method of evaluating sheet metal dies is now a common methodology at some Japanese car manufacturers. The calculations are simple and can be done very fast. So they can be used early in design when fast feedback from manufacturing is needed.

2.7 Aluminum extrusion process modeling

Early work in the modeling of the aluminum extrusion process demonstrated that the metal flow was related to the friction conditions between the metal and the die walls. A dead-metal zone stretching from the die face to the back of the billet was seen in almost all cases. Researchers modeled the extrusion loads as a function of the reduction ratio and the die cone angle, the ratio of billet length and billet diameter, billet-container friction and temperature changes during the extrusion process[Bla86]. Other researchers [SL91, KIOA89, AIOG83] simulated the hot extrusion process using finite-elements to determine temperature distributions and extrusion loads. The application of FEM to the extrusion process is difficult because large deformations cause the mesh to distort rapidly. Additional difficulties arise from the singularity of the metal flow around sharp corners at die entry and exit. To account for the dead-metal zone researchers have used two different constitutive equations, one for the fully plastic and one for the nearly rigid zone. However, the location of the rigid zone is not known beforehand[HPS92]. Due to the complexity of the governing equations, researchers have analyzed mostly axi-symmetric or otherwise simple shapes. It is not clear when this approach will reach a stage where it can be used to analyze the complex shapes needed in practice.

Other researchers have investigated the quenching process. [Boy88] discusses many aspects of the quenching process and the problems with distortion and residual stress in practice. [RKM92] describe a procedure to determine the optimum spray configuration to obtain uniform cooling rate, material properties and minimum distortion. [Bat87] uses quench factor analysis to select quenchants that can provide an adequately high heat transfer coefficient and sufficiently low quench factor to ensure that the design minimums can be achieved in the heaviest or critical sections. Many researchers have proposed material models for analyzing the problem of residual stresses and distortion during quenching. [PP84] presents a one-dimensional analysis using temperature dependent material properties and the rate-independent Ramberg-Osgood elastic-plastic constitutive model. They report good agreement between theory and experiment. [AAM92] describes the design, execution, and mathematical modeling of a beam quenched asymmetrically on one side only. The author compares simulation results (using two different rate and temperature dependent elastic-plastic constitutive models) with experimental measurement on pure aluminum and Al-4.6% Mg (probably 5000 series alloy) bars. The difficulty of predicting the residual stresses and the resultant curvature is evident. Even with these very sophisticated and highly complex material models, the predicted value is off by a large fraction (53% with one model and 25% with the other) from the experimental measurement.

[Nel64a, Nel64b, Nel64c] describe the variety of equipment needed in an extrusion plant to conduct various post-extrusion operations such as material handling, straightening, profiling, cutting to length, heat treating and quenching. [LS81, Hor67] are comprehensive references on the subject of extrusion.

2.8 Cost estimation in product design

According to [Mil72], a product or a service has good *value* if it has appropriate performance and cost. Value is increased by either decreasing the cost or improving the performance (as long as customers need. want and are willing to pay more for improved performance). He defines the objectives of the concepts and techniques of value analysis as "to make possible a degree of effectiveness in identifying and removing unnecessary cost." Value analysis begins with five questions:

- What is the item or service?
- What does it cost?
- What does it do?
- What else would do the job?
- What would that alternative cost?

The essence of value analysis is to differentiate between functions of the design that are critical for customer acceptance of the product and those that are merely incidental. Having identified the critical set of functions, the value engineer looks for alternative solutions to achieving them. The last step is to estimate the cost of the alternative solutions and compare with the cost of the original solution. This is the most difficult step in this process. According to [Mil72], " cost estimates within plus or minus 5% will usually be sufficient and often costs within a range of plus or minus 10% will help to determine whether the particular value alternatives are of sufficient interest to warrant more exact cost determination and further study." Such accurate cost estimates may be available for off-the-shelf or stock items such as screws, nuts, bolts and washers. However cost estimation for custom-designed parts made in relatively small quantities is an imprecise art.

[Mat83] describes how estimation is done in practice. It is clear from his description that manufacturing cost estimation is very much a black art. Estimators rely on a mix of experience and broad product parameters to judge the complexity of the part and the time needed to perform the various operations. The author points out that while labor may represent a small portion of the total cost it is often used as the basis for applying manufacturing overhead. Thus errors in time estimation are magnified by the, usually large, overhead factor.

[Bus87] describes a methodology for creating computerized models to estimate the cost of producing components by plastic fabrication techniques. The basic approach to cost modeling in [Bus87] is to assume that

$$\begin{aligned} Total\ cost &= Fixed\ cost + Variable\ cost \\ Fixed\ cost &= Machine\ cost + Tooling\ cost + Building\ cost \\ &\quad + Overhead\ labor\ cost + Maintenance\ cost + Cost\ of\ capital \\ Variable\ cost &= Material\ cost + Energy\ cost + Direct\ labor\ cost \end{aligned}$$

Theoretical considerations, engineering judgment and statistically derived relationships are used to derive the individual elements that contribute to the total cost. For example, the cost of tooling is estimated by using a regression model with part weight, projected area, number of actions, and toolmaker's shop rate as independent variables. [Bus87] proposes the use of complexity factors for geometric features to account for deviations from regression models for estimating tooling cost, maintenance cost, material scrap rate, cycle time and tooling life. He suggests four complexity factors which could potentially be determined for specific geometric features.

- The cost of tooling
- The material scrap rate
- The cycle time
- The life of the tooling

However it is not clear

- if the cost differences between the wide variety of shapes created by plastic fabrication processes can be adequately captured in this manner.
- how the complexity factors would be determined for different geometric features.

[UF90] lists the desirable attributes of manufacturing system models to estimate and communicate production cost information to product designers. The key attributes of such a cost modeling tool according to [UF90] are speed, accuracy, insight into cost causality and ease in modification. A system that is at least partially automated, uses enlightened accounting principles, has principled foundations, and is modular is expected to possess these desirable attributes.

[Kap90a] describes three case-studies where the use of traditional accounting methods showed level-to-increased unit manufacturing cost at a time when quality and throughput times were improving. He argues that in advanced manufacturing environments, the emphasis on direct labor expenses and direct labor efficiency causes companies to focus on a relatively unimportant factor of production. Product designers may, as a result, get distorted images of what product features actually cost. [Kap90a] illustrates this point with an example in which the cost of surface mounting a chip was estimated to be 12 times the cost of manual insertion because of the low capacity utilization of expensive, newly installed surface mount equipment. Product designers were thus discouraged from utilizing the higher insertion speed, higher board density and better functional performance of the surface mount technology.

[Kap90b, DKMS93] argue that an accurate cost accounting system that identifies the costs arising from product complexity is necessary to evaluate alternative product designs. The authors propose to assess the cost impact of product and process features by using different complexity factors to estimate supervision, tool maintainance, quality control and scrap costs. The paper presents a case-study from an injection molding plant that manufactures a variety of automobile lamps. The specific complexity factors proposed in [Kap90b, DKMS93] for this domain are *number of moving parts in mold*, *necessity of multi-colors molding*, *ratio of run-time to warm-up time of the molding machine*, *maximum depth of die cavity*, *number of different functions performed by molded part* and *replacement cost of molding machines*. These complexity factors were suggested by the plant managers interviewed by the researchers. The data collected at the test-site correlates well with the model proposed by the authors. However, in the absence of a principled method for identifying complexity factors, it is difficult to predict the extent to which the methodology would generalize to other plants or production processes.

2.9 Where this thesis fits in

This thesis can be viewed in one of several different ways. It can be seen as:

- proposing an approach to DFx that is an alternative to using geometric features or examples to represent and evaluate producibility. In Chapter 3, I classify production processes into *trajectory-dominated* and *process-physics dominated* processes. I propose that, for process-physics dominated processes, producibility can not be evaluated by considering geometric features independent of each other as producibility problems often arise because of the way these features interact. I propose instead to develop *process-model based metrics* to check for common failure-modes of the process.
- extending the work done in [TOHY85] on approximate process simulation.
- trying to bridge the gap between theoretical models of the aluminum extrusion process and the practical problems faced by extrusion designers and manufacturers in producing complex sections. In Chapter 4 and Chapter 5 I illustrate the identification and validation of metrics using aluminum extrusion as an example.
- exploring some issues related to measurement and prediction of costs related to design producibility. In Chapter 6 I propose an extension to activity-based costing using metrics to measure and estimate costs related to design producibility.

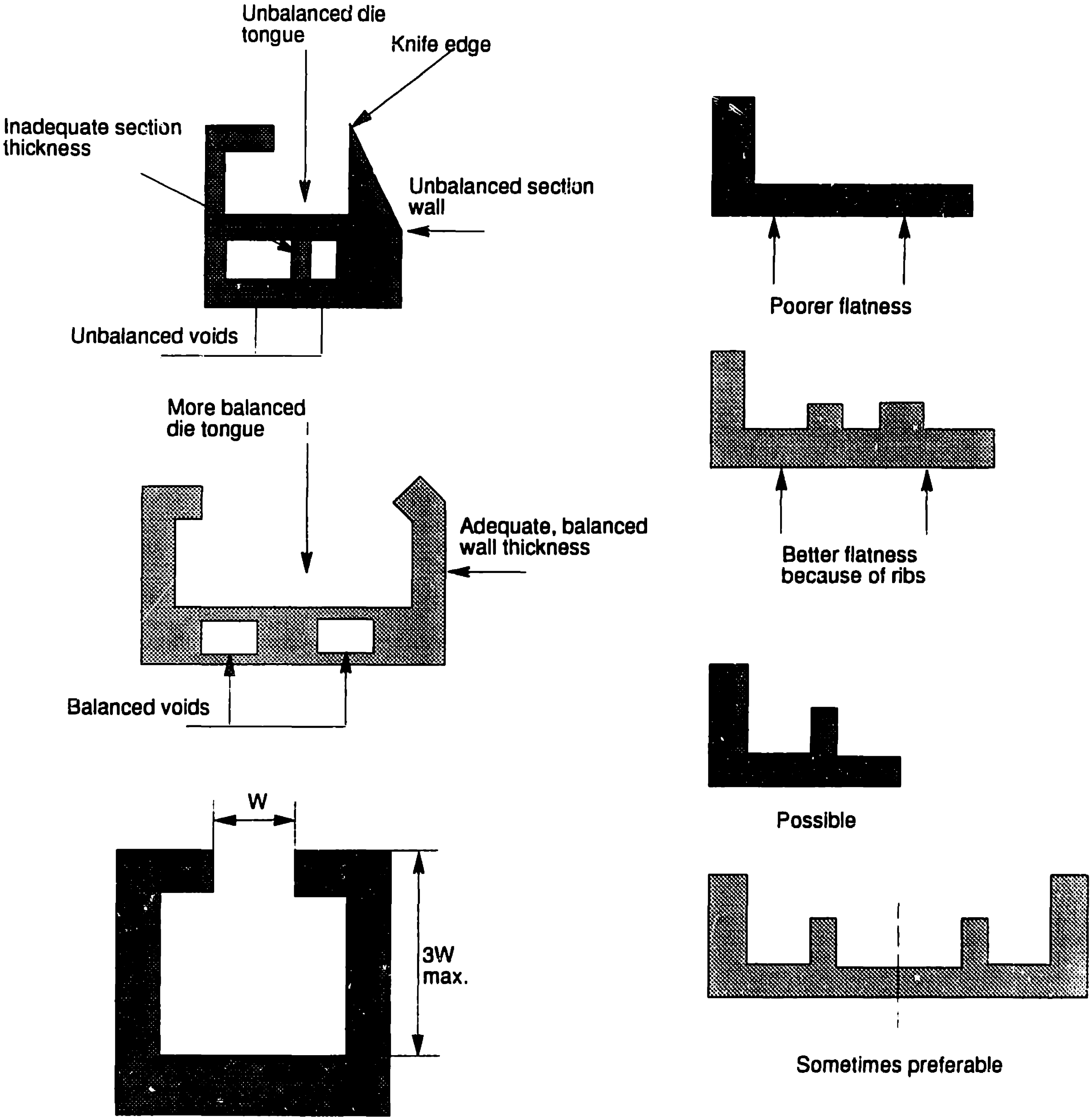

Figure 2-1: Good and bad design practice for extrusions (from [Bralla])

Chapter 3

Representation of producibility constraints

3.1 Why should producibility information be represented explicitly?

Producibility engineering has been defined as "being concerned with assuring that parts can be manufactured and assemblies made and tested to meet specifications with available or potentially available techniques, tooling and test equipment at costs compatible with the product's selling price" [How82]. This involves anticipating difficulties that may be encountered with a design based on experiences with "similar" designs in the past. The state of the art at present is to rely on the ability of experts to store, generalize, recall and apply past experiences. But real experts are scarce. Even when available their opinions may not always be consistent with their own opinion in the past or the future or with opinions of other experts.

An explicit representation of producibility information at an appropriate level of abstraction will help address many of these concerns. First it will allow automation or atleast partial automation of producibility analysis. It will distinguish what is producible from what is not producible in a consistent manner. Finally, representing information at an appropriate level of abstraction will allow predictions about parts that are not exactly identical to the specific parts that we have experience with.

The quest for an explicit representation that can be used to provide designers with appropriate and timely feedback of producibility information is the core theme of this chapter. *How should producibility information be represented?*

Some of the other questions that follow as corollaries are:

- Are certain representations more suitable for some processes than others?
- Is there a hierarchy of importance among the different issues that contribute to producibility or lack thereof? Is it possible to classify the different issues into primary or core issues and secondary or peripheral issues? To what extent is this influenced by our level of understanding of and control over the process?

3.2 How should producibility information be represented?

3.2.1 Classification of production processes

There are over 160 common production processes and this number grows with new processes being invented frequently. To have a representation that is potentially applicable over a broad range of these processes I start by classifying production processes into two groups[1]:

- **Trajectory-dominated** processes are processes in which the part shape is primarily determined by the trajectory of the tool. For these processes part

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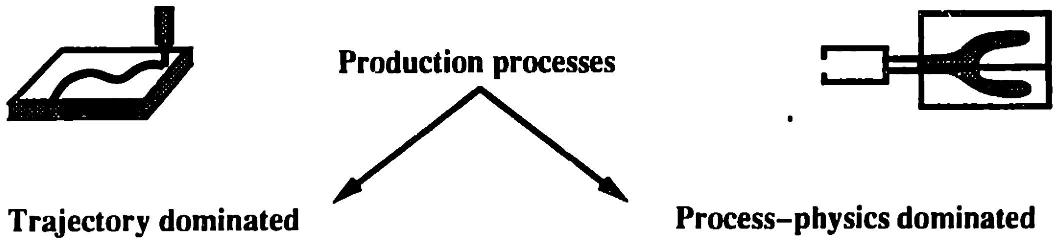
[1] A related taxonomy has been proposed in [Har91] classifying processes as either serial or parallel in nature. Serial processes are slow but flexible. They can be made to produce a variety of parts with minimum changeover effort. Parallel processes are inflexible within a part cycle framework but very fast. For a broad class of processes a flexible process is also one that can be closely controlled. In such situations a serial process is also trajectory-dominated and a parallel process is process-physics dominated. However exceptions exist. Among the different factors to determine flexibility, [Har91] gives predominance to the ability to modify output shape in real-time. A rolling process for sheet-metal production would be classified as serial. The ability to change the roll-spacing in real-time makes the process flexible even though the tooling is specific to sheet-metal production. I would classify rolling as a process-physics dominated process. I have defined my own terminology so as to minimize confusion over how a process should be classified.



ex:	Machining	Laser sheet metal blanking	ex:	Extrusion	Injection molding
	Laser sintering	CNC		Forging	Casting Stamping

Characteristics of trajectory–dominated processes	**Characteristics of process–physics dominated processes**
Gross geometry achieved by closed–loop control, geometry output is predictable.	Geometric transformation is spread out in space but happens nearly simultaneously
Part–independent tooling.	Gross geometry is achieved in open–loop mode, Difficult to predict geometry output without trial.
Processing time is relatively longer	Tool trajectory is simple

Figure 3-1: Classification of production processes

producibility can be evaluated to a large measure based on localized geometric information only. Examples of trajectory dominated processes are: machining, laser sheet metal blanking and laser sintering.

- **Process-physics dominated** processes are processes in which the part shape is primarily determined by the shape of the tool and is limited by the ability of the part to conform to tool shape due to the physics of the process. For these processes global geometric information is necessary for producibility evaluation. Examples of process-physics dominated processes are: extrusion, injection molding, forging, casting and stamping.

Fig 3-1 summarizes the main characteristics of these two classes of production processes. In trajectory dominated processes, a generic tool is moved in a pre-determined trajectory under closed loop control to create the desired shape. Because the transformation takes place in a sequential manner the processing time is often relatively large. By contrast, process physics dominated processes are very fast. The geometric transformation is spread out in space and is achieved in open-loop mode.

This classification of production processes suggests two distinguishing characteristics that can be used to guide the choice of representation for producibility constraints.

- Geometric transformation in trajectory-dominated processes is a series of transformations each of which is localized in space. In the case of process-physics dominated processes the geometric transformation is almost instantaneous but is spread out in space. This suggests that the geometric characteristics important for producibility analysis of trajectory-dominated processes are likely to be localized, while the characteristics needed for process-physics dominated processes are likely to be spread out over the part.
- In the case of trajectory dominated processes, the gross-geometry is achieved by close-loop control and the geometry output is predictable. In the case of process-physics dominated processes however, gross geometry is achieved in open-loop mode and it is difficult to predict the output geometry without trial. This suggests that we have good models to predict the physical response of machines and material for trajectory dominated processes but not for process-physics dominated processes.

These characteristics are further explored in the next two sections and are used to support arguments that

- current representations of producibility constraints are more suitable for trajectory-dominated processes than for process-physics dominated processes.
- process-model based metrics can be used to predict producibility problems in the case of process-physics dominated processes.

3.2.2 What are the issues in producibility analysis: Start-up and steady state feasibility

In this section, I consider the different issues involved in producibility analysis and argue that

- there is a hierarchy among the different issues that contribute to producibility.
- my classification of production processes allows me to group these issues into primary or core issues and secondary or peripheral issues for the two classes of processes.

The classification of the different producibility issues into primary and secondary categories leads to the operational definition of producibility used in this thesis.

The conventional model (see for example [Bus87]) for total unit cost of producing a part is:

$$\begin{aligned}
Total\ cost &= Fixed\ cost + Variable\ cost \\
Fixed\ cost &= Machine\ cost + Tooling\ cost + Building\ cost \\
&\quad + Overhead\ labor\ cost + Maintenance\ cost + Cost\ of\ capital \\
Variable\ cost &= Material\ cost + Energy\ cost + Direct\ labor\ cost
\end{aligned}$$

In this model, the cost of engineering problem solving, tool try-out and rework are lumped under tooling cost or under overhead labor. When parts are produced by processes that operate under *steady state* conditions[2] the cost contribution from start-up activities becomes vanishingly small as the number of total units produced increases. At this stage the total unit cost asymptotically approaches the sum of variable costs i.e material, processing and energy costs. However, for short run parts and for parts that are difficult to produce, start-up and debugging costs can be a significant component. Since the purpose of producibility feedback is to guide the designer in making choices that minimize total cost, producibility analysis itself may be decomposed into two major components.

The first has to do with costs associated with getting the process right i.e tooling, start-up and debugging costs. This aspect of producibility analysis is referred to as *start-up feasibility* analysis. The start-up costs of producing a design depend on the ability of the process engineers to predict the shape output by the process.

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[2] i.e a state at which the number of unanticipated events is minimal as all the bugs in the process have been ironed out.

The second has to do with *steady state* conditions. At this stage, total cost asymptotically approaches the variable cost. This aspect of producibility analysis is referred to as *steady-state feasibility* analysis.

[NW89] describe two types of process models: *technical models and economic models* which allow evaluation of these two aspects of producibility.

- *Technical models* represent the physical response of machines and materials.
- *Economic models* capture the economic consequences of these responses.

Good technical models can help achieve low or minimal start-up costs. With a good model, the process engineer will be able to design and operate the process ([NW89]) without excessive trial and error. Economic models can then be used to predict steady-state feasibility.

For processes in which the gross-geometry is produced by closed-loop control of a tool trajectory, predicting the shape output of the process is relatively easy i.e good technical models exist. Even at the time of design, it is possible to visualize the motion of the tool. When specifying a slot on an inclined face, the designer can visualize the mill creating the shape. During production, closed-loop control of the trajectory ensures that there are no large errors in the tool-path. Thus start-up feasibility is almost assured or at least easy to evaluate. The major task in producibility analysis is in estimating steady-state feasibility using economic models.

For other processes, in which the gross shape is determined in an open-loop fashion, the task of output prediction is harder. Some apparently simple shapes turn out to be difficult by a physics-dominated processes because of the lack of control. The open-loop manner in which the geometry is achieved makes it difficult for the designer and the process engineer to visualize or predict the output of the production process. The number of trial runs is much higher in this case because good technical models are not available. Thus start-up feasibility is a critical part of producibility analysis for such processes. Steady-state feasibility is a secondary issue that needs to be checked only for those designs whose start-up costs are within an acceptable range.

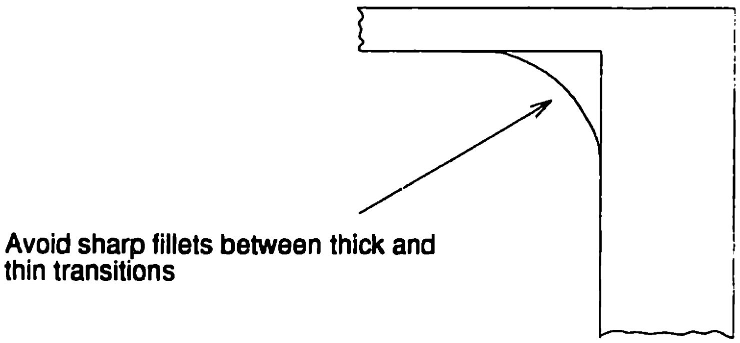


Figure 3-2: An example constraint for extruded parts from [Trucks]

The focus of this thesis is on approximate technical models to evaluate start-up feasibility for process-physics dominated processes. This leads me to define producibility in a more restrictive sense than for example [How82]. *A producible design is defined as one that avoids or minimizes costs associated with scrap, tool trials, rework/correction operations and frequent tool maintenance and repair.*

3.2.3 Is geometric feature-based representation more suitable for some processes than others?

A good abstraction of part shape for the purpose of representing producibility should make the important characteristics explicit. The predominant method of representing producibility information at the present time is in terms of geometrical features without dimensions: holes, flat faces, tapered surfaces, ribs, corners etc. These features are shown as examples of good or bad design practice. Such representation of producibility information is abstract in two different ways:

- the representation has the topological information of the feature but only some of the dimensions if at all, and
- portions of the design (other than the geometrical feature in question) are deleted from the representation. (See Figure 3-2 for an example.)

Producibility constraints represented in this manner, with localized topological information and some critical dimensions, are useful for production processes in which the process itself proceeds in a localized sequential manner i.e trajectory dominated processes. The geometric features often directly correspond to operations of the trajectory-dominated production process. For machining one can imagine features like a slot, a hole, a flat face etc. Each feature corresponds to a production operation and the set of features in a part corresponds to the number of different operations that have to be performed. Abstracting the part shape in terms of such features is tantamount to breaking up the problem of evaluating producibility into smaller, sub-problems. It is possible to attach different producibility conditions to the features. Tolerance information or surface roughness characteristics for example can be readily attached to a "hole" feature. It would easy to evaluate whether such a hole could be made on a bench drill or would need to be reamed or honed.

Unfortunately, localized geometric features do not provide this sort of decomposition for process-physics dominated processes. In other words, geometric features cannot be effectively analyzed independent of each other. The geometric transformation happens globally and almost at the same instant and producibility problems often arise because of the manner in which different geometric features interact with each other. The presence of a thin leg in an extrusion may or may not cause the extrusion to distort depending on its thickness relative to other sections of the extrusion. A narrow section in an injection mold may or may not lead to voids depending on the amount of plastic that must flow through it to reach other sections of the mold.

3.2.4 My approach

In this thesis I propose to decompose the problem of producibility evaluation for process-physics dominated processes in terms of different failure-modes of the process. Rather than decomposing the part in terms of geometric features, I propose to define different process-model based metrics to evaluate the severity of different failure modes. These metrics will indicate the degree to which process-physics will make the part conform to the ideal shape by systematically checking for previously encountered producibility problems. (See Figure 3-3.) However, rigorous technical models on which such metrics can be based are unavailable for even the most common

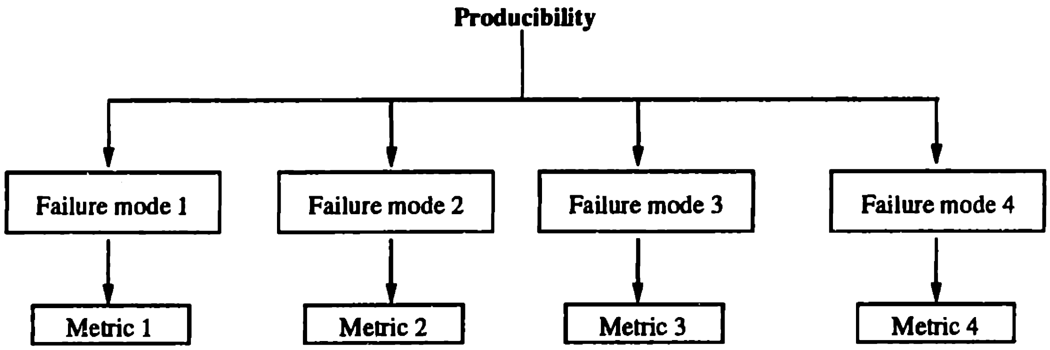


Figure 3-3: Failure driven producibility analysis

processes. Hence the metrics are based on approximations of the process-physics and must be validated to check if useful predictions can be made inspite of the approximations. I describe my methodology to identify and validate such metrics in more detail in Section 3.3.1.

3.3 Process-model based producibility metrics

A producibility metric is a process-model based abstraction of part-geometry whose value can be used to predict potential producibility problems. As an example consider the ratio of the diameter of the circle circumscribing the cross-section of an extrusion to the minimum wall thickness. The size of the press depends on this metric. Thin walls require high pressures to extrude. A large circumscribing diameter implies that the press has to be able to sustain this pressure over a larger area. This metric can be abstracted from the part geometry and can be used to predict whether the part can be extruded using available machinery. Empirically derived metrics have been used in producibility analysis for a long time. However, the metrics proposed in this thesis are based on approximate models of process physics. The power of modern day computers makes it feasible to compute such metrics relatively fast for many different parts.

The essential difference between features and producibility metrics is in their basis. I believe that the basis of some feature-types is the geometrical shapes created by trajectory-dominated operations. In [CD88], the authors argue that features used in a feature-based-design system have their basis in knowledge or reasoning in use by engineers. Either way, the foundations of features are clearly geometric. They have only a distant relation to the physics of the process. Parts made by two completely different production processes, machining and injection molding may have the same features. Producibility metrics, on the other hand, are based on models of the production process that explain the problem-causing phenomena. The metrics are defined such that their value measures some aspect of the physical phenomena.

3.3.1 Methodology to develop useful process-model based producibility metrics

The steps in identifying a set of useful metrics are (Figure 3-4 illustrates the following steps as a flow-chart):

- Identify the common producibility difficulties associated with the particular production process.
- Model each source of producibility difficulty as a stand-alone phenomenon with its own underlying physics such as: fluid flow, deformation due to applied forces, thermal expansion and shrinkage, abrasive wear etc.
- Derive metrics
    - from first principles (such as F = MA)
    - or by explaining or extending available empirical relationships from first principles
    - or by identifying causal factors that lead to occurrence of the problem in a set of sample parts. Production engineers and producibility experts can often list the different factors that they evaluate qualitatively when they are asked for their opinion on a design. (More on this in Section ??.) Once the basic concept is understood, make simplifying assumptions to define a measure that can be computed algorithmically. (Section 3.3.2 goes into this in more detail.) The simplifying assumptions may involve:

    - ∗ Using a simple constitutive relation to describe what is known to be a complicated phenomenon. For example, assuming isothermal, newtonian, incompressible flow for the polymer in the injection mold filling stage.
    - ∗ Geometric simplifications such as assuming
        - · two dimensional flow, when flow in the orthogonal direction is known to be small.
        - · uniform cross-section thickness when variations are small.
        - · uniform cross-section and negligible end effects as in beam theory

- Where possible, identify bounds or allowable values for these metrics from empirical knowledge about the problem phenomena. Metrics and their allowable values jointly represent the producibility constraints of the process. In situations where bounds cannot be easily defined, metrics can be used to rank alternative designs in the order of increasing or decreasing severity of the problem.

- Collect a set of sample parts and attempt to validate the metric by
    - Correlating the predictions made with metrics to expert opinion.
    - Correlating shop-floor experience with parts in-production with predictions made with metrics. (Passive experiments)
    - Conducting experiments to duplicate the process conditions and correlating measurements made with metric predictions.

- If a good correlation is obtained, then the metrics and the underlying modeling assumptions are validated. Depending on the complexity of the problem and the extent to which the assumptions deviate from reality, the validation exercise may occasionally fail to provide adequate supporting evidence for the metric. In such situations, some or all of the assumptions may have to be made progressively stringent till sufficient validating evidence can be obtained.

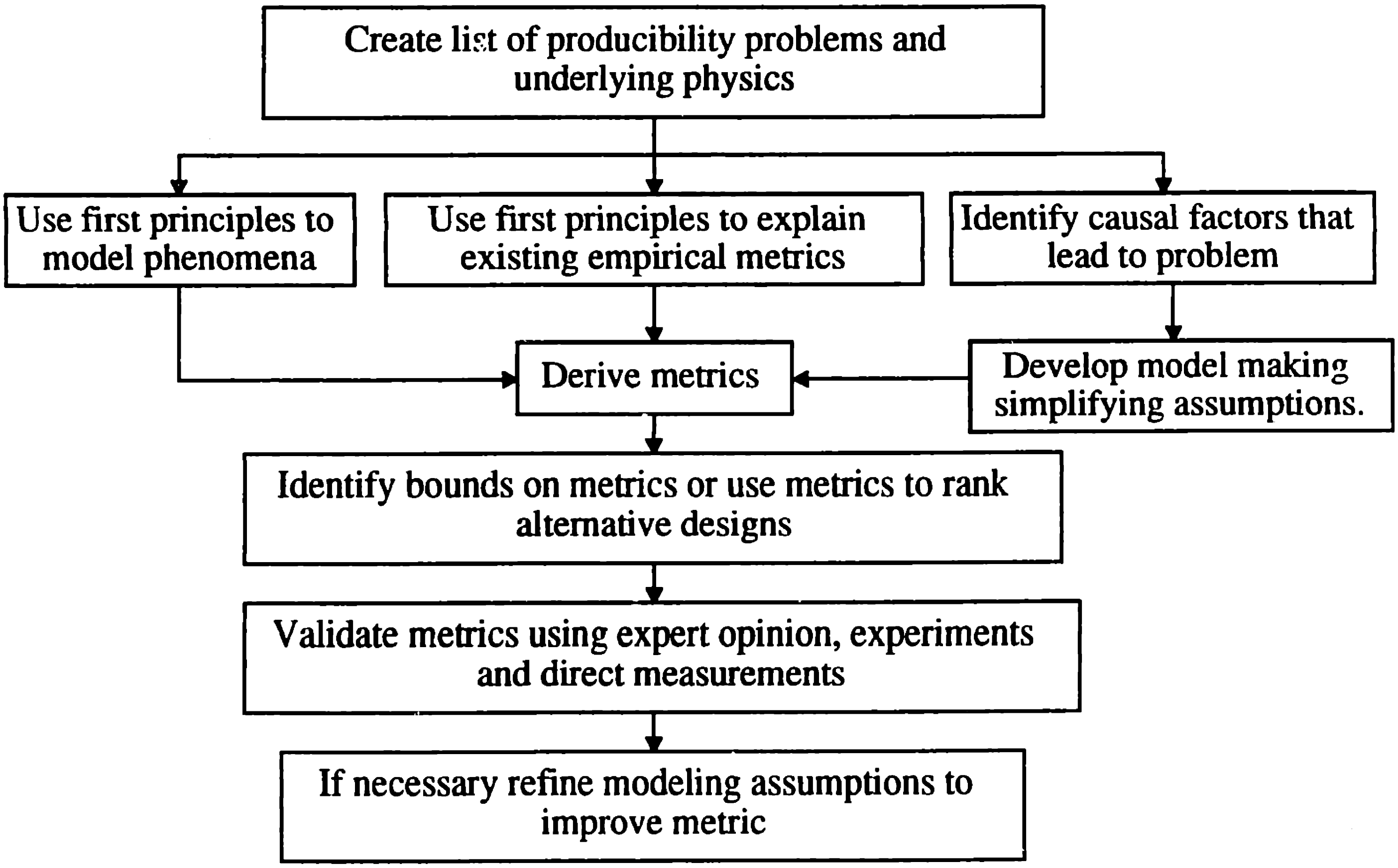


Figure 3-4: Methodology to develop process-model based metrics

3.3.2 Modeling assumptions: How accurate do they have to be?

Assumptions underlying a model need only be as accurate as the answers we expect from the model. Models that provide imprecise (approximate) answers to real problems are often quite useful. When models are unavailable, people who need answers to practical problems will rely on intuition or the next best available means. These solutions may be less optimal than what can be obtained based on a carefully thought out approximation.

Consider as an example the problem of bending of aluminum extrusion shapes at the die exit as a result of uneven rates of flow within the die. The physics underlying the problem are complicated enough to ward off attempts to apply finite-elements to analyze and predict the bending from first principles. However, die designers and die correctors are solving this problem on the shop floor on a regular basis using a combination of the approximate models that they carry in their heads and a trial and error approach.

It turns out that if we lower our expectations of the model, are satisfied with ranking alternative designs on their relative tendency to bend rather than try to predict the actual degree of bending, approximate models can serve us quite well indeed. Such an analysis can be used by extrusion designers to choose between alternative designs, and thus provide producibility feedback at a stage when it is most useful.

The power of the metrics clearly comes from the accuracy of the models and the underlying assumptions. More sophisticated models will lead to metrics with better predictive capability. However the effort involved in learning and applying such models, even when they are available, may be a barrier to their use by part designers. This thesis seeks to establish that it is possible to make useful predictions using simple assumptions and models. Fig.3-5 shows some of the different physical processes used in various common production operations and models that may be used to define metrics for these processes.

Process	Physics	Models	Metrics
Casting	Heat transfer Solidification	Chvorinov's approximation	Solidification time is proportional to $[\frac{\text{Volume}}{\text{Area}}]^2$
Forging	Plastic flow	Slab method	Forging load in plane-strain section $\frac{[\text{Dimension in metal flow direction}]^2}{\text{Dimension in orthogonal direction}}$
Injection molding	Flow Polymer orientation	[Wang – 88]	Modeling of cavity filling stage

Figure 3-5: Different physical phenomena in production processes

Chapter 4

Metrics for hot aluminum extrusion based on approximate models of process physics

4.1 Aluminum extrusion

There are a number of excellent texts [LS81, Bla86, AlOG83, Hor86] which describe the aluminum extrusion process in detail. This section presents a brief overview of the process by summarizing some salient points from these texts.

Hot aluminum extrusion is a process in which a hot billet of aluminum is forced by compression through a shaped orifice to produce long bars of uniform cross-section in the shape of the orifice. (See Figure 4-1.)

Different alloys of aluminum are extruded for various applications. The high strength hard alloys (2000 and 7000 series) are commonly used for aircraft structural applications, while the soft alloys (6000 series) are more common in construction, appliance and transportation applications. [Ass90] lists the different commercially available aluminum alloys and their approximate compositions.

Aluminum alloys are usually extruded without lubrication using flat-faced dies. Before the extrusion process can begin, the extrusion die, the billet container and billet are heated to a sufficiently high temperature. The die is then loaded into the

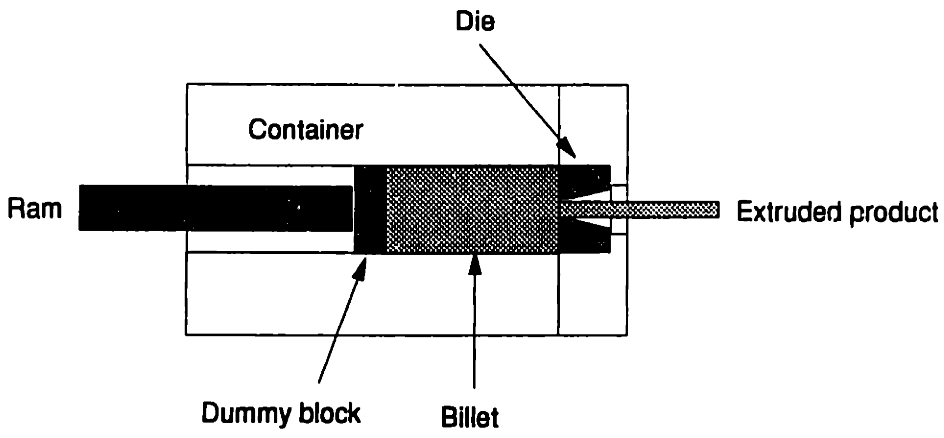


Figure 4-1: Direct extrusion

press and the extrusion process starts. A hot billet is placed in the container. A dummy block is placed behind it. The ram (hydraulically actuated) applies pressure. Eventually "break through" (the exit of the frontal section of the extrusion) occurs. The frontal section is grabbed by the puller (either manual or mechanical) who (which) keeps the extruding piece under tension. The ram stops about an inch or so short of the die face and the extrusion is broken off or sheared at the die. The remaining metal in the container is discarded as scrap. The extruded piece is pushed on to rollers on a table beside the press and moved for subsequent operations. A new billet is loaded into the press and the operation begins all over again.

The extruded part usually goes through a number of post-extrusion steps to transform it into a straight, distortion free product with desired metallurgical properties. The raw extrusion is stretched by about 2% to remove any kinks and make it straight. Depending on the alloy and the intended function it may be subject to different types of heat treatment. The extrusion may be cooled by quenching in water or it may be allowed to cool in air. Some heat treatments involve maintaining the extrusion at elevated temperatures for prolonged periods of time in an aging process. The extrusion is then stretch-straightened and de-twisted. It may also be roll-straightened after final heat treatment. [Byr73] estimates that up to 30% of the total cost of manufacturing an extruded shape can be attributed to post-extrusion processesing. [Nel64a, Nel64b, Nel64c] describe equipment required for these post extrusion operations.

Extrusion dies are subject to high temperatures, prolonged stresses, thermal shock and frictional wear. Usually they are electro-discharge machined (EDM) out of 5% chromium hot-worked tool steels (H-11, H-12, H-13)[Huf70, Bla86]. A backing die is also provided to support the die plate which forms the extruded shape. This has a less detailed cross-section than that of the die and allows clear passage to the extrusion. (See Figure 4-5.)

In extrusion of shapes, non-uniform section thickness across the shape leads to non-uniform flow. This may cause the extruded shape to bend and twist. Die designers try to compensate for this effect by varying the die land length (bearing surface) between 2 and 10 mm. Thinner sections are provided with less land length than thicker sections in order to control the metal flow. (See Figure 4-4 and Figure 4-5) Die correctors start with a die that is approximately correct and fine-tune it by running some trial billets. The die corrector studies the front end of the extrusion to get an idea of how the metal is flowing inside the die: which sections are moving too fast and which are moving too slow. The bearing land lengths are adjusted accordingly. If a production die wears out or becomes otherwise unusable before the required tonnage of extrusion is produced, a new die must be prepared. Vendors do not usually charge the extrusion buyer for such additional dies. However, they attempt to economize on the number of additional dies by making the die opening smaller than the nominal dimensions and as close to the lower tolerances as possible. As the die wears, the opening slowly grows first to the nominal dimensions and then to the outer tolerance limits. At this stage the die has to be discarded on account of wear. The hot metal shrinks as it cools down from the extrusion temperature and the die designer must account for this. The die opening is therefore made with shrinkage allowances such that on cooling, the part shrinks to the correct dimensions. All these factors make die design and correction more of an art than an exact science at the present time.

Table 4.1 from [AlOG83] provides some typical data for aluminum extrusion.

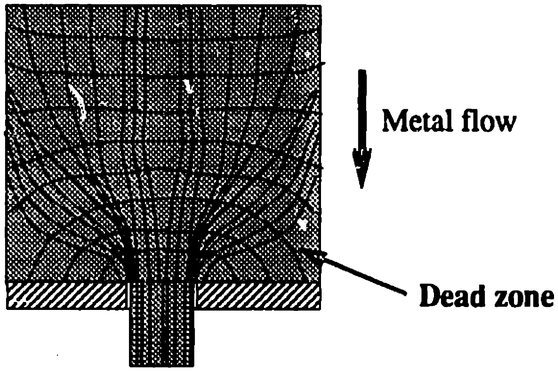


Figure 4-2: Flow pattern observed in aluminum extrusion (from [Laue])

Typical extrusion parameters	
Minimum section thickness (*in*)	0.04
Extrusion temperature ($^\circ F$)	$550 - 1050$
Extrusion exit speed, (*fpm*)	$4 - 300$
Extrusion ratio $\ln(A_0/A_1)$	4
Extrusion press diameter (*in*)	8.5

(4.1)

A_0 is the cross-sectional area of the billet; A_1 is the cross-sectional area of the extruded shape.

Speed of extrusion varies substantially depending on the alloy. Soft alloys run at 125 - 300 feet per minute while hard alloys can be extruded at a rate of 10 - 15 feet per minute. Friction at the container wall and at the die surfaces leads to a dead zone at the interface of the billet and the die while material in the center is accelerated towards the die. The shearing action requires very high extrusion forces and generates heat. (See Figure 4-2.)

Other sources of heat generation and removal are [AlOG83]:

- Plastic deformation of the aluminum billet.
- Friction between aluminum and the tooling.
- Heat transfer within the billet.
- Heat transfer between aluminum and the tooling

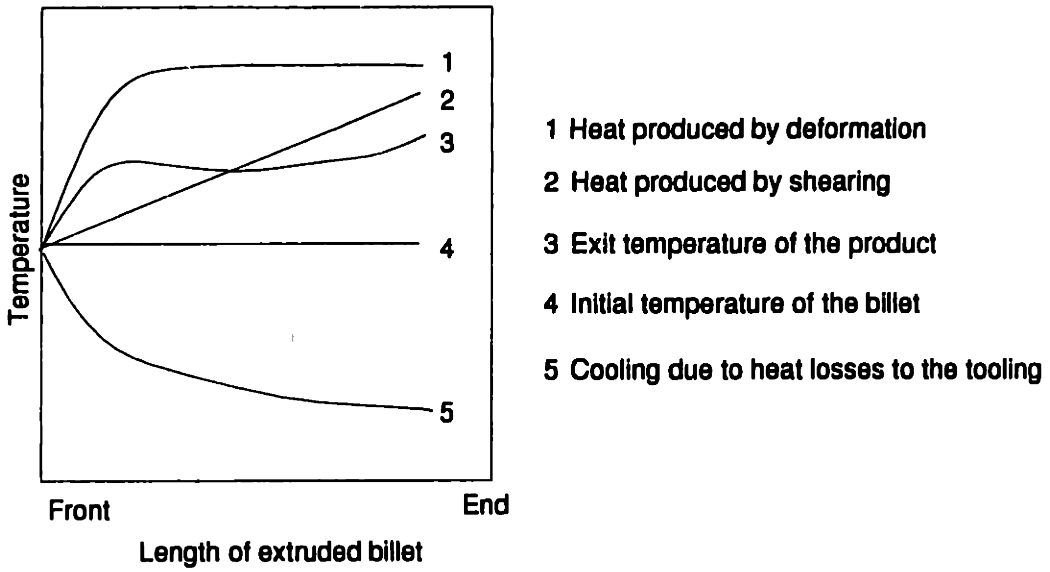


Figure 4-3: Combined effect of heat production and heat conduction (from [Laue])

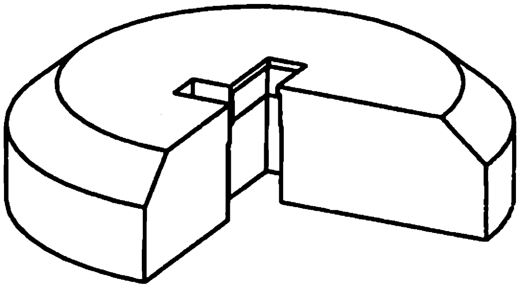


Figure 4-4: Extrusion die

- Heat transported with the extruded product.

[LS81] provides a comparison of the different sources of heat generation and removal. (See Figure 4-3.) In general, heat generation dominates over heat removal and the temperature of exiting product is higher than the initial temperature of the billet.

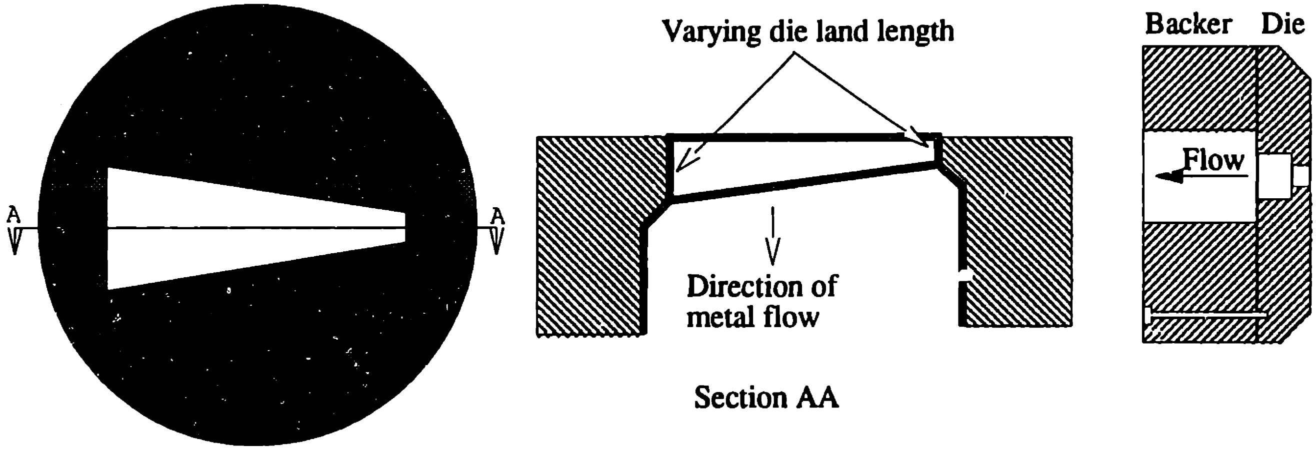


Figure 4-5: Extrusion die and backer

4.2 Producibility problems with aluminum extrusion

The first step in my methodology (as described in Section 3.3.1) for producibility analysis is to create a list of potential producibility problems. In this section I list the different producibility problems encountered during hot extrusion of aluminum alloys to make custom shapes. These problems were identified by extensive discussions with numerous production engineers, die correctors and die designers, and by surveying the available literature on extrusion practice. While the list of all possible producibility problems is potentially limitless, the effort here is to focus on commonly occurring problems. I classify producibility problems into three broad categories:

- Problems with engineering communication (Drawing and drafting errors)
- Problems with tolerance specifications.
- Problems due to extrusion shape.

While any of these three classes of problems may arise with particular extrusions my approach and the producibility metrics in Section 4.3 are oriented towards predicting problems arising from the shape of the extrusion. Difficulties in tolerance specification and engineering communication are identified but not explored any further in this thesis.

4.2.1 Problems due to engineering communication

Extrusion sections are subject to the usual problems of under and over dimensioning. Occasionally, the designer will specify dimensions on the part that are difficult to measure for quality control purposes. Vendors usually redraw an extrusion section before die design. This is done for several reasons. First the set of dimensions specified by the extrusion designer are often different from the dimensions needed to cut the extrusion die. Secondly, extrusion vendors want the drawings given to the tool and die maker to have some uniformity. Finally, the die corrector at the extrusion house may incorporate remarks or suggestions to the die maker regarding shrinkage allowances and bearing length dimensions. At Boeing, Standards is responsible for comparing and certifying this new drawing against the original. Dimensioning and other transcription errors are occasionally noticed and rectified after consultation with the vendor.

4.2.2 Problems due to tolerance specification

The standard tolerances that can be met by vendors is detailed in [Ass90], a booklet published by the Aluminum Association. These include tolerances on linear and angular dimensions in addition to flatness, straightness and twist. Extrusion tolerances differ from tolerances for machined parts in subtle ways. While specifying the tolerance on the gap in a channel section, the designer must be aware that achievable tolerance limits widen with the channel depth. The published tables have different columns for metal dimensions and space dimensions. Space dimensions between two leg-like projections are further classified by the distance of the dimension location from the base of the leg. The published tables have significant gaps in them in which case the buyer is expected to negotiate with the vendor on a case by case basis. Annealed extrusions are typically given three times the standard tolerances. Standard tolerances on angles are particularly loose. [Ass90] gives a range of plus/minus one degree for angle specifications. When tight tolerances are prescribed on parts that have non-uniform section thicknesses, the vendor typically meets the specification by post extrusion cold-working. As mentioned before, this builds in residual stresses, causing deformation at a later stage. Designers are often unaware of these nuances and this can lead to delays while the problems are sorted out.

4.2.3 Problems due to extrusion shape

Die tongue breakage

In order to produce an indent in an extrusion shape such as a channel section, the extrusion die must have a corresponding tongue to block the metal flow. This die tongue is subject to bending and shear stresses as a result of the metal pressure against the die. With deep channels the tongue might fracture under the metal pressure. Imbalance in flow on either side of the tongue could deflect the tongue to one side or the other. Die tongue deflection can cause the die opening to become narrower or wider than its nominal size and this can cause the extruded shape to go out of tolerance.

Bending of extrusion

The net effect of the drag force and the ram force could produce a significant moment that tends to bend the extrusion as it exits the die. (See Figure 4-6.) A shape comprising of elements of differing thickness tends to flow differently in different locations. Severe unevenness in flow can lead to distortion. This distortion can often be clearly seen, during trial runs of the die, in the frontal section of the extrusion as it comes out of the die. Left uncorrected, these varying flow characteristics in different parts of the extrusion would cause the part to bend and twist severely.

Waviness

With some extrusions, especially those with long thin projecting sections, waves tend to form at the thin end of the section. See Figure 4-7 for an example.

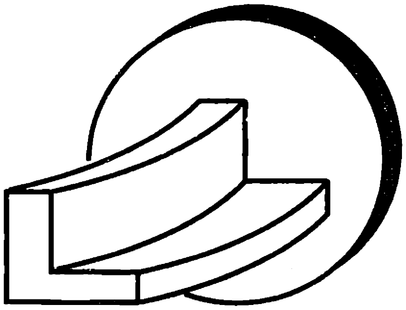


Figure 4-6: Bending of extrusion at die exit

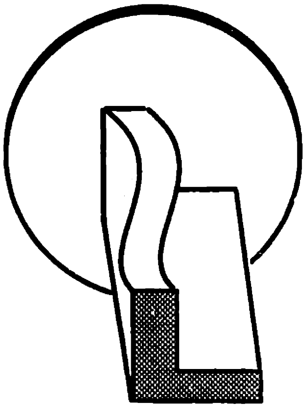


Figure 4-7: Waviness in extrusion

Hot shortness

During the extrusion process, heat is generated by various sources as described in Section 4.1. If this exit temperature, resulting from the initial billet temperature and the heat produced at the extrusion speed, is too close to the solidus temperature of the alloy, the surface tears and roughens. This is called hot shortness.

Distortion due to residual stresses

Structural aluminum extrusions are typically solution treated (precipitation hardened) after extrusion. This involves raising the temperature to about $875^{\circ}F$, quenching rapidly and then going through a prolonged aging process. The process of heating and rapid cooling produces distortion and residual stresses in the extrusion. Non-uniform section thicknesses heat and cool non-uniformly and this condition is the greatest cause of distortion. Following heat-treatment extrusions are stress-relieved and straightened by stretching. Depending on the extent of the distortion and the tolerance on straightness and flatness, extruders may perform additional cold-working operations using rollers for profile correction. Cold working can introduce substantial residual stresses in the extrusion. Such extrusions may bend and distort upon finish machining.

Die wear

Die wear is not as much of a problem with aluminum as it is with heavy metals such as copper alloys and steels because of the lower extrusion temperatures. However, sharp corners, high extrusion pressures and large surface to volume ratios can increase die wear.

Large extrusion press

Extrusion pressure increases as the wall thickness of the section is reduced. The presence of a dead-zone makes it harder to fill sections of the extrusion that are farther away from the center of the die. So a thin section farther away from the center of the die requires higher pressure to fill properly than a similar section close to the center. The press has to sustain forces approximately equal to the flow stress of the extruding metal times the circumscribing circle area. Hence the diameter of the circumscribing circle and the minimum cross-section thickness together determine the minimum press size necessary to extrude a section.

Floppy shapes

Extrusion sections are made in lengths of about twenty to sixty feet depending on material, size and weight. If the extrusion section lacks stiffness, the extrusion becomes floppy and hence difficult to handle and straighten.

4.3 Metrics for aluminum extrusion

The next step in the methodology described in Section 3.3.1 is to define metrics to predict the severity of the different producibility problems such as those discussed in the previous section. Fig 4-8 summarizes the metrics and the corresponding producibility problems.

4.3.1 Gap ratio

The gap ratio[1] is a metric to predict die tongue breakage. Fig 4-9 shows a channel section. The die to extrude such a section must have a tongue to block the metal flow. Metal pressure acting on the die face could bend and even fracture the die tongue if it is not strong enough. I define the gap ratio to be proportional to the ratio of permissible stresses in the die tongue to the level of actual stresses.

The assumptions underlying this definition are:

- In a flat-faced die, the metal pressure is uniform across the face of the die. There is no shear force acting along the die face perpendicular to the direction

---

[1] Extrusion manufacturers currently refer to $\frac{(void\ area)}{(throat\ width)^2}$ as the gap ratio. This is a purely empirical definition. My definition of gap ratio is based on physical principles and differs considerably from this.

of metal flow.

- Die deflections are small and other beam theory assumptions apply.
- Die tongue thickness is uniform.
- Deflection and stresses due to shear are small when compared to the effect of the bending moment.

$$Bending\ moment = (flow\ stress)(void\ area)(distance\ of\ void\ c.g\ from\ throat)$$

$$Stress = \frac{(Bending\ moment)(Distance\ from\ neutral\ plane)}{Moment\ of\ inertia}$$

$$Maximum\ stress = \frac{6(Bending\ moment)}{(throat\ width)(die\ thickness)^2}$$

$$= \frac{6(flow\ stress)(void\ area)(distance\ of\ void\ c.g\ from\ throat)}{(throat\ width)(die\ thickness)^2}$$

$$\frac{Permissible\ stress}{Actual\ stress} = \frac{(throat\ width)(Permissible\ stress)(die\ thickness)^2}{6(void\ area)(distance\ of\ void\ c.g\ from\ throat)(flow\ stress)}$$

Permissible stress, die thickness and flow stress are all constants. The gap ratio is defined as:

$$\frac{throat\ width}{(void\ area)(distance\ of\ void\ c.g\ from\ throat)}$$

Hence it is proportional to the ratio of permissible stresses in the die material to the actual stress level on the tongue cross-section.

4.3.2 Section balance

The section balance metric is defined to predict the tendency of the extrusion to bend at the die exit due to the moment caused by the non-colinarity of the ram force and the drag force acting on the metal flowing through the extrusion die. To define this metric several simplifying assumptions were made:

- Drag forces act uniformly around the periphery of the extrusion.
- There is no pressure differential across the cross-section of the extrusion i.e there is no flow in the plane of the cross-section close to the die exit.
- Plane cross-sections remain plane close to the die exit.

As the metal flows through the die, it is subject to drag forces acting along its perimeter. This drag force is directed opposite to the ram force acting to push the metal through the die. If the extrusion is not accelerating, the net magnitude of the drag force equals the product of flow-stress of the metal and the cross-section area of the extrusion. The resultant drag force acts through the center of perimeter, while the resultant of the forces tending to push the metal through the die acts through the center of area. The two are not collinear unless the center of perimeter coincides with the center of area. The moment acting on the section is equal to the product of flow-stress of the metal, the cross-section area of the extrusion, and the distance between the center of perimeter and the center of area. This tends to bend the metal exiting the die. However the moment of inertia of the cross-section counteracts this tendency. The metric is therefore defined to be the ratio of the bending moment and the resisting moment. (See Fig 4-10).

$$
\begin{aligned}
X_{area} &= \frac{\int_A x\,dA}{\int_A dA} \\
Y_{area} &= \frac{\int_A y\,dA}{\int_A dA} \\
X_{perimeter} &= \frac{\oint_{perimeter} x\,dl}{\oint_{perimeter} dl} \\
Y_{perimeter} &= \frac{\oint_{perimeter} y\,dl}{\oint_{perimeter} dl} \\
\Delta X &= X_{area} - X_{perimeter} \\
\Delta Y &= Y_{area} - Y_{perimeter} \\
\Theta_x &= \frac{\Delta X \; Area \; flowstress}{I_y} \\
\Theta_y &= \frac{\Delta Y \; Area \; flowstress}{I_x} \\
Sectionbalance\ \Theta &= \sqrt{(\Theta_x)^2 + (\Theta_y)^2}
\end{aligned}
\tag{4.2}
$$

4.3.3 Slenderness ratio

The slenderness ratio is defined to predict waviness of long thin leg-like sections of extrusions. I model the projecting leg as a cantilever beam loaded at the end. The maximum deflection at the end of the beam is proportional to the ratio of the length of the leg and its thickness. For a cantilever with a rectangular cross-section and unit width:

$$\delta_{max} = \frac{F\,L^3}{3\,E\,I} = \frac{4F}{E}\left(\frac{L}{d}\right)^3$$

Hence the slenderness ratio is defined as $\frac{L}{d}$.

4.3.4 Radius of curvature

The radius of curvature metric is defined to predict the tendency of extrusions to distort as a result of heat treatment and quenching.

When an extrusion is quenched, non-uniform section thicknesses cool non-uniformly. This condition produces temperature differentials, residual stresses and distortion. The tendency of the section to distort because of the temperature differential across the section is countered by the inherent stiffness of the section. The actual phenomenon is quite complicated. It involves boiling and temperature-dependent heat transfer coefficients as well as elastic-plastic deformation.

But by making simplifying assumptions such as:

- Convective heat-transfer on the external boundary, constant coefficients of heat transfer, no boiling or local vortices.
- Constant (temperature and rate independent) Young's modulus and coefficient of thermal expansion.
- Uniaxial stresses within elastic limit and other elementary beam theory assumptions .

it is possible to arrive at a closed form expression for the radius of curvature of the extrusion. It was expected that, inspite of the assumptions, sufficient physics would be captured in the model so that the metric could be used to rank order extrusions in the order of increasing distortion.

By making these assumptions, I reduce the heat-transfer problem to one of two-dimensional conduction with convective boundary conditions. This problem can be easily solved using FEM. The different constants input to the analysis program are listed below. (See Appendix C for further explanations and related derivations.)

$$\begin{aligned} Density &= 0.101\ \tfrac{lb}{in^3} \\ Specific\ heat &= 0.208\ \tfrac{Btu}{sec.^\circ F} \\ Heat\ transfer\ coefficient &= 0.00017\ \tfrac{Btu}{sec.in^2.^\circ F} \\ Thermal\ conductivity &= 0.00234\ \tfrac{Btu}{sec.in.^\circ F} \\ Initial\ temperature &= 842^\circ F \\ Water\ temperature &= 68^\circ F \end{aligned} \tag{4.3}$$

The finite-element analysis program outputs temperatures at various points inside the cross-section as a function of time. The next stage of the analysis is to use this temperature data to determine the extent of deformation. Given temperature as a function of time and position, and a temperature dependent elastic-plastic material model it is theoretically possible to simulate the deformation of the extrusion over the quench time period and estimate the final curvature of the extrusion. However, with an elastic material model such an analysis is not of much use as the curvature will go to zero as the temperature differentials across the cross sections vanish with time. To compare different cross-sections using an elastic material model, we must compare the curvature at a time instant when there is substantial temperature differential across the cross-section. For the sample extrusions in this study, a lumped system analysis indicated that a quench time period of five seconds would be appropriate for comparison purposes. (See Appendix D for this derivation.) Hence the heat-transfer finite-element analysis program was used to output the temperature at various points in the cross-section, five seconds after quench start. The output temperature profile was input to a stress analysis program to compute the radius of curvature. Fig 4-11 shows the different steps in the computation of the metric.

$$\epsilon_{total} - \epsilon_{elastic} - \alpha\Delta T = 0 \tag{4.4}$$

$$\epsilon_{total} + \frac{(y - y_c)}{\rho_y} = 0 \tag{4.5}$$

$$\sigma - E\,(\epsilon_{elastic}) = 0 \tag{4.6}$$

$$\int_{Area} \sigma dA = 0 \tag{4.7}$$

$$\int_{Area} \sigma(y - y_c) dA = 0 \tag{4.8}$$

$$\int_{Area} \frac{(y - y_c)}{\rho_y} + \int_{Area} \alpha\,\Delta T\,dA = 0 \tag{4.9}$$

$$\int_{Area} \frac{(y - y_c)^2}{\rho_y} + \int_{Area} \alpha\,\Delta T\,(y - y_c) dA = 0 \tag{4.10}$$

$$\beta - \int_{Area} E\,Y\,dA = 0$$

$$\gamma - \int_{Area} E\,Y^2\,dA = 0$$

$$\delta - \int_{Area} E\,dA = 0$$

$$\zeta - \int_{Area} E\,\alpha\,\Delta T\,dA = 0$$

$$\eta - \int_{Area} E\,\alpha\,Y\,\Delta T\,dA = 0$$

$$\rho_y - \frac{\gamma\delta - \beta^2}{\zeta\beta - \eta\delta} = 0 \tag{4.11}$$

$$y_c - \frac{\zeta\gamma - \eta\beta}{\zeta\beta - \eta\delta} = 0 \tag{4.12}$$

Equations 4.4 and 4.5 are strain-compatibility equations. Equation 4.6 is the stress-strain constitutive equation. Equations 4.7 and 4.8 are the equilibrium equations enforcing the condition that sum of externals forces and moments is equal to zero. Fig 4-12 shows the co-ordinate axes for this derivation. y_c is the y co-ordinate of the neutral axis and ρ_y is the radius of curvature in the y direction. By substituting Equations 4.4, 4.5 and 4.6 into Equations 4.7 and 4.8, closed form expressions for the radius of curvature in the y direction and the y co-ordinate of the neutral axis have been obtained (Equations 4.11 and 4.12). Similar expressions can be obtained for the curvature and neutral axis location in the x direction. (See Appendix B for details on how these integrals were evaluated.) The radius of curvature metric is the smaller of the radius in the x and y directions. This radius is a metric defined to predict the severity of bending due to temperature differentials created by varying rates of cooling during a quench operation.

4.3.5 Shape factor

The shape factor is a measure of the limits on extrusion rate because of hot shortness and also die wear due to metal friction [LS81]. The larger the perimeter for a given area greater the frictional effects. Heat generation, temperature of the extruded part, and die wear increase correspondingly.

The shape factor is defined as:

$$Shape\ factor = \frac{Section\ perimeter}{Section\ area}$$

4.3.6 Form factor

The form factor has been defined in [LS81] and correlated with the size of the press necessary for the extrusion.

$$Form\ factor = \frac{Circumscribing\ circle\ radius}{Thinnest\ wall\ thickness}$$

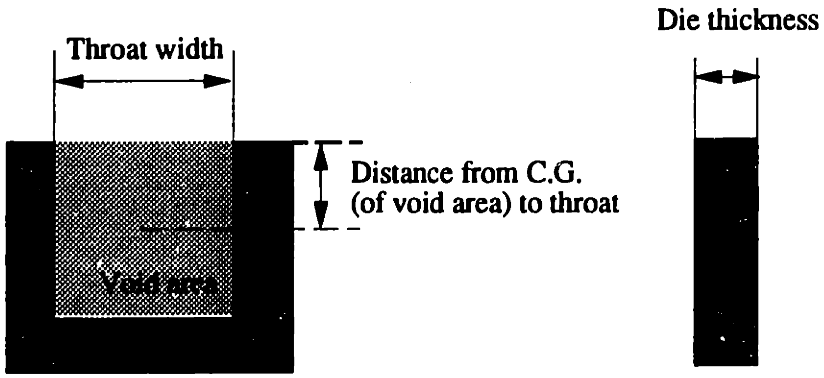
4.3.7 Section stiffness

The section stiffness is a measure of the difficulty of handling and transporting extrusions within the plant from station to station. Often extrusions are handled when hot and hence susceptible to deformation. Extrusions are made in lengths ranging from twenty to sixty feet. They can be modeled as long beams of uniform cross-section. The smaller the moment of inertia of the beam section, the greater its deflection under a given load. Hence, section stiffness is defined to be the minimum moment of inertia of the cross section.

Producibility Problem	Metrics	Higher metric value is ...
Die tongue breakage	Gap ratio	better
Bending of extrusion	Section balance	worse
Waviness	Slenderness ratio	worse
Distortion and residual stresses following heat treatment	Radius of curvature	better
Die wear, hot shortness	Shape factor **	worse
Large extrusion press	Form factor **	worse
Floppy shape, difficulty in handling and straightening	Section stiffness	better

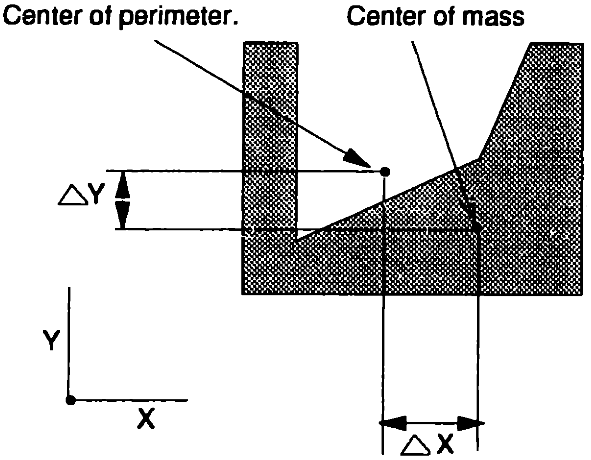
** pre–existing metrics defined elsewhere

Figure 4-8: Metrics indicate potential producibility problems



$$\text{Gap ratio} = \frac{\text{throat width}}{\text{(void area) (distance of c.g. from throat)}}$$

Figure 4-9: Gap Ratio



$$\theta_X \text{ is proportional to } \frac{\Delta X \ \text{Area} \ \text{flow stress}}{I_{yy}}$$

$$\theta_Y \text{ is proportional to } \frac{\Delta Y \ \text{Area} \ \text{flow stress}}{I_{xx}}$$

$$\text{Section balance } \theta = \sqrt{\theta_Y^2 + \theta_X^2}$$

$$\Delta X = X_{perimeter} - X_{area}$$

$$\Delta Y = Y_{perimeter} - Y_{area}$$

Figure 4-10: Section Balance

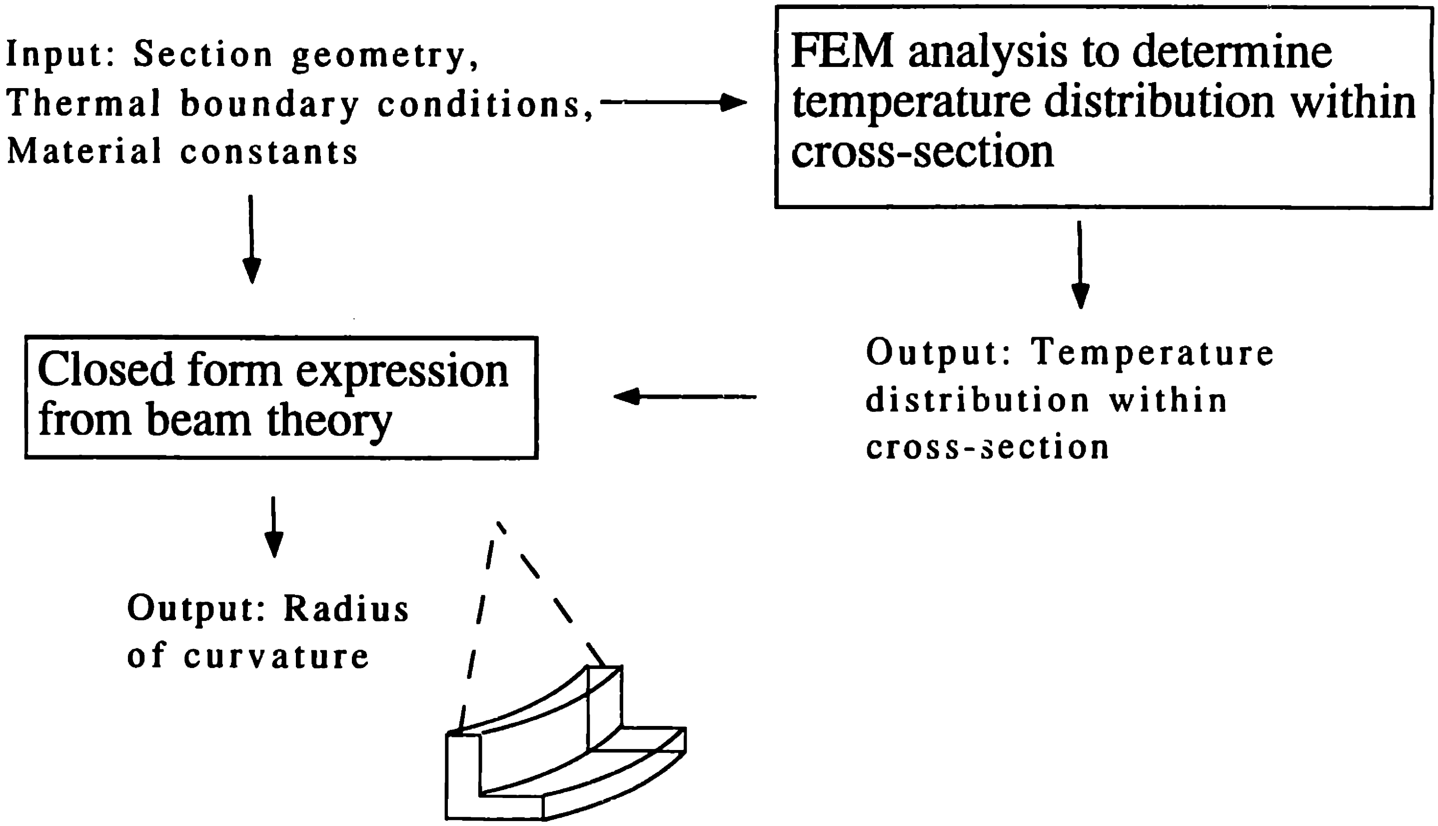


Figure 4-11: Computation of radius of curvature

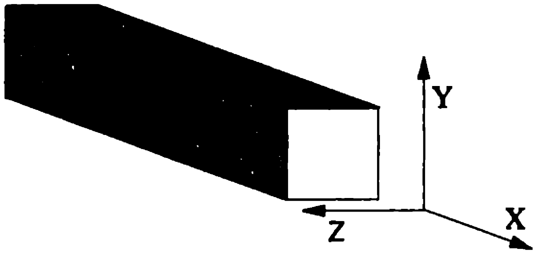


Figure 4-12: Co-ordinate axes for radius of curvature metric

Chapter 5

Validation of aluminum extrusion metrics

5.1 What needs to be validated and why?

In this chapter I discuss the validation of the aluminum extrusion metrics. The metrics are validated on two counts. First, I show that the metrics do indeed predict the severity of the producibility problem with some accuracy. Secondly, I show how metrics can be used by designers to improve producibility. Correlation of metrics to the producibility problem must be checked because metrics are based on approximate process models. Because the physics underlying the process was not completely understood, simplifying assumptions were made in order to define the metrics. Metrics are thus heuristics and the process of validation confirms how reliable they are.

5.2 What are the different sources of validating evidence?

Evidence to validate the metrics comes from several different sources. Figure 5-1 summarizes the different metrics, the associated producibility problems and indicates the source of the validating evidence. Expert opinion is the most common source.

Metrics	Expert opinion of extrusion manufacturers	Experimental measurement	Literature review	Industry practice and first principles
Gap ratio				x
Section balance	x	x		
Slenderness ratio	x			
Radius of curvature	x	x		
Shape factor	x		x	
Form factor			x	
Section stiffness	x			x

Figure 5-1: Sources of validating evidence

Other sources are results from experiments and measurements, review of published literature for data from experiments conducted by other researchers and finally industry practice. Metric can also be validated by building arguments from well known and understood first principles. Examples can be used to illustrate the usefulness of metrics in design.

5.3 Evidence from correlations with expert opinion

5.3.1 Data collection

- The first step was to collect a random sample of extrusions from the large number of extrusions designed for Boeing 777 project.

- Metrics were computed for 24 of these extrusions. A representative sample of 10[1] extrusions was chosen such as to evenly cover the range of metrics. Table 5.1 lists the metric values for these ten extrusions.

Extrusion Number	*Section balance*	*Slenderness ratio*	*Radius of curvature*	*Shape factor*	*Form factor*	*Section stiffness*
2633	$5.06E-03$	$1.56E+01$	$2.84E-01$	$2.61E+01$	$1.70E+01$	$4.59E-02$
2639	$1.99E+00$	$3.13E+00$	$6.80E-03$	$2.35E+01$	$1.09E+01$	$1.22E-03$
2641	$1.42E-01$	$7.50E+00$	$4.39E-02$	$6.05E+00$	$1.16E+01$	$2.09E+00$
2646	$2.07E-01$	$2.20E+01$	$2.56E-02$	$1.67E+01$	$1.76E+01$	$3.68E-01$
2648	$5.79E-01$	$1.09E+01$	$9.80E-03$	$1.84E+01$	$2.71E+01$	$2.99E-02$
2672	$2.22E+00$	$8.20E+00$	$2.30E-02$	$8.96E+00$	$9.60E+00$	$1.93E-01$
2674	$7.02E-02$	$1.50E+01$	$2.70E-01$	$1.03E+01$	$2.23E+01$	$7.73E+01$
2685	$5.25E-01$	$2.96E+01$	$1.59E-01$	$3.98E+01$	$1.68E+01$	$6.75E-03$
2686	$6.73E-01$	$2.50E+01$	$3.90E-02$	$3.28E+01$	$1.62E+01$	$5.69E-03$
2691	$1.21E+00$	$1.25E+01$	$2.70E-05$	$2.86E+01$	$6.33E+00$	$1.24E-04$

(5.1)

- Producibility experts at two participating extrusion vendors were given the extrusion drawings and a description of the six producibility problems listed below. They were asked to consider the problems one at a time and classify the 10 extrusions into high, medium and low categories depending on potential severity of the problem as they perceived it. Table 5.2 shows the response from the vendors.

---

[1] I chose to ask the experts to rank 10 data points only because there are practical difficulties in getting busy production engineers to volunteer their time for my validation exercise. That placed severe constraints on the number of data points.

Response from vendor 1

Extrusion Number	*Bending*	*Waviness*	*Hot Shortness*	*Heat treat distortion*	*Die wear*	*Floppy shape*
2633	*L*	*L*	*M*	*L*	*M*	*L*
2639	*L*	*L*	*M*	*L*	*M*	*M*
2641	*M*	*L*	*L*	*L*	*L*	*L*
2646	*M*	*M*	*M*	*M*	*M*	*L*
2648	*L*	*L*	*L*	*L*	*M*	*M*
2672	*M*	*L*	*L*	*M*	*L*	*L*
2674	*M*	*L*	*L*	*L*	*L*	*L*
2685	*M*	*M*	*H*	*M*	*H*	*M*
2686	*M*	*L*	*M*	*M*	*H*	*L*
2691	*L*	*H*	*M*	*L*	*M*	*H*

Response from vendor 2

2633	*L*	*L*	*H*	*L*	*M*	*L*
2639	*M*	*M*	*M*	*M*	*M*	*M*
2641	*H*	*L*	*L*	*H*	*L*	*L*
2646	*M*	*M*	*H*	*H*	*M*	*L*
2648	*H*	*L*	*H*	*L*	*M*	*M*
2672	*H*	*M*	*M*	*H*	*M*	*L*
2674	*L*	*L*	*M*	*L*	*M*	*L*
2685	*L*	*L*	*H*	*L*	*H*	*H*
2686	*L*	*L*	*H*	*L*	*H*	*M*
2691	*L*	*L*	*M*	*M*	*M*	*H*

(5.2)

5.3.2 Data analysis

From the response sheets (such as shown in Table 5.2) extrusions were chosen in pairs, one from each group of high, medium or low, for each of the six producibility problems. Appendix E contains several tables (Table E.1 through E.12) in which the expert predictions have been correlated with the metric value. Table E.7 for instance correlates the prediction made by vendor 1 with the metric value for hot shortness problem. The first column contains the extrusion which was judged to have more severe problems than the one in the second column. The metric corresponding to this problem is shape factor and its value is shown in the third and fourth columns. The last column is the sign (+) or (-) which indicates whether the difference in metric value is in the same direction as expert's prediction or in the opposite direction. This is the data for the Sign test, a non-parametrical statistical test for ordinal variables on matched samples [NS87]. The Sign test, as the name implies, focuses on the signs of the differences. If expert's predictions of hot shortness and the metric (shape factor, in this case) were uncorrelated, we would expect that on the average half the signs would be (+) and the other half (-). In this case, out of 29 data points, there are 28 (+)'s and one (-). The question that this test answers is: What is the likelihood that this a purely random occurrence? or in other words, if the probability of getting a (+) or a (-) is 0.5, then what is the probability of getting this result or something better. The probability is calculated using the Binomial distribution and the result in this case is much smaller than 10^{-5}.

5.3.3 Results

The results from Tables E.1 through E.12 have been summarized in Table 5.3. Depending on the metric definition its value is either positively or negatively correlated with problem severity. For instance, if the value of of the shape factor is higher for extrusion A than it is for extrusion B, we would expect that extrusion A is more susceptible to hot shortness. The expected correlation is positive in this case. On the other hand, if the section stiffness is higher, the extrusion is less floppy and hence the expected correlation is negative. The expected correlation can be compared with the observed correlations with predictions made by the two vendors. If a significant portion of the trials resulted in a (+) then a positive correlation is indicated. Table 5.4 lists the probability that the results in Table 5.3 could arise by random chance (i.e if there were no correlation between the metric and the expert prediction).

Summary of data in Appendix E						
Metric	*Producibility Problem*	*Expected correlation*	*Expert* 1		*Expert* 2	
			(+)'s	(−)'s	(+)'s	(−)'s
Slenderness ratio	*Waviness*	*Positive*	18	5	6	15
Shape factor	*Hot shortness*	*Positive*	28	1	23	6
Shape factor	*Die wear*	*Positive*	31	0	23	0
Section stiffness	*Floppy shapes*	*Negative*	2	25	2	29
Radius of curvature	*Heat treat distortion*	*Negative*	11	13	10	21
Section balance	*Bending at die exit*	*Positive*	12	12	20	11

(5.3)

Probability that Sign Test correlation is random			
Metric	*Producibility problem*	*Expert* 1	*Expert* 2
Slenderness ratio	*Waviness*	0.005	0.040
Shape factor	*Hot shortness*	$\ll 0.001$	0.001
Shape factor	*Die wear*	$\ll 0.001$	$\ll 0.001$
Section stiffness	*Floppy shapes*	$\ll 0.001$	$\ll 0.001$
Radius of curvature	*Heat treat distortion*	0.270	0.030
Section balance	*Bending at die exit*	0.580	0.070

(5.4)

There is an anomaly in the prediction of waviness by vendor 2. I expected a positive correlation between the metric and the expert prediction. The results from vendor 2 however indicate a strong negative correlation. I believe that this is indicative of a mis-communication of results. The experts were asked to group the designs into categories of high, medium and low problem severity. It is possible that the expert for some reason mis-interpreted this instruction and ranked the parts in order of high, medium and low producibility. Such a ranking would be negatively correlated with the metric value.

With that caveat, several important observations can be made from this data. First, this experiment shows a good correlation between the two experts as well as with the metric for four of the producibility problems:

- Slenderness ratio and waviness
- Shape factor and hot shortness
- Shape factor and die wear
- Section stiffness and floppy shapes

For the two remaining metrics (section balance and radius of curvature), the response from one of the experts indicates a much better correlation than the response from the other. But when predictions made by two experts do not concur well with each other, the correlation of one set of predictions with the metrics cannot be used as validating evidence. Under these circumstances one or both experts may be wrong or the metric may not correlate well with the problem. We must look elsewhere for evidence to support or disprove the metric.

Modified section balance metric

In Section 4.3 the section balance metric was defined to be proportional to the ratio of the bending moment to the resisting inertia.

$$\textit{section balance} = \sqrt{(\frac{\Delta X}{I_y})^2 + (\frac{\Delta Y}{I_x})^2}$$

An expert utilizing this model would have to visualize the cumulative effect of four different quantities. This is a hard task to do by just looking at the shape. I hypothesized that the experts were using a modified section balance model that was somewhat simpler to evaluate. The modified section balance metric is proportional to the bending moment rather than to the ratio of the bending moment and the moment of inertia.

$$section\ balance = \sqrt{(\Delta X)^2 + (\Delta Y)^2}$$

Table 5.5 lists the section balance metric values using the original as well as the revised definition.

Section balance values with original and modified definitions		
Extrusion Number	*Original definition*	*Modified definition*
2633	$5.06E-03$	$2.32E-04$
2639	$1.99E+00$	$1.38E-02$
2641	$1.42E-01$	$2.96E-01$
2646	$2.07E-01$	$7.65E-02$
2648	$5.79E-01$	$1.89E-02$
2672	$2.22E+00$	$4.47E-01$
2674	$7.02E-02$	$6.30E-02$
2685	$5.25E-01$	$3.74E-03$
2686	$6.73E-01$	$6.38E-03$
2691	$1.21E+00$	$1.92E-04$

(5.5)

Tables E.13 and E.14 correlate the modified value of the section balance with expert predictions. Table 5.6 summarizes the results. A high degree of correlation can be seen with this revised definition of the metric. The probabilities that the results could arise from random chance are $\ll 0.001$ in both cases. This suggests that the experts could in fact be using a simpler model than was used in the definition of the original section balance metric. However, physical insight suggests that the tendency to bend depends on the bending moment as well as the resisting inertia. Thus, in this case, the metric which is based on a relatively simple model accounts for more of the physics than what experts normally do.

Correlation of revised section balance metric						
Metric	*Producibility Problem*	*Expected correlation*	*Expert* 1		*Expert* 2	
			(+)'s	(−)'s	(+)'s	(−)'s
Section balance	*Bending at die exit*	*Positive*	20	4	28	3

(5.6)

5.4 Evidence from experimental measurements

5.4.1 Section balance

The section balance metric was defined to predict the tendency of the extrusion to bend at the die exit due to non-colinearity of the ram force and the resultant of the drag forces acting around the periphery of the cross-sections. In practice, die designers address this issue by varying the bearing land lengths around the periphery of the section as was discussed in Section 4.1.

Data collection

In order to validate the section balance metric, I picked a set of 10 production dies from a large collection of dies at an extrusion plant. I measured the die bearing length around the periphery for each die. This could be accomplished by first measuring the die thickness and then using the depth gage in a vernier caliper to read the depth of relief surface from the die face. The difference is the length of the bearing at that location. Figure 5-2 shows one such extrusion. The numbers around the periphery are the bearing lengths (in inches) for the corresponding section. The die thickness for this extrusion was one inch.

From the die bearing measurements and the extrusion section drawings, it is possible to compute the center of area, the center of perimeter and also an effective center of perimeter as defined in Table 5.7.

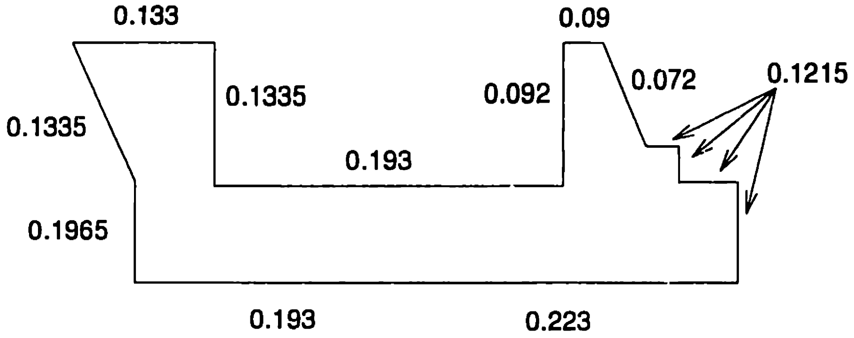


Figure 5-2: Bearing length (in inches) around periphery in extrusion die

	X	Y
Center of area	$\frac{\Sigma x_i.A_i}{\Sigma A_i}$	$\frac{\Sigma y_i.A_i}{\Sigma A_i}$
Center of perimeter	$\frac{\Sigma x_i.P_i}{\Sigma P_i}$	$\frac{\Sigma y_i.P_i}{\Sigma P_i}$
Effective center of perimeter	$\frac{\Sigma w_i.x_i.P_i}{\Sigma w_i.P_i}$	$\frac{\Sigma w_i.y_i.P_i}{\Sigma w_i.P_i}$

(5.7)

A_i is the i^{th} area element. P_i is the i^{th} perimeter element. x_i and y_i are the co-ordinates of the center of i^{th} area and perimeter element. w_i is the bearing length at the i^{th} perimeter element.

Analysis

The sequence of arguments is as follows:

- Using the measurements I show that the distance between the effective center of perimeter (effective CP) and the center of area (CA) is less than the distance between nominal center of perimeter (CP) and the center of area (CA).
- In other words, measurements indicate that the die corrector assigns the bearing lengths in a way as to bring the effective CP closer to CA.
- In my model, the distance between CP and CA is proportional to the bending moment on the section.

- The original definition of the section balance is the ratio of this distance to the moment of inertia of the cross-section.

$$\mathit{section\ balance} = \sqrt{(\frac{\Delta X}{I_y})^2 + (\frac{\Delta Y}{I_x})^2}$$

- The modified definition of section balance is the distance between CP and CA itself.

- The measurements provide validating evidence for both.

From the extrusion drawings and the bearing dimensions, the center of area, perimeter and weighted perimeter were computed. Table 5.8 lists the distance between

- the center of perimeter and area in column 2

- the weighted perimeter center and the center of area in column 3

- the weighted perimeter center and the perimeter center in column 5

Column 4 in Table 5.8 records whether column 2 is larger than column 3 (indicated by a (-)) or smaller (indicated by a (+)). Figure 5-3 illustrates the data in Table 5.8 graphically.

1	2	3	4	5	6
Ext Num	*Distance(Area, Perimeter*	*Distance(Area, Eff Perimeter)*	*Change*	*Distance(Perimeter, Eff Perimeter)*	$\frac{Dist(Area,\ Perim)}{Perim}$
4301	0.0288	0.0257	(−)	0.0498	0.017
4355	0.0240	0.0440	(+)	0.0201	0.005
4391	0.0457	0.0318	(−)	0.0280	0.018
4310	0.3642	0.0556	(−)	0.4161	0.045
4535	0.1482	0.0168	(−)	0.1319	0.013
3937	0.1919	0.0480	(−)	0.1439	0.015
4532	0.0032	0.0137	(+)	0.0167	0.001
4083	0.0762	0.0666	(−)	0.0097	0.009
4346	0.0686	0.0153	(−)	0.0574	0.026
3879	0.0325	0.0381	(+)	0.0159	0.003

(5.8)

Section balance values before and after correction			
Extrusion Number	*Before correction*	*After correction*	*Change*
4301	27.000	33.000	+
4355	0.588	0.990	+
4391	50.000	22.000	−
4310	1.850	0.599	−
4535	2.400	0.280	−
3937	0.265	0.066	−
4532	0.269	0.827	+
4083	8.865	7.740	−
4346	38.000	8.910	−
3879	0.680	1.106	+

(5.9)

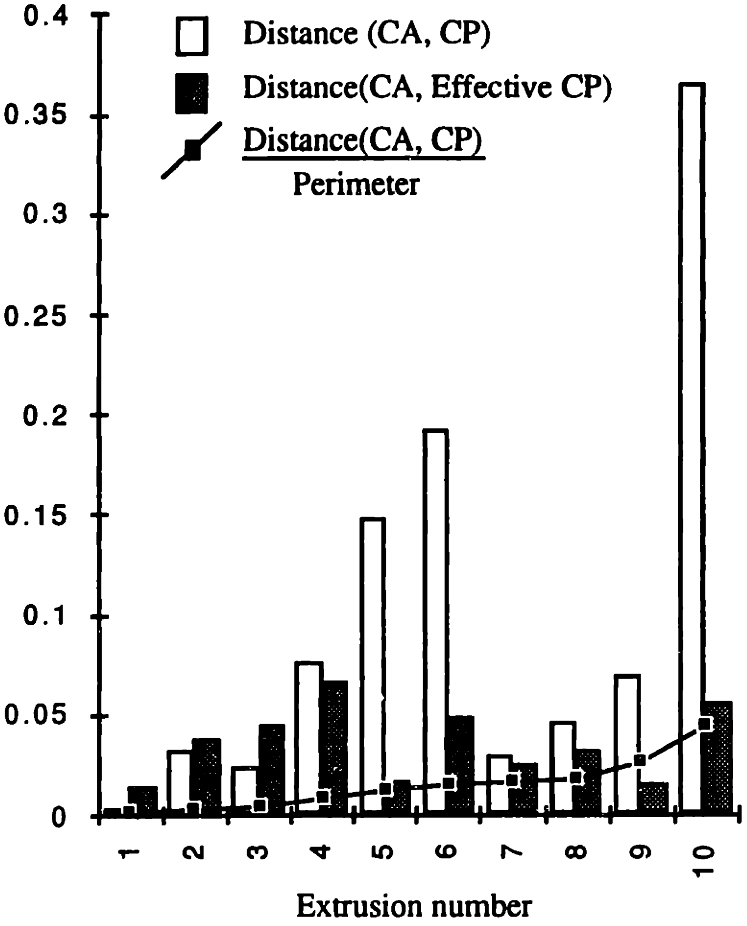


Figure 5-3: Relative distances for the ten extrusions

Results and Discussion

The data in column 4 of Table 5.8 indicates that the movement of the effective center of perimeter is *towards* the center of area. A (-) indicates that the effective center of perimeter has moved closer and a (+) indicates that the effective center of perimeter has moved farther from the center of area. Seven of the ten dies measured show a movement *towards* the center of area. This can be seen in Figure 5-3 also. The discrepancy in the three remaining cases can be explained as follows.

- Errors in measurement could have accumulated. In the 3 deviant cases, the distance between the center of perimeter and the center of area is small relative to the total perimeter. Hence small errors in the measurement of the bearing lengths could lead to a high level of noise in the final result.
- The underlying assumption, that the assignment of bearing lengths by the die designer improves the straightness of the extrusion, is reasonable in the case of poorly balanced extrusion sections. However when the extrusion section is not prone to bending in the first place this assumption may no longer be true.

Column 6 in Table 5.8 gives the ratio of the distance of the center of perimeter from the center of area to the total perimeter of the section. It can be seen that in the three cases where the effective center of perimeter seems to move away, this ratio is of an order of magnitude smaller than the value in the other cases.

With these caveats, the measurements indicate that the die corrector assigns bearing lengths in order to make CP closer to CA. And hence the distance between CP and CA (the modified section balance metric) is a measure of the tendency of the section to bend.

Table 5.9 lists the value of the original section balance metric before and after die correction. In the ideal case, the metric value is expected to decrease after correction in all ten cases. As shown in Table 5.9 this is true in six of the ten cases. In Table 5.8, we saw that the distance between CP and CA increased after die correction in three cases. The same three extrusions show an increase in the value of the section balance metric in Table 5.9. In one case the moments of inertia I_x and I_y differ by an order of magnitude. In this case, Table 5.8 shows that the distance between CP and CA decreases after correction however the metric value in Table 5.9 increases.

Thus actual die measurements provide evidence to indicate that the section balance metric correlates with extrusion bending. The evidence for the revised or the simplified definition is slightly stronger than for the original definition of section balance.

5.4.2 Radius of curvature

The radius of curvature metric was defined to predict the degree of distortion caused by solution treatment and subsequent quenching. During solution treatment, the extrusions are maintained at about 870 F for as long as it takes for the metal to attain that temperature. The extrusion is then brought down to room temperature as quickly as possible by quenching it in a bath of water. As a result of uneven rates of cooling in different parts of the section the extrusion develops residual stresses and distorts. Extrusion vendors correct this distortion by stretching or otherwise cold working the extrusion. This builds in residual stresses in the part which can then deform on finish machining.

Data collection

In order to validate the radius of curvature metric, I collected 6 samples of Al 7075 extrusions that had been designed at Boeing. Each piece was cut to a length of 12 inches. To eliminate the effect of residual stresses from previous cold working and heat treatment, I stress-relieved (annealed) each part by keeping it at a temperature of 842 F for three hours and letting the part cool down in air. I then placed the part on a surface table and measured the maximum deviation from straightness by inserting feeler gages between the surface table and the extrusion. This is the initial deviation d_1. The extrusions were then heated to 870 F for 2 hours and quenched in a tub of room temperature water. I measured the post quench deviation from straightness (d_2).

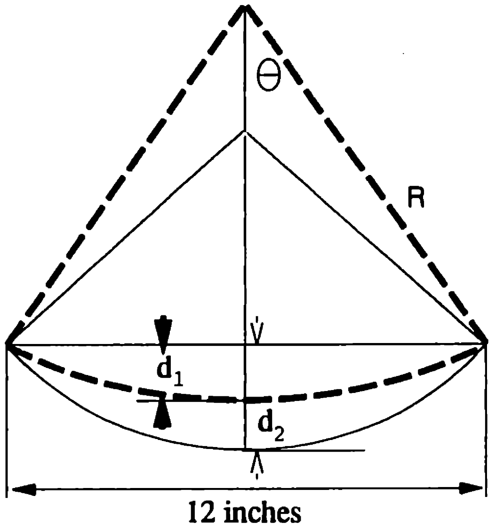


Figure 5-4: Computing the radius of curvature

Figure 5-4 illustrates how the radius of curvature may be computed by measuring the deviation from straightness.

If R be the radius of curvature of the the section and d be the deviation then

$$\begin{aligned} d &= R\,(1 - Cos\theta) \\ Cos\theta &= (1 - \frac{\theta^2}{2}) \\ \theta &= Tan\theta\ (for\ small\ \theta) \\ Tan\theta &= \frac{6}{R} \\ R &= \frac{18}{d} \end{aligned}$$

The change in the radius of curvature is given by

$$\Delta R = R_2 - R_1 = \frac{18(d_2 - d_1)}{(d_2 d_1)}$$

I gave samples and engineering drawings of the six extrusion sections to two participating vendors and asked them to rank the extrusion in the order of potential distortion. The extrusions were also ranked by computing the value of the radius of curvature metric. Table 5.10 lists the measured and computed data.

Ext Num	*Measured change in curvature*			*Metric Value*	*Expert1 Rank*	*Expert2 Rank*
	d_2	d_1	$\frac{18(d_2-d_1)}{(d_2d_1)}$			
1447	0.0270	0.0055	2606 (4)	47.5 (1)	3	2
1255	0.0580	0.0100	1489 (3)	37.1 (2)	1	1
1587	0.0115	0.0090	434 (1)	10.7 (3)	6	3
6250	0.0100	0.0080	450 (2)	9.5 (4)	4	4
2270	0.0400	0.0010	17550 (6)	7.5 (5)	5	6
1665	0.0160	0.0030	4875 (5)	6.7 (6)	2	5

(5.10)

Sign test results			
	Measurement	*Expert1*	*Expert2*
Metric	9 (0.3)	8 (0.5)	13 (0.003)
Measurement	–	6 (0.85)	11 (0.06)
Expert1	–	–	10 (0.15)

(5.11)

For the data in Table 5.11 the number of trials was 15 in each case. The table show the number of trials that showed the correct correlation. The number in the parenthesis is the probability that this result could be obtained from random chance.

Results and Discussion

Unfortunately, the data collected in this experiment (as shown in Table 5.11) does not suggest a good correlation between the rankings. The best correlation 13 (0.003) is obtained between expert number 2 and the metric. This reflects what we already observed in the section on expert opinion where we saw expert 2 correlate with the metric much better that expert 1. However the correlation value of 9(0.3) between the ranking based on experimental measurements and the ranking based on the metric suggests that a more involved model might be better suited for this problem. As it stands, the metric is more effective at predicting expert 2 than the problem. Alternatively, it is possible that the experiment or the measurement was faulty. Further, the poor correlation between the predictions of expert 1 with the experimental measurements indicates that experts have difficulty with this problem also.

The definition of the radius of curvature metric rests on several assumptions.

- Convective heat transfer during quenching with no boiling or local vortices.
- Temperature and rate independent material properties.
- Uni-axial stresses within elastic limit and other beam theory assumptions.

These assumptions were made even though the actual physics was known to be much more complicated. It was hoped that a simple metric defined with these assumptions would capture sufficient physics to be able to rank order the extrusions in the order of increasing distortion. Unfortunately our experimental results indicate otherwise. Hence, at this stage, we must go back to our assumptions and make one or more of them more stringent. For example, the simple temperature and rate independent elastic material model could be replaced by a Ramsberg-Osgood elastic plastic model with temperature dependent co-effiencients, k and n. [2]

$$\epsilon = \frac{\sigma}{E} + k(\frac{\sigma}{E})^n$$

We could for the present retain the two other assumptions of convective heat transfer and uni-axial stress. With a temperature dependent non-linear elastic-plastic model, it is no longer possible to solve for the radius of curvature in closed form as was done in Section 4.3.4. Rather we must recourse to finite-elements and numerical solution of the governing equations. While such an approach of gradually making assumptions more stringent till theory correlates with experiment is likely to yield the correct metric, it was felt that such work is outside the scope of this thesis and hence is not pursued any further here.

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[2] [PP84] presents a one-dimensional analysis of residual stresses in a Al 7075 with this model and reports good agreement between theory and experiment.

5.5 Evidence from survey of available literature

5.5.1 Form factor

[LS81] provides data (sample shown in Table 5.12) which illustrates the relationship between section thickness, circumscribing circle diameter and extrusion pressure. The table lists the thinnest possible sections than can be extruded given the circumscribing circle diameter of the extrusion. It also shows the extrusion pressure required. Although [LS81] is not explicit about this, it seems that this table was drawn up based on some range of commercially available press sizes. In general, the thickness of the thinnest section dictates the pressure required for extrusion. The circumscribing circle diameter must be smaller than the diameter of the press-bore. Hence the form factor, which is the ratio of the circumscribing circle diameter to the minimum section thickness, may be used to predict the size of extrusion press. Figure 5-5 illustrates the relationship between minimum wall thickness and circumscribing circle diameter for AlMg3 alloy as given by Table 5.12.

	Circumscribing circle diameter of section, mm										
	< 25	< 50	< 75	< 100	< 150	< 200	< 250	< 300	< 350	< 400	< 450
Alloy	*Minimum wall thickness of section, mm*										
AlMg3	1.0	1.0	1.2	1.5	2.0	2.5	3.0	4.0	4.0	5.0	6.0
AlMg5	1.0	1.0	1.2	1.5	2.0	2.5	3.0	4.0	4.0	5.0	6.0
AlCuMg1	1.2	1.2	1.2	1.5	2.0	3.0	5.0	5.0	6.0	7.0	8.0
AlCuMg2	1.2	1.2	1.2	1.5	2.0	3.0	5.0	5.0	6.0	7.0	8.0
Extrusion Pressure	10 *MN*			25 *MN*		35 *MN*	50 *MN*		80 *MN*		

(5.12)

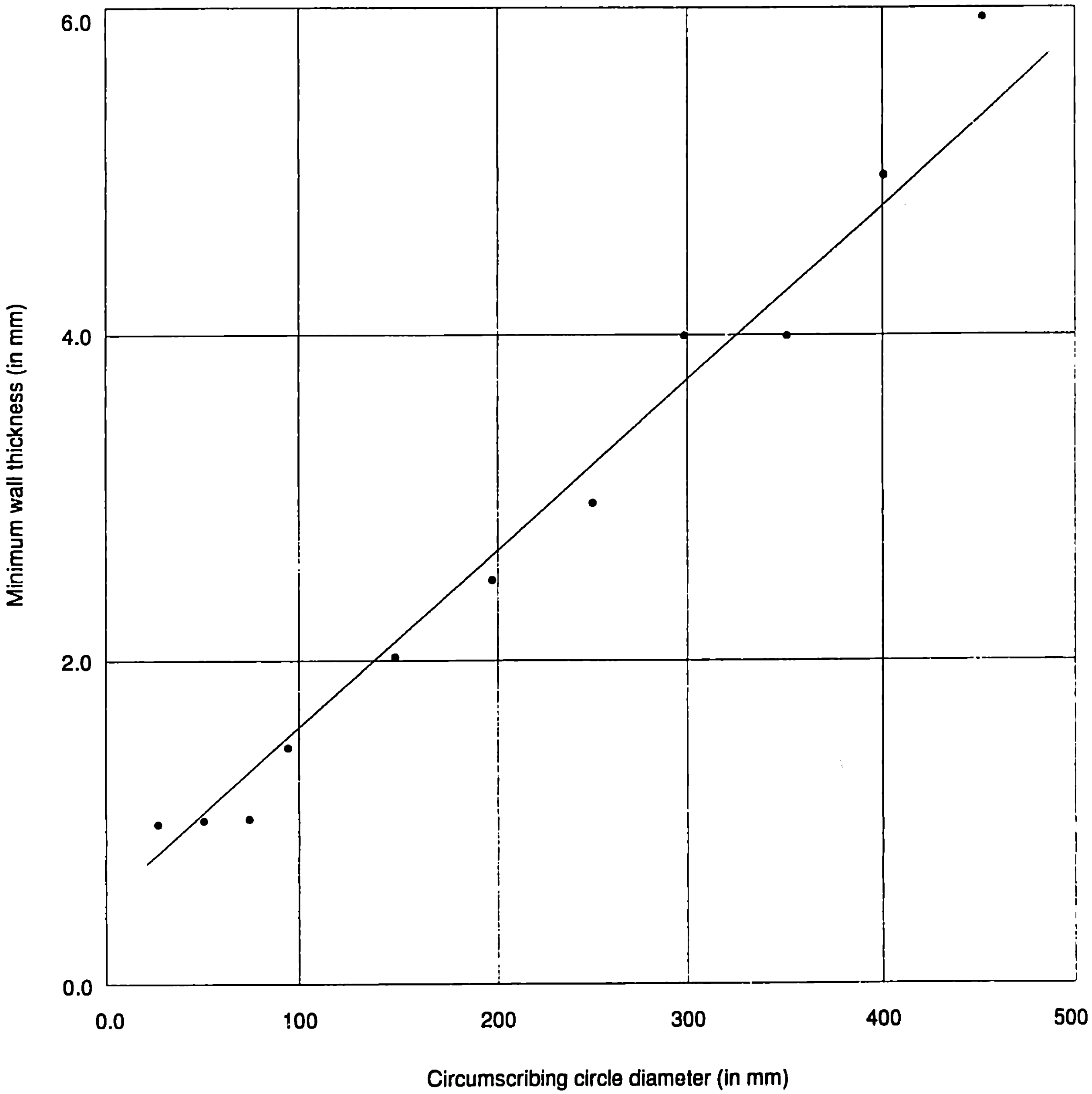

Figure 5-5: Minimum wall thickness as a function of circumscribing circle diameter for AlMg3

5.5.2 Shape factor

[VH69] studied the correlation of section shape to extrusion load. They define circumferential ratio f_s as

$$f_s = \frac{Section\ perimeter}{Circumference\ of\ round\ bar\ with\ same\ area}$$

They then related the extrusion loads measured during the lubricated extrusion of aluminum section to this shape factor. [LS81] reproduces the results obtained by [VH69]. The experimental results indicate a parabolic relationship between f_s and extrusion load. (See Figure 5-6).

If P be the perimeter and A be the area of the cross section, then $f_s = \frac{P}{\sqrt{4\pi A}}$. Hence the data in [VH69] suggests that the extrusion load increases with perimeter and decreases as the area increases. The shape factor as defined in Section 4.3 is given by $\frac{P}{A}$. Hence the general tendency of the extrusion load is to increase with shape factor. Higher extrusion loads lead to more heat generation and die wear. Thus the data in [VH69] provides additional evidence to support the use of shape factor as a measure of hot shortness and die wear.

5.6 Industry practice, beliefs and first principles

5.6.1 Gap ratio

In current industrial practice as well as in design guides, the gap ratio is defined as the ratio of the depth of the die tongue to its width. [Bra86] for instance recommends that this ratio not exceed 3 for aluminum alloys to prevent tongue breakage or distortion. Unfortunately no justification other than "industrial practice" is presented either for the relevance of the ratio or for the suggested limits on its value.

The gap ratio as defined in this thesis is based on the following assumptions:

- In a flat faced die, the metal pressure is uniform over the die face. There is no shear stress acting along the flat face of the die perpendicular to the direction

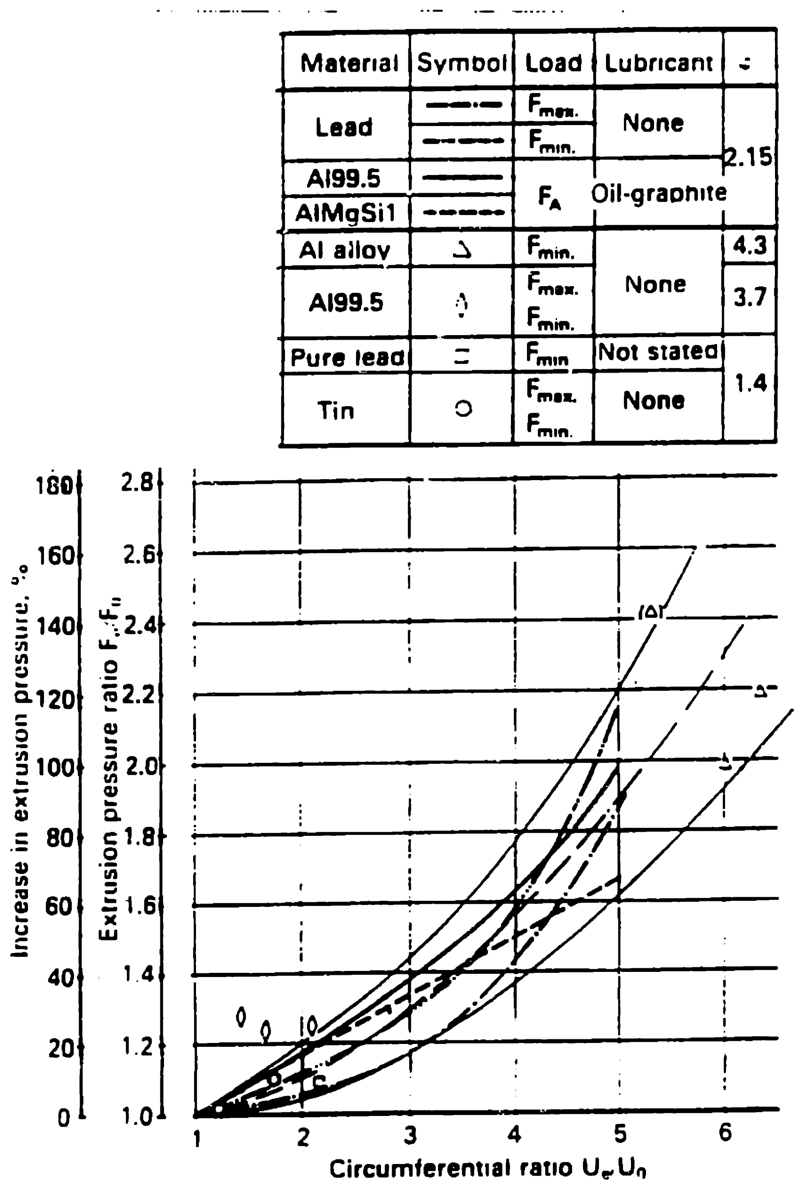

Figure 5-6: Increase in extrusion load as a function of the circumferential ratio (from Laue)

of metal flow.

- The die tongue thickness is uniform.
- The die tongue deflects (by a small amount) like a cantilever (a beam fixed at one end) under the influence of the metal pressure.
- Deflection due to shear force is small when compared to deflection due to the bending moment.

With these assumptions, the maximum stress in the die tongue can be predicted by using simple beam theory. The gap ratio is defined to be the ratio of the maximum permissible stress to the maximum stress. While it seems reasonable, short of actually measuring the die-stresses as the extrusion proceeds, we must rely on the reader's belief that a gap ratio based on beam theory would better capture tongue deflection and breakage than a ratio that is purely empirical.

5.7 Summary of validation results

Figure 5-7 summarizes the results of the validation exercise. On the basis of evidence presented here, we have reason to believe that six of the seven proposed metrics can be used to make useful predictions regarding producibility.

5.8 Use of metrics to improve design producibility

This section illustrates, with an example, the use of metrics in improving design producibility. Figure 5-8 shows an extrusion designed for the Boeing 777 aircraft. Table 5.13 lists the different metrics and their values. The number in parenthesis adjacent to the metric value is the ranking of this extrusion in a group of ten; the larger the rank, the worse off the design on the corresponding aspect of producibility. As the design scores poorly in *section balance* and *radius of curvature*, it is appropriate

Metrics		Expert opinion	Experimental Measurement	Literature review	Industry practice and first principles
Section balance	Original	X	✓		
	Modified	✓	✓		
Slenderness ratio		✓			
Radius of curvature		X	X		
Shape factor		✓		✓	
Form factor		✓		✓	
Section stiffness		✓			✓
Gap ratio					✓

Figure 5-7: Summary of validation results

to explore alterations which may improve performance in these aspects. The *section balance* worsens as the centers of perimeter and area move farther apart. It improves as the moment of inertia of the section increases. From Figure 5-8, we can see that large circular area in the lower left corner would tend to move the center of perimeter away from the center of area. Hence in the suggested alternatives, this solid area is replaced by a arc of thickness comparable to the other elements of the section. Figure 5-9 and Figure 5-10 are two possible alternatives[3]. Table 5.13 lists the metrics values for these alternatives. As can be seen from the rankings, the alternatives are better than the original in *section balance* and *radius of curvature* but are slightly worse on the other metrics. The alternatives rank in the middle range of all the metrics whereas the original was poor in two but good in the other four. I hypothesize that the strategy of distributing the complexity more or less evenly between different metrics may yield the best results over all.

The modified designs of Figure 5-9 and Figure 5-10 need a tongue in the die. To ensure that the die tongue does not break, the gap ratio must be kept within the limits prescribed by the die material. A third alternative (see Figure 5-11) was generated but metrics were not evaluated in this case. The shape of the die tongue in this design introduces a twisting moment on the throat section. Extrusion vendors prefer not to have this condition. However the gap ratio metric as proposed here does not capture this effect.

Ext Num	*Section balance*	*Slenderness ratio*	*Radius of curvature*	*Shape factor*	*Form factor*	*Section stiffness*
2672	$2.2E{+}00$ (10)	$8.2E{+}00$ (3)	$2.3E{-}02$ (7)	$8.9E{+}00$ (2)	$9.6E{+}00$ (2)	$1.9E{-}01$ (4)
*Alt*1	$9.0E{-}02$ (3)	$8.2E{+}00$ (3)	$8.9E{-}02$ (4)	$1.2E{+}01$ (4)	$1.2E{+}01$ (5)	$1.5E{-}01$ (5)
*Alt*2	$5.0E{-}02$ (2)	$9.8E{+}00$ (4)	$2.9E{-}02$ (6)	$1.3E{+}01$ (4)	$1.3E{+}01$ (5)	$1.6E{-}01$ (5)

(5.13)

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[3] Unfortunately, I have no way of knowing the functional constraints that may have driven the designer to the Figure 5-8. Under the circumstances, the alternatives are just best guesses trying to keep the functionality of the part intact.

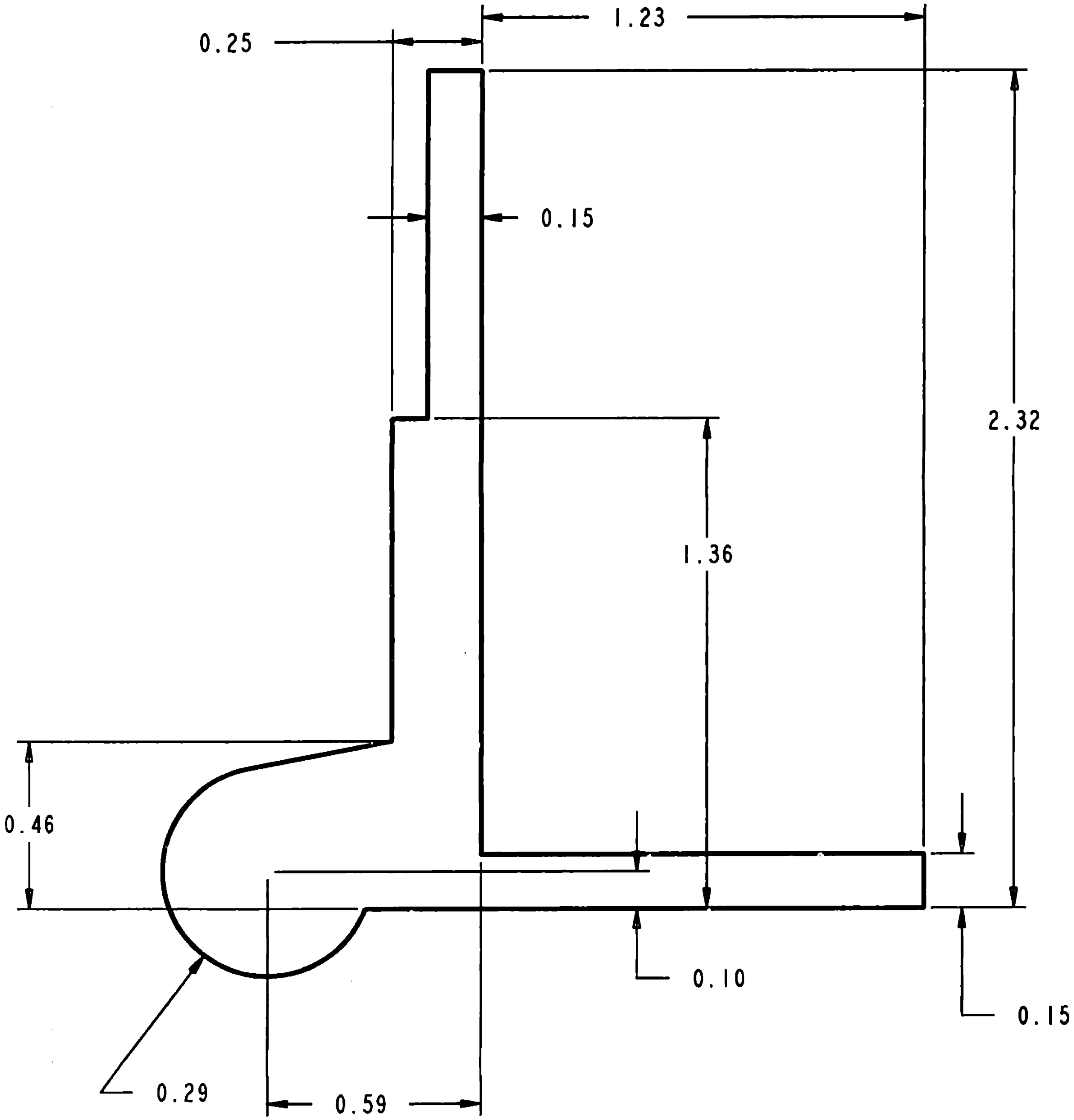

Figure 5-8: Original design of extrusion BAC 1520-2672

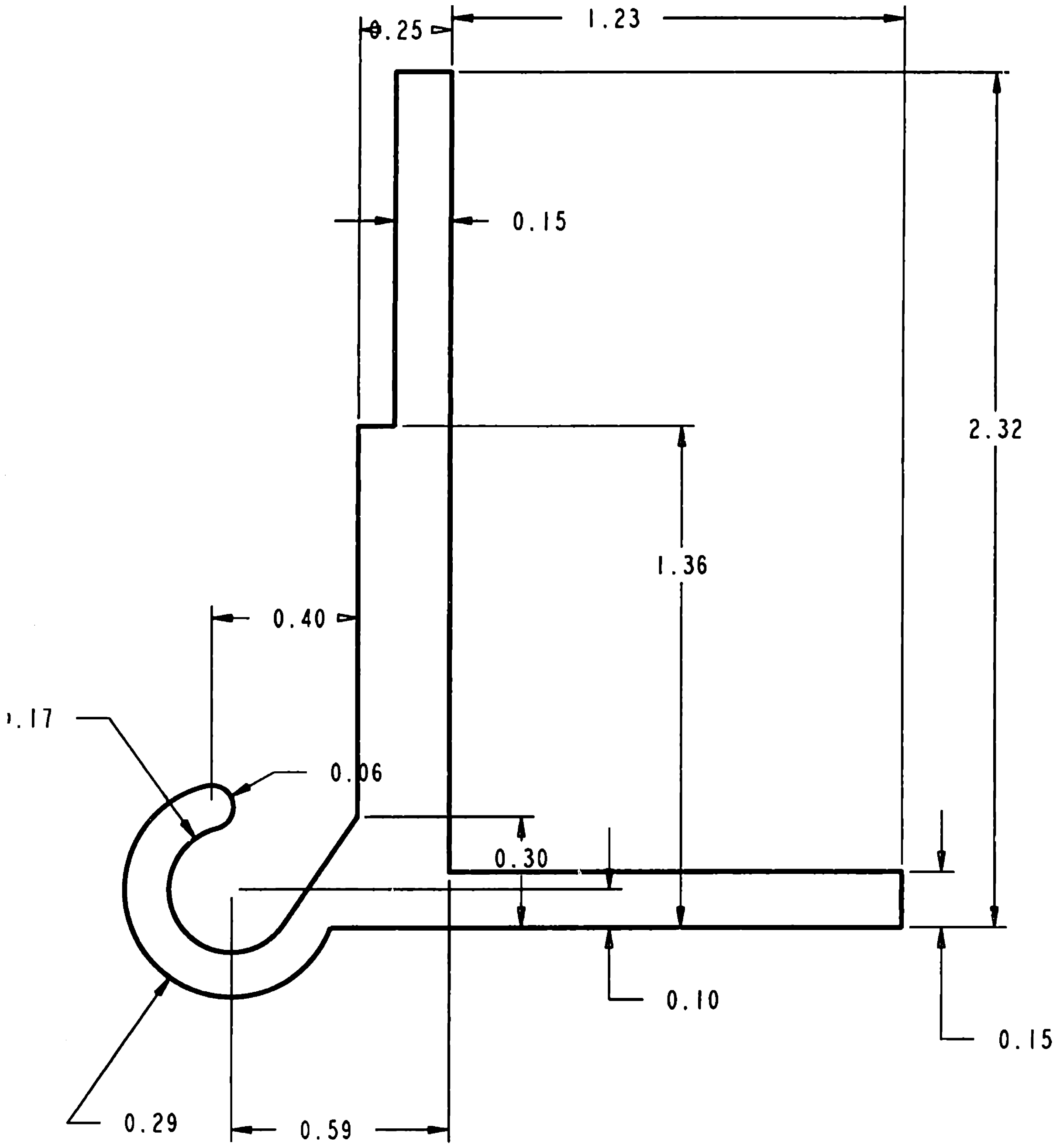

Figure 5-9: Alternative one for extrusion BAC 1520-2672

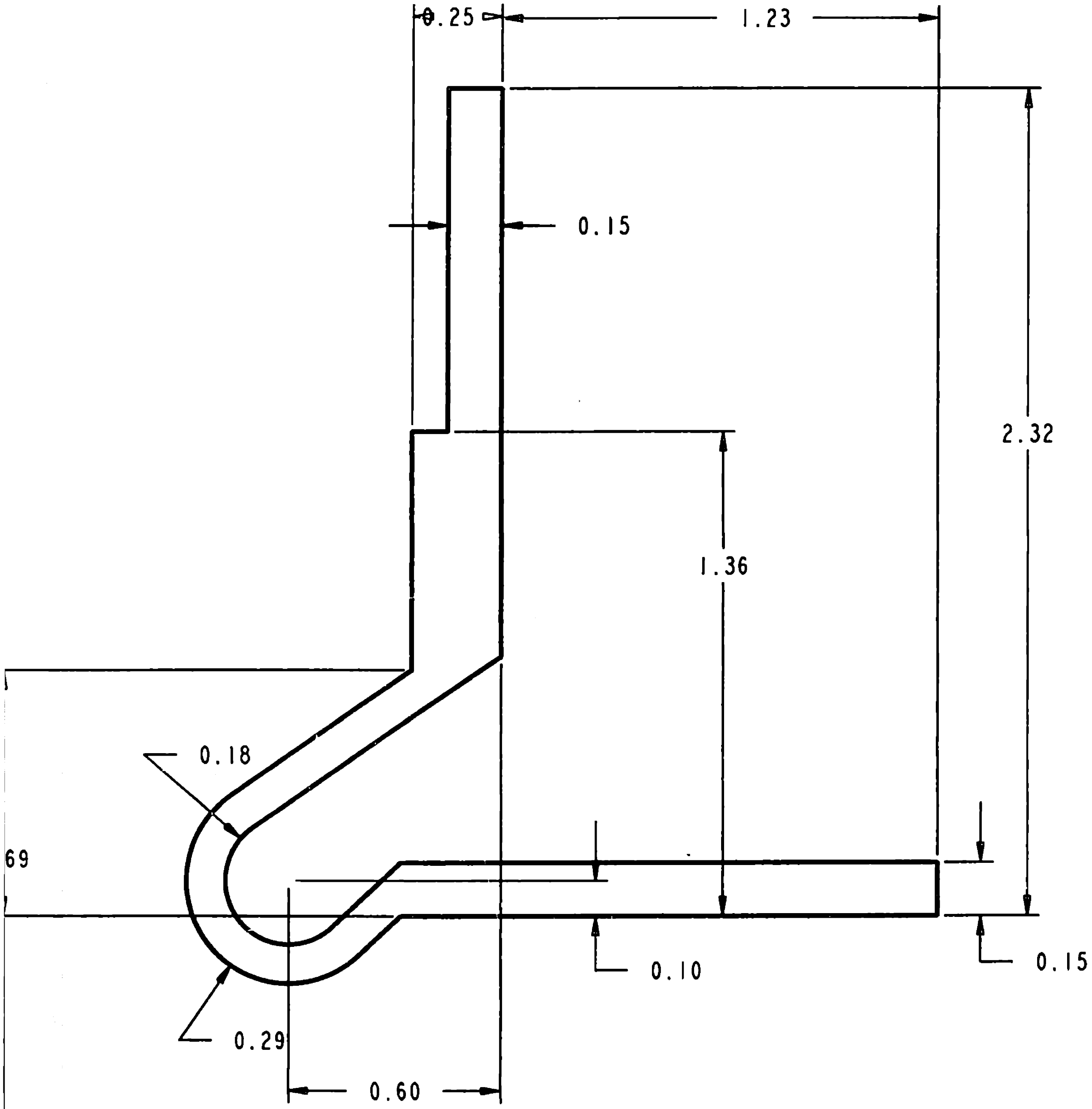

Figure 5-10: Alternative two for extrusion BAC 1520-2672

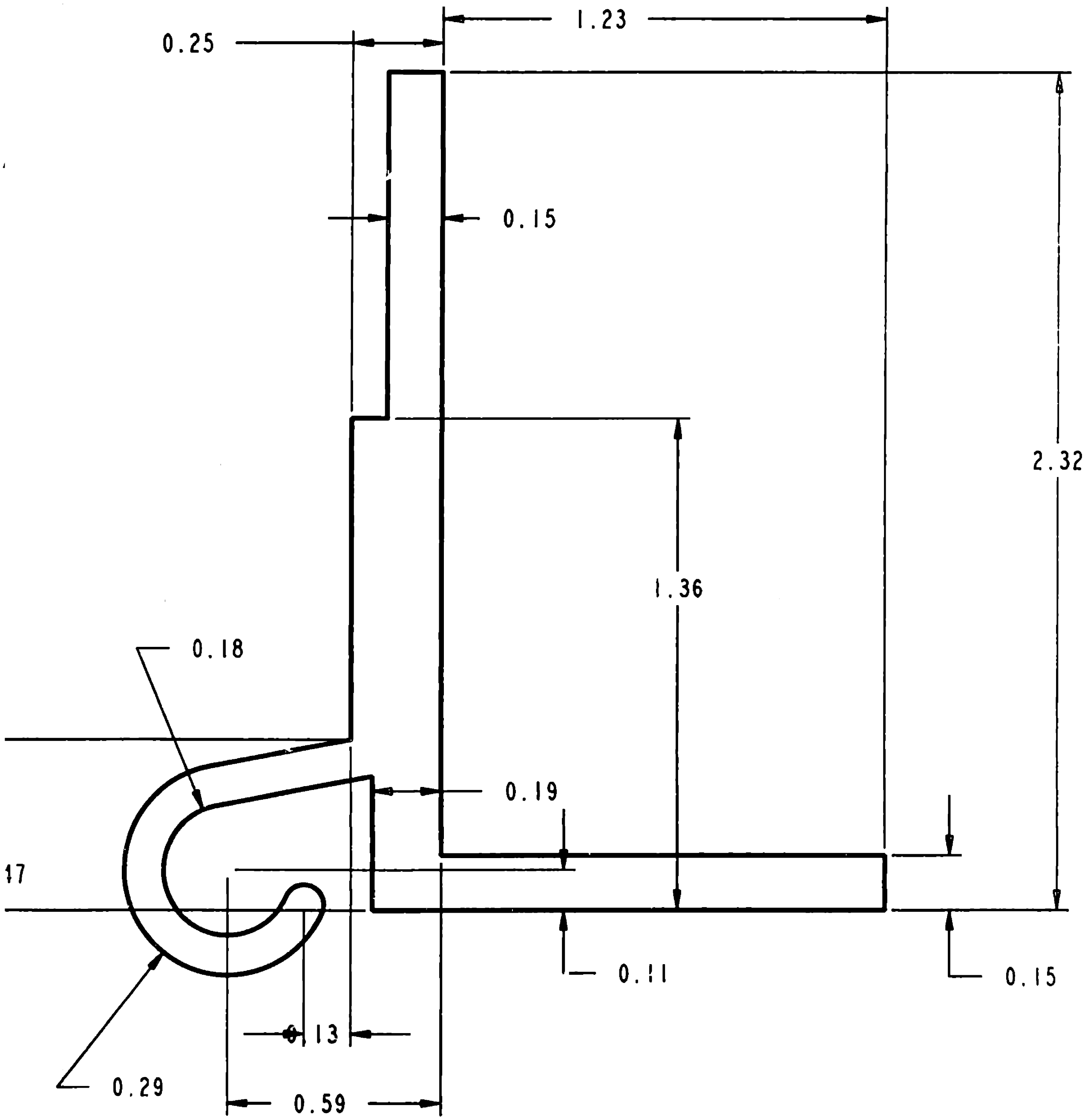

Figure 5-11: Alternative three for extrusion BAC 1520-2672

Chapter 6

Use of metrics in technical cost modeling

In this chapter, I propose four main points:

- There is some preliminary data to suggest the predominance of competitive market forces over production costs in driving the pricing of custom aluminum extrusion shapes. (Section 6.1)
- *Manufacturing extra* or production engineering overhead costs associated with tool maintenance, engineering problem solving, tool try-out, rework and scrap are a significant portion of overall costs for short run parts that are difficult to produce. (Section 6.2)
- Existing cost models fail to adequately account for the role of part producibility in determining the magnitude of *manufacturing extra* costs. (Section 6.3)
- Process-model based metrics can be used as the basis for a system to estimate the *manufacturing extra* cost. (Section 6.4)

6.1 Should price correlate with producibility?

Improving producibility of a design often involves sacrificing some aspect of its functionality. To prevent waviness in an extrusion, the designer may make a section thicker. Such an extrusion may weigh more than the absolute minimum weight necessary to carry the specified load and satisfy geometric constraints. On the other hand, an extrusion with few producibility problems may cost less to produce. In a perfect market price would follow cost. The lower price of extrusions with improved producibility would compensate for any non-optimality in functional performance.

To check if extrusion prices actually correlated with producibility, I collected fifty different extrusions from a large set of extrusions that were designed for the Boeing 777 project. I asked two competing vendors to provide me the prices they had quoted Boeing on these fifty extrusions. One vendor provided a price estimate for 25 shapes while the other estimated 20 of the 50 shapes. Both vendors quoted on 14 of the extrusions. Table 6.1 shows the normalized[1] data. Figure 6-1 is a plot of the data in Table 6.1.

As can be seen from Figure 6-1, the two price estimates do not correlate very well. The Pearson product-moment correlation coefficient is 0.6. While 14 data points is a small number, the lack of price correlation between the vendors in a competitive market such as this, may be attributed to one of several reasons:

- The cost structures of the vendors may be different. Vendors may have their niche markets for which their equipment is best suited. Labor costs could vary between different geographical areas. Trade secrets and proprietary techniques could allow some vendors to achieve better performance. In this case producibility constraints of one of the vendor may differ from that of the other.
- One of the vendors may be farther down the learning curve i.e they may have prior experience with a similar extrusion.

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[1] To protect confidentiality of price data the figures have been normalized with different scales and shifts

- Vendor may be using a price estimation procedure that reflects the competitive nature of the market but not the real costs of production. Other issues that may be playing a major role in price determination:
  - Backlog of orders
  - Predatory pricing seeking to expand market share.
  - Entrenched vendor may demand premium price because of the cost of qualifying a new vendor.

Normalized price quotations from two competing vendors		
Part	*Vendor* 1	*Vendor* 2
1	0.709	0.239
2	0.297	0.028
3	0.219	0.304
4	0.260	0.212
5	0.681	0.231
6	0.635	0.203
7	1.000	0.466
8	0.219	0.038
9	0.260	0.212
10	0.254	0.322
11	0.513	0.142
12	0.819	0.727
13	0.765	0.656
14	0.731	0.208

(6.1)

The two vendors in this case are located in the same geographical area. Both vendors have significant experience in this mature industry. Key personnel have moved back and forth. It seems unlikely that the vendors would differ widely on extrusion producibility. It seems more likely that the difference arises from the ad hoc nature of price estimation rather than from any systemic causes. If the vendors do not have different producibility constraints, then the low correlation between the vendors suggests that atleast one of the vendors is not tracking producibility very well. Linear regression models relating metrics to price quotes are shown in Figure 6-2 and Figure 6-3. Quotes from vendor 1 fit quite well with the model. However quotes from vendor 2 fit very poorly.

The vendor's price is Boeing's cost. If prices are uncorrelated to producibility, then Boeing's extrusion costs would appear independent of producibility. While this may appear advantageous in the short-run, allowing Boeing's designers to optimize to meet functional targets, it can cause problems in the long run because it is economically unsustainable.

6.2 Relative importance of production engineering overhead costs

The conventional model (see for example [Bus87]) for total unit cost of producing a part is:

$$\begin{aligned}
Total\ cost &= Fixed\ cost + Variable\ cost \\
Fixed\ cost &= Machine\ cost + Tooling\ cost + Building\ cost \\
&\quad + Overhead\ labor\ cost + Maintenance\ cost + Cost\ of\ capital \\
Variable\ cost &= Material\ cost + Energy\ cost + Direct\ labor\ cost
\end{aligned}$$

In this model, the cost of engineering problem solving, tool try-out and rework are lumped under tooling cost or under overhead labor.

When parts are produced by processes that operate under *steady state* conditions[2] the cost contribution from start-up activities becomes vanishingly small as the number of total units produced increases. However with shortened product cycles some production processes may never reach steady state. In such a situation *manufactur-*

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[2] i.e a state at which the number of unanticipated events is minimal as all the bugs in the process have been ironed out.

ing extra or production engineering costs associated with start-up and debugging a production process become increasingly important as the total number of units produced decreases. Further, these same costs increase as the producibility of a design decreases. So for short run parts with low producibility it is critical to obtain a good estimate of these costs.

To show that production engineering costs increase in magnitude as parts become more complex, I compare the cost structures [Bus87, Kap90b] of two injection molding plants in Table 6.2. One plant produces RubberMaid trash cans and the other manufactures a variety of lamps for automobiles and trucks. Trash cans have fairly simple geometry in comparison to some of the more complex automobile lamps which may have special features such as multi-color molding, horizontal and vertical stripes, curvatures, and special contours. Injection molding of these lamps requires molds with complex, high-precision moving parts. Although both these cost structures are for processes that operate in steady state, higher fraction of costs for supervision, quality control, and tool maintenance in the automobile lamp plant indicates that production engineering costs increase in magnitude as parts become more complex. In the same paper [Kap90b], data and arguments are presented to show that the cost-structure in Table 6.2 is biased such that lamps which are less complex are over costed while more complex lamps are under costed. (See Table 6.3). For instance, the revised estimate of the cost of tool maintenance for complex rear lamp is 27% higher than the original estimate which did not differentiate between various lamp models. The discrepancy arises because complex parts consume far more then their share of supervision, quality control, and tool maintenance. If this were true, then we can be even more certain that production engineering costs increase as parts become more complex.

Percentage distribution of total cost		
Category	*Trash can*	*Automobile lamp*
Material	54.78	41.00
Direct labor	10.80	17.00
Commercial burden	7.20	7.00
General burden	4.80	7.00
Supervision *Quality control* *Inspection*	2.40	9.24
Tool maintenance	0.25	
Machine maintenance	0.25	18.76
Depreciation	9.70	
Utilities	7.40	
Production control *Material handling*	1.30	
Scrap	1.12	
Total	100	100

(6.2)

Ratio of revised costs to original costs by product category			
	Supervision	*Quality control*	*Tool maintenance*
Complex Rear Lamp	1.04	1.04	1.27
Noncomplex Rear Lamp	0.97	0.96	0.68
Park and Signal Lamp	0.88	0.78	0.73

(6.3)

Hard data to show that the costs associated with startup and debugging activities are significant for short-run parts has been difficult to come by. Discussions with aluminum extrusion and injection molding vendors, however, reveal some anecdotal evidence. The plant manager at one extrusion plant estimated the percentage of scraped metal to be 40% for hard alloys. This includes the one inch or so of every billet that is scrapped at the end of the press stroke. If the average length of the billet is assumed to be about 12 inches, then the scrap losses due to other causes amounts to about 32 % for these alloys.

Aluminum extrusion vendors usually employ a die corrector who makes modifications on the die by filing, filling die gaps, increasing or decreasing die-land lengths and a variety of other small changes to make the part extrude right. This is very much a skilled art. After every significant modification the die is loaded into the extrusion press and tried out. Extrusion vendors suggest that the number of die try-outs may be a good measure of the start-up and debugging cost. Out of a sample of eleven extrusion dies I found that eight extruded without repeated tool trials. However there was considerable die-trial and scrap with the remaining three extrusions. Table 6.4 summarizes the data. The billets used in this particular press cost about $25 each. Even with eight scrapped billets the cost of scrapped metal is only about $200. However the long lead time and the engineering effort associated with repeated die trials can add significantly to production cost.

Try out costs for three dies (6.4)

Extrusion number	*Number die try – outs*	*Number of scrapped billets*	*Number of weeks*
4310	3	7	2
4083	3	6	3
3937	7	8	9

Injection molding die makers usually undertake to deliver a sample part and a die in about sixteen to twenty-four weeks. However, if problems are encountered, compensating modifications have to be made in the die. As with aluminum extrusions this is a skilled art and the time and effort involved varies widely depending on part complexity. After a working tool is delivered, the molder will go through a tool qualification process in which they try to identify the optimum operating window. [Bud93] studied the tool qualification process at an injection molding plant manufacturing electrical connectors for the automotive industry. According to [Bud93] the process of tweaking the processing variables in the die try-out stage may take as much as six weeks.

6.3 Accounting for part producibility with existing cost models

Conventional approaches to cost modeling do not adequately account for the influence of part producibility on the production cost. In the injection molding model proposed by [Bus87], for instance, the complexity of part geometry is considered in estimating tooling cost, maintenance cost, material scrap rate, cycle time and tooling life. The model provides a default suggestion of 4.2% for the cost of maintaining injection molding equipment and tooling. The cost of tooling is estimated by using a regression model with part weight, projected area, number of actions, toolmaker's shop rate as independent variables.

However [Bus87] also says that "maintenance costs are a complex function of the type and age of the equipment, the complexity of the tooling and the design of the component and can vary from this default value significantly". Further [Bus87] seems ambivalent to the use of complexity factors for geometric features to account for deviations from regression models for estimating tooling cost, maintenance cost, material scrap rate, cycle time and tooling life. He suggests four complexity factors which could potentially be determined for specific geometric features.

- The cost of tooling
- The material scrap rate
- The cycle time
- The life of the tooling

But later on he says that this approach is not viable because

- It is impossible to produce a simple but comprehensive list of molded part shapes.

- Even with identifiable shapes it is impossible to define them in other than subjective terms or by lists of examples

In addition, it is not clear how the complexity factors would be determined for a specific geometric feature.

In trying to decompose the complexity of an injection molded part in terms of geometric features [Bus87] has essentially run into the same problem as was described in Section 3.2.3. Complexity in the case of process-physics dominated processes arises from the way in which geometric features interact with each other. This makes it difficult to analyze the geometric features independently and assign complexity factors to them.

6.4 Framework for estimating manufacturing extra

In this subsection, I propose an extension to the activity-based costing approach to account for part producibility in manufacturing cost estimation. Manufacturing a product such as an aluminum extrusion involves a myriad of activities such as purchasing, production, maintenance, cost-accounting, and marketing. A relatively small number of these activities are seriously impacted by part producibility. The purpose of this section is to describe an approach to estimate the costs associated with this smaller set of activities that typically occur during the start-up phase[3] while the bugs in the process are still being ironed out. These costs are referred to as *manufacturing extra.*

The essence of the proposed method for cost estimation is:

- Identify the commonly occurring producibility difficulties (typically during start-up phase of production). These producibility problems necessitate activities

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[3] There is a trade-off between investing effort and dollars into debugging the process and performing rework or additional steps after the fact to compensate for the imperfections in the process. Manufacturers may choose to operate at a point which best suits their capabilities and also the exigencies of the situation. Hence rework costs or costs associated with after the fact activities are also included.

which contribute to the manufacturing extra cost. The manufacturing extra cost for a given part is the sum total of the costs of all activities undertaken to solve its producibility problems.

- Develop process-model based metrics which can predict severity of different producibility problems for a given design.
- Create a database, by direct measurement, of cost information from parts currently being produced. This database should contain the part number, the associated metric values and the resource consumption of activities necessary to solve different producibility problems.
- Utilize the one-to-one mapping between producibility problems and the metrics to define a regression model relating metric value to the resource consumption of the corresponding activity.
- For a new design, compute metrics and use regression model to estimate costs associated with each necessary activity. The manufacturing extra cost for a given part is the sum total of the costs of all activities undertaken to solve its producibility problems.

In order to understand the proposed approach, it is necessary to become familiar with the following activity-based costing (ABC) terminology and definitions[4].

Cost object The reason for performing an activity. A product such as BAC 1520-2672 (an extrusion in the 777 airplane) is a cost object.

Resources are economic elements directed to the performance of activities. They are the sources of cost. Some typical resources are labor, equipment, material, and energy. The three engineers working in an extrusion plant represent a resource. They have to be paid a salary and hence they are a source of cost.

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[4] The first three definitions have been taken almost verbatim from [Tur91].

Activity A description of the work that goes on in the organization and consumes resources. Some of the activities involved in the production of aluminum extrusions are

- Die maintenance due to tongue breakage, wear or distortion.
- Rework.
- Separation and disposal of scrap.
- Die try-out.
- Material handling.
- Engineering supervision or problem solving

Activity trigger An event or causal factor that causes the performance of activities and the resulting consumption of resources. In my model, producibility problems are the activity triggers. Wear out of the die is an activity trigger that triggers the die maintenance activity. An activity may have more than one trigger. For instance, extrusions may have to be reworked because they were bent on exit from the die, distorted due to heat treatment or had some waviness. (See Figure 6-4).

Other activity triggers are

- Bending of extrusion as it exits die
- Waviness
- Distortion due to heat treatment
- Hot shortness due to high extrusion rate.

Cost driver A cost driver is a measure of the consumption of an activity by a cost object (such as a product). The number of different parts in a product is a cost driver that could be used to predict the expenditure in the purchasing department for that product. Greater the number of parts, more the paperwork and personnel involved in purchasing activities. In my model, process-model metrics are used as cost drivers to predict resource consumption of different problem solving activities. For instance, the value of the section balance metric would be used to predict the number of hours devoted by production engineers to solve problems associated with bending of the extrusion as it exits the die.

In activity based costing the first step is to define a set of activities. These activities usually consume different amounts of resources. For instance, to estimate the cost of punching holes in an automatic press, two activities *set-up* and *punch hole* would be defined. Then, a cost driver is determined for each activity. *How many holes have to be punched? How many different set-ups have to be done?* The next step is to identify the resource consumed when the activity is performed once. *How much time does it take to do one set up? What is the machine rent and operator salary for this time period?* This may be done by observing the time taken to make several parts with different numbers of set-ups and holes and fitting a regression model to the data. Finally, the net cost contribution is obtained by plugging in the value of the cost drivers into the regression expression.

As a precursor to creating a model for estimating manufacturing extra we need to create a database of cost information on parts that are currently being produced. Table 6.5 shows the information that must be collected. The first column records a part identification number. The second column lists the activities that had to be performed during production. The third column associates these activities with specific production problems that necessitated the activities. The final column lists the resource consumption associated with each producibility problem and the corresponding problem solving activity. The entries in the last column have to be obtained by direct measurement.

Database of cost information for regression model			
Cost object *(Part number)*	*Activity*	*Activity trigger* *(Producibility problems)*	*Resource consumption*
BAC 1520 – 2672	*Rework*	*Bending*	*sd*001
	,,	*Waviness*	*sd*003
	,,	*Heat treat distortion*	*sd*004
	Die maintenance	*Die wear*	*sa*001
	,,	*Waviness*	*sa*003
	Material handling	*Floppy shape*	*sb*001
	Engineering problem solving	*Floppy shape*	*sc*001
	,,	*Waviness*	*sc*003
	,,	*Heat treat distortion*	*sc*004
BAC 1520 – 2673	*Rework*	*Bending*	*td*001
	,,	*Waviness*	*td*003
	,,	*Heat treat distortion*	*td*004

(6.5)

It is also necessary to create a database of parts and associated metrics. Table 6.6 shows some entries from such a database. Because there is a one-to-one mapping (See Fig 4-8) between the metrics and the activity triggers (producibility problems) a regression model can be defined relating the metric values in Table 6.6 to the resource consumption by the corresponding activity as shown in Table 6.5.

Database of metrics for regression model

Part number	*Gap ratio*	*Section balance*	*Slenderness ratio*	*Radius of curvature*	*Shape factor*	*Section stiffness*
2672	0.19	0.37	0.57	1.1	1.7	3.1
2673	0.93	0.90	0.53	2.9	2.8	4.2
2674	0.77	0.53	0.59	3.7	3.9	1.4
2675	0.51	0.16	0.55	4.5	4.0	2.3

(6.6)

The form of the regression equations could be as follows:

$$Cost\ of\ Rework = a_0 + a_1(section\ balance) + a_2(radius\ of\ curvature) + a_3(slenderness\ ratio)$$

- The first step in estimating manufacturing extra for a new design is to evaluate all metrics. Table 6.7 is an example of what may be obtained.

Metric values for new design

Metric	*Metric value*
Gap ratio	0.52
Section balance	0.98
Slenderness ratio	0.56
Radius of curvature	2.13
Shape factor	3.22
Form factor	7.66
Section stiffness	12.48

(6.7)

- Use regression equations developed above to estimate costs associated with the different activities necessary to solve producibility problems. The net *manufacturing extra* cost is given by the sum of these individual costs.

The salient features of this method of estimating *manufacturing extra* cost are:

- Assumptions of *independence* of producibility problems and *super-position* of associated costs. The task of estimating the manufacturing extra cost for the part has been sub-divided into estimating the cost of solving a set of producibility problems. The net manufacturing extra cost is determined by superposing the costs associated with individual problem solving activities. It is expected that this divide and conquer strategy will yield better results than picking "similar" parts and using their costs as an estimate for a new design.

- This approach ties in well with activity based costing principles which say that *Activities consume resources and contribute to cost.* By linking activities to specific producibility problems it is possible to associate a dollar cost to solving any given producibility problem.

- The components of cost are obtained by summing regression expressions relating metrics to activity resource consumptions. Regression prevents noisy or extreme values from influencing the results drastically.

- Some of the costs modeled in this framework are incurred by the extrusion vendor and others by Boeing. Cost of die try-outs and billet scrap will eventually show up in the price charged by the vendor. Other costs, such as putting shims to correct for post machining distortion are incurred by Boeing.

- Such a cost model, if refined, validated, and shared between Boeing and the extrusion vendor, could be used by Boeing designers to trade-off functional performance against production cost. It could also be used by the extrusion vendor to gain a better appreciation of how resources are utilized in operations.

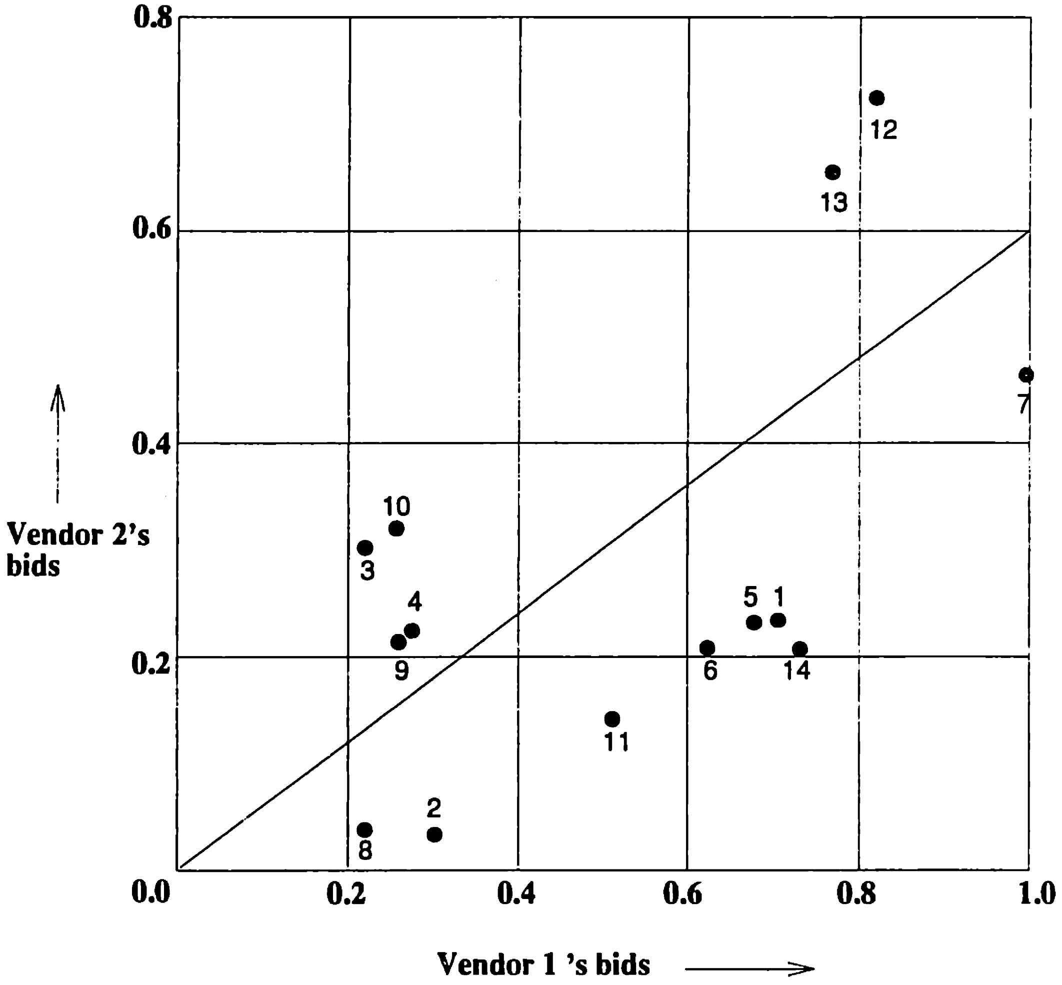

Figure 6-1: Bids from two vendors do not correlate well

Dependent variable is: Price quotation from vendor 1

$R^2 = 90.4\%$ R^2 (adjusted) = 84.4%

s = 0.1061 with 14–6 = 8 degrees of freedom

Source	Sum of squares	df	Mean Square	F–Ratio
Regression	0.845646	5	0.169129	15.0*
Residual	0.090024	8	0.011253	

Variable	Coefficient	s.e.of Coeff	t–ratio
Constant	0.0628	0.1515	0.415
Section balance	0.0201	0.0095	2.110
Slenderness ratio	–0.0042	0.0051	–0.821
Radius of curvature	0.3972	0.2902	1.370
Shape factor	0.0287	0.0038	7.490
Form factor	–0.0084	0.0053	–1.580

$*F > F_{(alpha\ =\ 0.01)} = 6.63$ $t_{(alpha\ =\ 0.1)} = 1.860$ $t_{(alpha\ =\ 0.01)} = 3.355$

Figure 6-2: Model fits vendor 1 quotes well

Dependent variable is: Price quotation from vendor 2

$R^2 = 36.2\%$ R^2 (adjusted) = −3.7%

s = 0.2863 with 14−6 = 8 degrees of freedom

Source	Sum of squares	df	Mean Square	F−Ratio
Regression	0.3716	5	0.0743	0.907
Residual	0.6556	8	0.0820	

Variable	Coefficient	s.e of Coeff	t−ratio
Constant	0.3422	0.4087	0.837
Section balance	−0.0137	0.0258	−0.530
Slenderness ratio	−0.0106	0.0138	−0.770
Radius of curvature	−0.2967	0.7831	−0.379
Shape factor	0.0197	0.0103	1.910
Form factor	−0.0087	0.0143	−0.608

$F_{(alpha\ =\ 0.01)} = 6.63$ $t_{(alpha\ =\ 0.1)} = 1.860$ $t_{(alpha\ =\ 0.01)} = 3.355$

Figure 6-3: Model fits vendor 2 quotes poorly

	Activities					
	Die Maintenance	Rework	Scrap	Try-out	Engineering problem solving	Material handling
Activity triggers	Die wear	Waviness	Bending	Die wear	Bending	Floppy shape
	Die tongue breakage	Heat treat distortion	Heat treat distortion	Die tongue breakage	Waviness	
	Bending	Bending	Waviness	Bending	Heat treat distortion	
	Waviness			Waviness	Die wear	
					Floppy shape	
					Die tongue breakage	

Figure 6-4: Activities may have multiple triggers

Chapter 7

Summary and conclusions

7.1 Summary

Lack of effective communication and coordination between part design and process design (manufacturing) engineers is one particular instance of the general problem of coordination and communication when large teams of engineers collaborate to solve design problems too complex for a single individual. It is widely believed that if the designer is made aware of the constraints imposed by what is practical on the manufacturing side, he or she would take this information into account when making design decisions. That motivated the question which I have tried to address in this thesis: *How should producibility information be represented to facilitate feedback to designers regarding the producibility of their designs?*

Design and manufacturing handbooks commonly represent producibility information through illustrative examples of good and bad design practice. But such a representation is inadequate in several ways. Visualize a designer trying to evaluate the producibility of a particular part he has designed. Because the shape in question is unlikely to be exactly similar to the examples shown in the handbook, the designer has to decide which and to what extent the recommendations are applicable to his solution. Secondly, the examples show one solution of the many alternatives that may mitigate potential producibility problems. Finally, without dimensions the designer has no way of telling whether the design guideline applies to his case even if the shape were similar.

Representation of producibility constraints in terms of geometric features (localized topological information) is most useful for production processes in which the process itself proceeds in a localized sequential manner. I call such processes *trajectory-dominated* because the part shape is created by moving a generic tool through a pre-specified trajectory. The geometric features often correspond directly to the operations of the trajectory dominated process. And the set of features in a part corresponds to the number of different production operations that have to be carried out to make it. Abstracting the part shape in terms of geometric features was tantamount to breaking up the problem of producibility evaluation into smaller, sub-problems.

However, for processes where the geometric transformation to define the shape happens globally almost at the same instant, localized geometric features do not provide this sort of problem decomposition. I call such processes *process-physics dominated.* For such processes, I decompose the problem of producibility evaluation in terms of the different failure-modes of the process. For each process, I define a set of process-model based metrics to predict the severity of the different failure-modes. Rigorous, analytical models of process-physics are often unavailable or are far too complex in the few cases where they are available. I therefore make use of approximations and simplified models in order to define the metrics. The metrics and the underlying models are then validated using evidence obtained from expert opinion, experimental results, direct measurements on tooling or by constructing arguments from first principles. The metrics are simple and can be calculated fast. So they can be used early in design when fast feedback from manufacturing is needed.

I propose a methodology to define and validate the process-model based metrics. Aluminum extrusion has been used as an elaborate example to illustrate the details of the methodology. Seven[1] metrics were proposed to cover different aspects of extrusion producibility. Evidence to validate the metrics was gathered by collecting a set of extrusions designed for the Boeing 777 airplane and comparing the predictions made by the metrics with those obtained on the basis of expert opinion, direct measure-

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[1] Of the seven, two were pre-existing metrics defined elsewhere

ments, experimental results, and literature survey. Some metrics were substantiated by arguing from first principles. The results of the exercise indicate that six of the metrics yield predictions that correlate well with the predictions made by extrusion experts. In one case, I conclude that the assumptions and the model underlying the metric need to be refined.

In the chapter on technical cost modeling, I present some preliminary data that suggests predominance of market forces over production costs in driving the pricing of custom aluminum shapes at the present time. I argue that, for short run parts, cost associated with tool maintenance, engineering problem solving, tool try-out, rework and scrap can be significant. I then describe some existing frameworks for cost modeling and show how they are inadequate in accounting for the role of part producibility. Finally, I propose a framework in which producibility metrics are used to estimate the cost impact of producibility. If validated and refined, this costing model would allow designers to visualize tangible benefits of taking producibility constraints into consideration.

Figure 7-1 and Figure 7-2 summarize my approach to producibility analysis and show how it could be used to improve extrusion design process at Boeing.

7.2 Discussion

7.2.1 Why use simple, approximate models?

Based on my observations of the difficulties in communication between designers and manufacturing engineers over organizational barriers at Boeing, I believe that metrics would be useful even though they are approximate and not error proof. If all else remained the same, complicated process models would incorporate more of the governing physics and lead to more accurate predictions. However, such models are often not available for even the most common processes. Rigorous analytical models are based on assumptions that restrict their application to fairly simple geometries. In cases where they are available, the effort required to learn and apply them may

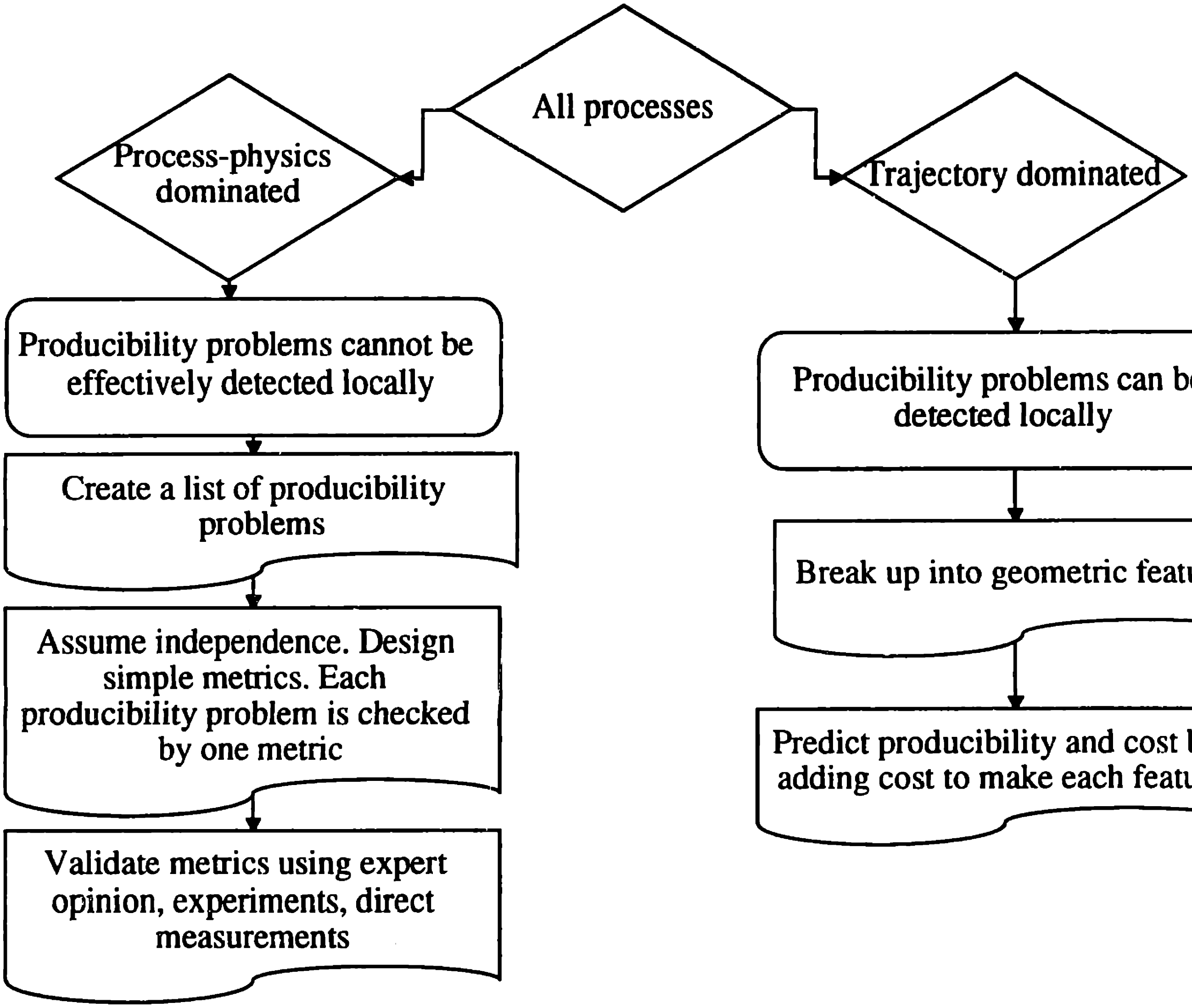

Figure 7-1: Approach to producibility analysis

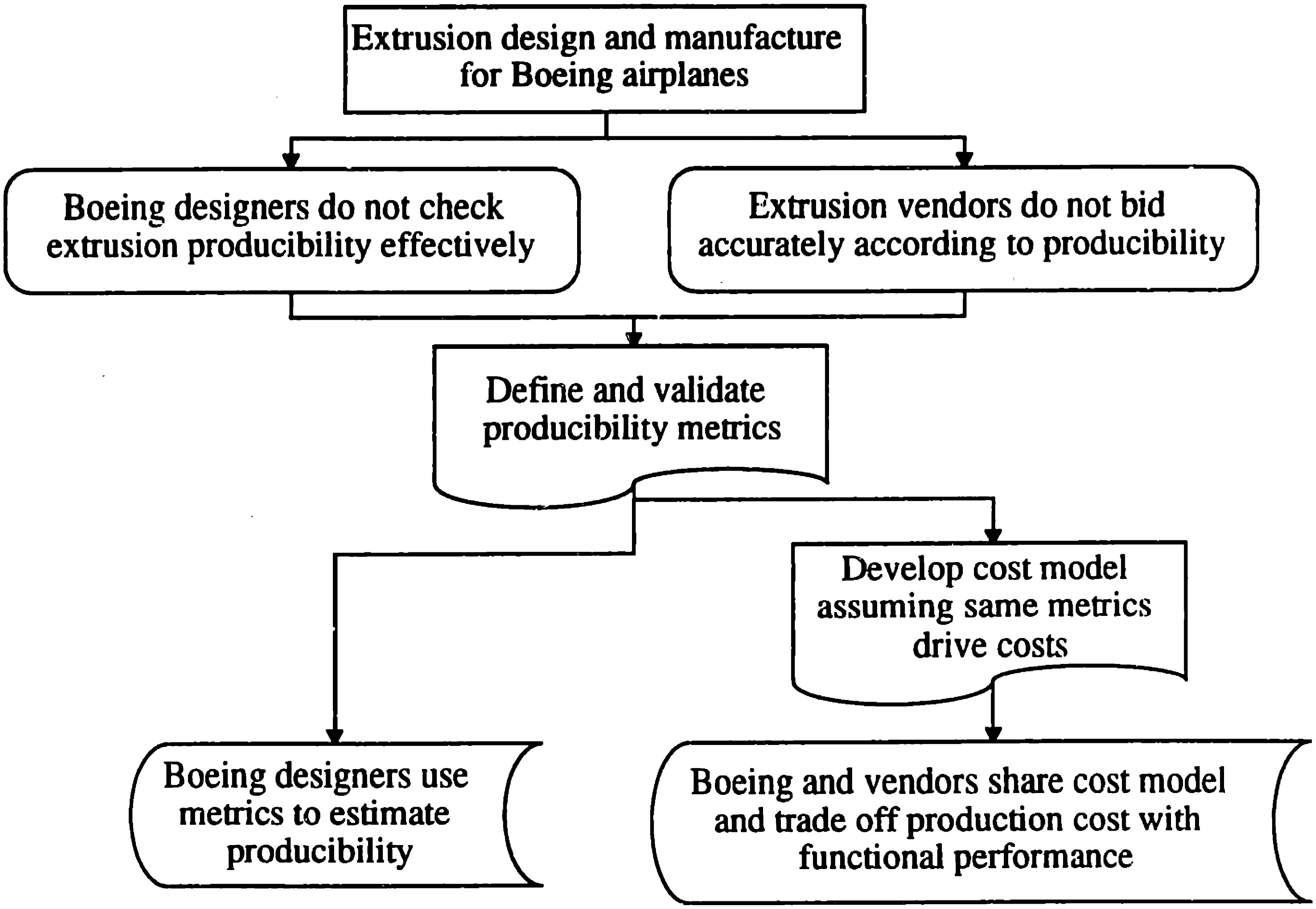

Figure 7-2: Extrusion producibility and cost estimation using metrics

prove a barrier to many part designers. Such analysis programs often fall under the realm of the process designer (manufacturing engineer) or a process expert rather than part designers. It is my belief that part-designers prefer using simple, if approximate, tools such as metrics to investing significant resources in learning and using more complicated process modeling tools.

These conclusions are based on my interviews with a number of different people (end users, part designers, process and tooling engineers, personnel in software development, user training, sales and marketing) associated with C-MOLD, a commercially available injection molding analysis package. C-Mold has two modules for melt flow analysis C-Flow/EZ and C-Flow. The C-Flow/EZ module uses a simple isothermal newtonian fluid flow model. C-Flow, on the other hand, models the shear thinning effect as well as the effect of heat transfer due to temperature differentials. C-Flow needs about 15 different inputs, C-Flow/EZ needs just the gate location. A new user may take up to a year to become competent at using C-Flow and interpreting its results. C-Flow/EZ on the other hand is very straight forward. A CAD program such as Pro-Engineer can be used to automatically generate a suitable finite-element mesh. The designer can then specify the gate locations at one or more of the finite element mesh nodes. With this data. C-Flow/EZ will predict the approximate location of the weld lines, the uniformity of the melt flow velocity, tendency of the part to warp due to orientation of the polymer chains and the danger of air traps or gas burns. Many companies have purchased this software intending to incorporate it into their injection molded part design and manufacturing process. These companies send process engineers to receive specialized training in the use of C-Flow. These engineers then act as internal consultants or process experts for part designers within the company. On the manufacturing side. C-Flow is seen as a tool to determine the correct processing window without excessive trials. Because of its complexity C-Flow is seen as a process expert's tool rather than something that can be quickly mastered and applied by part designers.

7.2.2 How robust are the metrics? Do we know when they fail?

Metrics are heuristics which reduce the probability of problems during production. As with other heuristics, there is no easy way to know apriori when a metric would fail. Other heuristics such as *Reduce part count*, *Make all insertions from one side only during assembly* have been proven to be very useful even though we don't know when they fail. However unlike these qualitative guidelines, metrics are quantitative. By evaluating metrics and checking the predictions for a large number of parts it is possible that one may discover an empirical numerical range in which the metrics are most reliable. However such information is not available at present.

7.2.3 How can a relative ranking between the metrics be obtained?

The relative importance of the metrics depends on the cost impact of the producibility problem they predict. In Chapter 6, I proposed a framework to estimate the cost impact of producibility by using metrics as cost drivers in an ABC model. This model expresses the cost impact of producibility as a linear function of the different metrics. The relative magnitudes of coefficients of the different metrics in the cost expression determines the relative importance of the metrics.

7.2.4 What are the pros and cons of using expert opinion as validating evidence for the metrics?

The pros are:

- Expert opinion is generally considered a valid source of evidence because the experts have observed the phenomena over an extended time period.

- Independent experts agreed in their conclusions.

- State of art of producibility analysis today, the "team" approach relies on experts.
- More feasible than conducting a large number of experiments to cover range of producbility problems.

The drawbacks in using expert opinion as evidence are:

- No hard data available to prove ability of experts.
- Observation is different from prediction.
- Experts may have an error range. They may not be able to correctly rank two extrusions which are very simillar to one another.

7.3 Contributions and future work

I believe that four contributions result from this thesis:

- Metrics have been identified as an alternative to geometric features to represent and evaluate producibility.
- A methodology to identify and validate metrics has been proposed.
- A set of metrics for aluminum extrusion have been identified and validated.
- It has been established that metrics based on approximate models of process physics can yield useful predictions.

I see three potentially rewarding directions for future research and follow-up theses:

- The results of my exploration with aluminum extrusion and injection molding lead me to believe that the approach of defining and using metrics to predict producibility problems is worth exploring for other process-physics dominated processes also.

- Are the metrics themselves generalizable across processes? One can think of classifying production processes and associated producibility problems by the different physical effects that dominate them. It may be possible to define metrics that capture these physical effects and thus generalize across production processes.

- The cost model framework proposed in Chapter 6 needs to be validated and perhaps refined. Designing for producibility may lead to designs that are functionally sub-optimal. To offset this loss in functionality the designer would prefer to see the benefits from improved producibility in tangible terms. While pricing may always be dominated by competitive forces, vendors would no doubt benefit from having a better grasp of how extrusions differ in internal consumption of resources. Thus a validated cost model that is shared by the designer and the manufacturer would be of great use to both.

Appendix A

Approximate process-physics model based metrics for injection molding

There are several texts which describe the injection molding process in detail [RR86, Kal85]. The injection molding process has also been the subject of intense research over at least two decades and there are many excellent papers on various aspects of the process. (See for example [WH88].) My purpose in this section is to recast the work done elsewhere into the framework of metrics to provide another example in which approximate models of process physics have been used to define metrics to make useful predictions of producibility problems.

A.1 Producibility problems in injection molding

Injection molding is a process in which pellets of plastic are melted in a cylinder and the melt is forced under pressure into a mold and cooled. When the plastic cools sufficiently and solidifies the mold is opened and the part ejected and the cycle repeats once again.

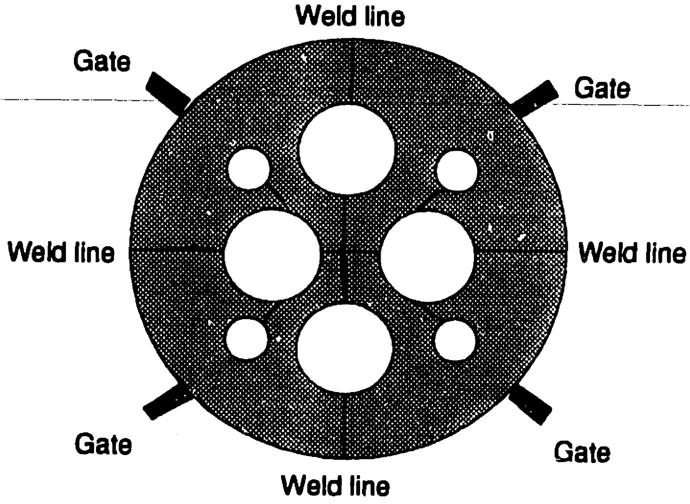

Figure A-1: Injection molding with four gates exhibits weld lines

This section[1] lists some of producibility problems encountered during injection molding. The following section presents a set of metrics that can be used to make useful predictions about these problems.

Visual defects, stress concentrations, structurally weak locations Visual defects, high stress concentrations or otherwise structurally weak zones can arise in a injection molded part where two advancing melt fronts meet each other. This typically happens when a cavity is fed by more than one gate. In other situations, the flow might split to go around a cored hole or an insert in the part. See Figure A-1.

Warpage The orientation of the molecules of the polymer is determined by the velocity direction when the melt front reaches a given location. For polymers, the magnitude of thermal shrinkage is much greater in the direction of molecule orientation than in the transverse direction. Hence, drastic changes in the direction of the velocity can cause significant warpage as the part cools. For the part in Figure A-2, the flow orientation is from top to bottom. Because of differential shrinkage in the directions transverse and parallel to flow this part would become out of round.

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[1] The material in this section draws heavily from [Tec]

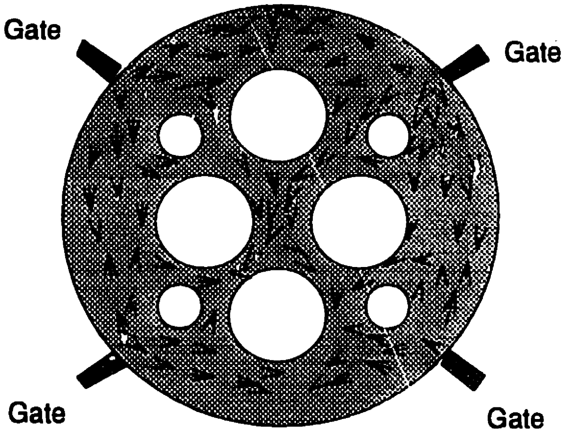

Figure A-2: Molded part with flow hesitation and potential warpage

Flash, shorts, over-packing Unbalanced melt flow can give rise to a variety of problems in injection molded parts. Unbalanced flow occurs when some sections of the cavity get filled much before other sections. This could happen when section thicknesses vary over a wide range. Areas that are filled earlier in the cycle will start to cool and experience over packing. In extreme cases, thin sections may cool solid and block melt flow to other sections of the cavity. In an attempt to reach these difficult sections of the cavity the molder might increase the injection pressure to a point that the melt flows into the gap between the die halves leading to flash.

Air traps, Gas burns, incomplete fills Depending on the geometry of the part and the speed of melt flow in various sections, pockets of air can become trapped and surrounded by melt fronts. If the air pocket is formed close to an edge of the part it can be removed by placing a vent. But even this is not always a complete solution as vents can get clogged with dirt and debris leading to defective parts. Air pockets in the middle of the part are worse. They will become very hot as the air gets compressed due to melt pressure. Such pockets of hot air can cause burn marks or incomplete fill.

A.2 Metrics for injection molding

For a first cut analysis, the following simplifications have been proposed [Tec]:

- Isothermal, newtonian incompressible fluid flow.
- Thin walled parts with uniform thickness.
- Two dimensional flow.

The analysis essentially involves solution of the Laplace equation for a pressure field using finite elements.

$$\nabla^2 P = 0$$

$$V_x = \frac{h^2}{3\mu}\frac{\partial P}{\partial x}$$

$$V_y = \frac{h^2}{3\mu}\frac{\partial P}{\partial y}$$

P is pressure, V_x and V_y are velocities in x and y directions, h is half the part thickness and μ is viscosity. The results of this analysis determine the following quantities to predict the severity of the problems discussed before.

Location of weld lines As a result of the analysis it is possible to track the advancement of the melt front as it arrives at each node in the finite element mesh of the part. A weld line is formed when two advancing melt fronts meet each other. This line represents the boundary of material from two different flow paths. In some cases the weld line becomes a visual defect detracting from the uniform appearance of the part. It is also a structurally weak zone and is a potential failure location. Hence can must be taken to either eliminate the weld lines or at least place them away from regions of high stress.

Standard deviation of melt front velocity direction Following the numerical solution, the velocity of the melt front in various sections of the cavity can be plotted at any given percentage of fill. As this analysis is independent of process-conditions such as injection rate, the absolute value of the velocity does not have any significance and is normalized. The direction of the flow can however be determined from the relative magnitudes of the different components. If there is considerable variation in the velocity direction, the part may warp as it shrinks differentially in various directions due to molecular orientation. The standard deviation of the velocity vector direction can be used as a measure of this problem.

Standard deviation of melt front area Melt front area is defined as the cross-sectional area of the advancing melt front. This area is given by the product of the length of melt front and the part thickness. Alternatively, it could be the cross-sectional area of the runner. When the flow in a die cavity is unbalanced some sections of the melt front may reach a dead-end in the cavity while other sections are still moving. The melt front area changes suddenly whenever such a situation occurs. The standard deviation value of the melt front area can hence be used as a quantitative index to compare the balance of flow between two designs.

Air traps Air traps are identified as nodes surrounded by melt fronts. Air traps that are in the middle of a part are difficult to vent and may lead to gas burns or incomplete fills.

These measures of producibility have been implemented in a commercially available program (C-Flow/EZ)[2]. Examples illustrating the utility of this simple model can be found in [Nag88, Wei91, Saj91]. My purpose in recasting the work done in CFLOW/EZ into the framework of metrics is to provide another example in which approximate models of process physics have been used to define metrics to make useful predictions of producibility problems.

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[2] CFlow/EZ is the simpler version of the more complex CFLOW program which uses a viscosity model with shear-thinning effects, accounts for heat transfer between the mold walls and the polymer and needs more detailed input about the processing conditions. There is some evidence to believe that part designers prefer using simpler, if approximate, tools such as C-FLOW/EZ to learning and using more complicated analysis programs such as CFLOW. Programs such as CFLOW often fall into the domain of a resident producibility expert or mold builders who need to decide on gating locations and cooling channels for the mold.

Appendix B

Numerical integration using Gauss quadrature

This section summarizes the Gauss quadrature technique used to evaluate the integrals in Equation 4.11 and Equation 4.12.

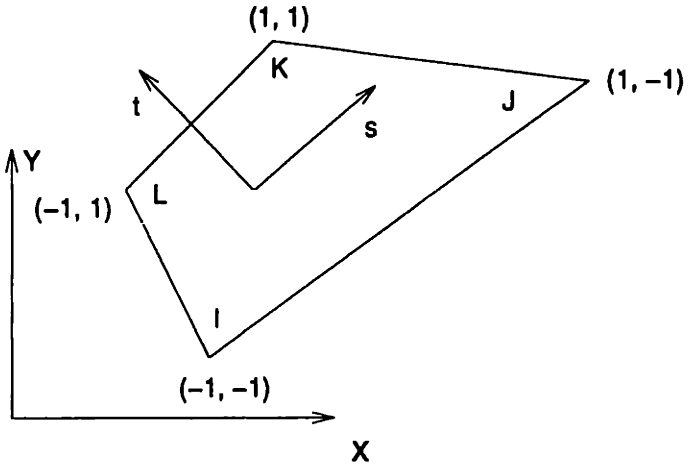
In Gauss quadrature, a function $f(x,\ y)$ to be integrated over an area is transformed into non-dimensional form $\phi(s,\ t)$ and is evaluated at various integration points within the domain. The approximate value of the integration is then obtained by summing the terms multiplied by appropriate weighting factors w_j.

Thus,

$$\begin{aligned} I &= \int_X \int_Y f(x,\ y)\, dx\, dy \\ &= \int_{-1}^{1} \int_{-1}^{1} \phi(s,\ t)\, |J|\, ds\, dt \\ &= \sum_{j=1}^{n} w_j \phi(s,\ t)_j \end{aligned}$$

The Jacobian J is given by:

$$|J| = \begin{vmatrix} \frac{\partial x}{\partial s} & \frac{\partial y}{\partial s} \\ \frac{\partial x}{\partial t} & \frac{\partial y}{\partial t} \end{vmatrix}$$



$$\begin{bmatrix} T \\ X \\ Y \end{bmatrix} = \frac{1}{4} \begin{bmatrix} T_I & T_J & T_K & T_L \\ X_I & X_J & X_K & X_L \\ Y_I & Y_J & Y_K & Y_L \end{bmatrix} \begin{bmatrix} (1-s)(1-t) \\ (1+s)(1-t) \\ (1+s)(1+t) \\ (1-s)(1+t) \end{bmatrix}$$

Figure B-1: Four noded quadrilateral element

The FEM mesh used to solve the heat-transfer problem is a triangular mesh obtained from four-noded quadrilateral elements with two coincident nodes.

Figure B-1 shows the transformation from the $(X,\ Y)$ co-ordinates to the $(s,\ t)$ co-ordinates. Elements in the mesh used to solve the heat-transfer problem have the nodes K and L coincident.

The four gauss-quadrature integration points are $(-\sqrt{1/3},\ -\sqrt{1/3})$, $(\sqrt{1/3},\ -\sqrt{1/3})$, $(\sqrt{1/3},\ \sqrt{1/3})$, $(-\sqrt{1/3},\ \sqrt{1/3})$. The associated weight in each case is 1.0.

Appendix C

Heat transfer coefficient and other inputs to heat-transfer analysis

To solve the two-dimensional heat-conduction problem with convective boundary conditions for the heat transfer between the extrusion and the water the following constants were input into the FEM program.

$$\begin{aligned}
Density &= 0.101\ \frac{lb}{in^3} \\
Specific\ heat &= 0.208\ \frac{Btu}{sec.^{\circ}F} \\
Heat\ transfer\ coefficient &= 0.00017\ \frac{Btu}{sec.in^2.^{\circ}F} \\
Thermal\ conductivity &= 0.00234\ \frac{Btu}{sec.in.^{\circ}F} \\
Initial\ temperature &= 842^{\circ}F \\
Water\ temperature &= 68^{\circ}F
\end{aligned} \tag{C.1}$$

Density, specific heat and thermal conductivity of aluminum are constants and can be found in the appendix section of any text on heat transfer. The numbers used here were obtained from [Ozi85].

The value for the heat transfer coefficient is derived from correlation for free convection over flat plates [Ozi85].

$$0.5 = \frac{Nu}{(Gr\ Pr)^{\frac{1}{4}}}$$

$$
\begin{aligned}
Nu &= \frac{h\ L_s}{K} \\
Gr &= \frac{g\beta(T_w - T_\infty)L^3}{\nu^2} \\
Pr\ (Prandtl\ number) &= 4\ (for\ water\ at\ 25^\circ C) \\
\beta &= 0.00018 \\
g &= 9.8 \\
\nu &= 1.00\ \times\ 10^{-6}\ (for\ water\ at\ 25^\circ C) \\
T_w &= 480^\circ C \\
T_{infty} &= 25^\circ C \\
L_s &= 0.3\ m\ (Length\ of\ the\ extrusion) \\
K &= 0.6\ (for\ water\ at\ 25^\circ C)
\end{aligned}
$$

From the above equations, h comes out to be 500 $\frac{W}{m^2.^\circ C}$ which is equal to 0.00234 $\frac{Btu}{sec.in.^\circ F}$ $\blacksquare$

Appendix D

Derivation of time constant for heat transfer analysis

For reasons explained in Section 4.3.4, it was necessary to decide on a suitable time constant to stop the quench analysis such that a substantial temperature differential would be present in the cross section. This appendix describes why I picked a value of 5 seconds.

I first decided that I did not want the temperature at center of the thinnest section in the extrusion to fall more than half way to the ambient water temperature i.e below 387°F.

According to [Ozi85], a lumped system analysis is valid if the Biot number is greater than 0.1. The Biot number is defined as

$$Bi = \frac{h\ L_s}{K}$$

L_s is a characteristic length and is given by the ratio of volume to surface area. For a thin leg section, this characteristic length would equal its thickness. The constants h and K, described in Appendix C are (0.00017) and (0.00234) respectively. Hence the lumped system anlysis is valid for $L_s < 1.4$. Since we are interested in making sure that the center of the *thinnest* section does not fall below 387°F this condition is automatically satisfied.

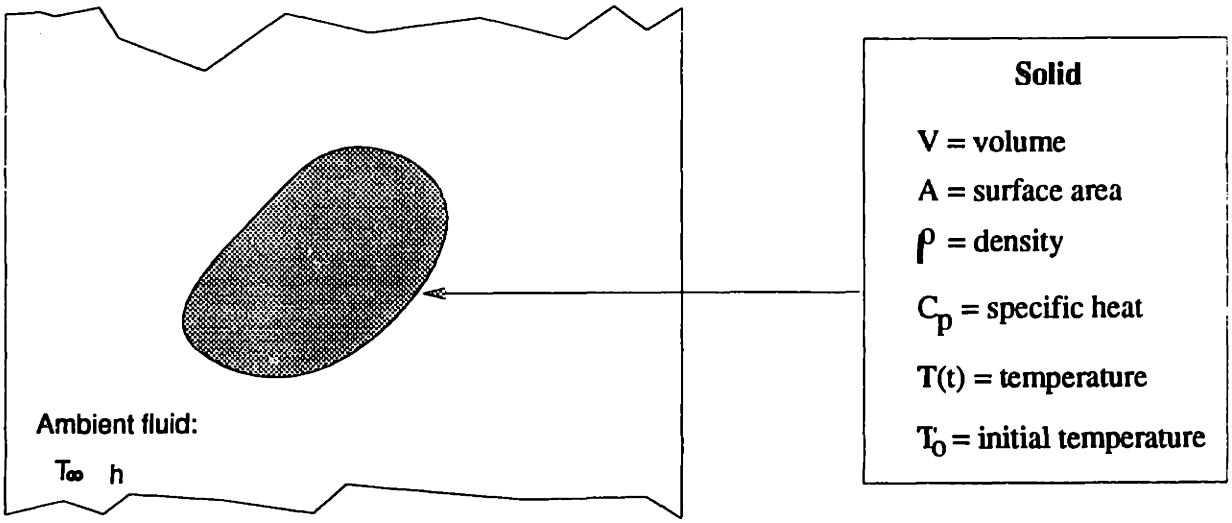


Figure D-1: Lumped system analysis of transient heat flow

From [Ozi85] the equation for temperature $T(t)$ is given by:

$$\frac{T - T_\infty}{T_{initial} - T_\infty} = e^{-mt}$$

where $m = \frac{h}{\rho\, c_p\, L_s}$. The thinnest section in the extrusions considered had a wall thickness of 0.06 inches. Substituting $t = 5$ and other constants into the above expression we get $T = 744°F$ which is greater than 387. Hence the time constant of 5 seconds was used in the heat transfer analysis.

Appendix E

Data for Sign test results

Data for waviness validation (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2639	2646	3.13	22.0	(+)
2639	2685	3.13	29.0	(+)
2639	2691	3.13	12.5	(+)
2648	2646	10.90	22.0	(+)
2648	2685	10.90	29.0	(+)
2648	2691	10.90	12.5	(+)
2633	2646	15.75	22.0	(+)
2633	2685	15.75	29.0	(+)
2633	2691	15.75	12.5	(+)
2641	2646	7.50	22.0	(+)
2641	2685	7.50	29.0	(+)
2641	2691	7.50	12.5	(+)
2672	2646	8.20	22.0	(+)
2672	2685	8.20	29.0	(+)
2672	2691	8.20	12.5	(+)
2674	2646	15.00	22.0	(+)
2674	2685	15.00	29.0	(+)
2674	2691	15.00	12.5	(−)
2686	2646	25.00	22.0	(−)
2686	2685	25.00	29.0	(+)
2686	2691	25.00	12.5	(−)
2646	2691	22.00	12.5	(−)
2685	2691	29.00	12.5	(−)
Result : 23 *trials* 18 (+)'s 5(−)				

(E.1)

Data for waviness validation (Vendor 2)				
Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More*	*Metric Value Less*	*Sign*
2639	2633	3.13	15.6	(−)
2639	2641	3.13	7.5	(−)
2639	2648	3.13	10.9	(−)
2639	2674	3.13	15.0	(−)
2639	2685	3.13	29.0	(−)
2639	2686	3.13	25.0	(−)
2639	2691	3.13	12.5	(−)
2646	2633	22.00	15.6	(+)
2646	2641	22.00	7.5	(+)
2646	2648	22.00	10.9	(+)
2646	2674	22.00	15.0	(+)
2646	2685	22.00	29.0	(−)
2646	2686	22.00	25.0	(−)
2646	2691	22.00	12.5	(+)
2672	2633	8.20	15.6	(−)
2672	2641	8.20	7.5	(+)
2672	2648	8.20	10.9	(−)
2672	2674	8.20	15.0	(−)
2672	2685	8.20	29.0	(−)
2672	2686	8.20	25.0	(−)
2672	2691	8.20	12.5	(−)
Result : 21 *trials* 15 (−)'s 6(+)'s				

(E.2)

Data for floppy shapes validation (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2633	2639	$4.59E-02$	$1.22E-03$	(−)
2633	2648	$4.59E-02$	$2.99E-02$	(−)
2633	2685	$4.59E-02$	$6.75E-03$	(−)
2633	2691	$4.59E-02$	$1.24E-04$	(−)
2641	2639	$2.09E+00$	$1.22E-03$	(−)
2641	2648	$2.09E+00$	$2.99E-02$	(−)
2641	2685	$2.09E+00$	$6.75E-03$	(−)
2641	2691	$2.09E+00$	$1.24E-04$	(−)
2646	2639	$3.68E-01$	$1.22E-03$	(−)
2646	2648	$3.68E-01$	$2.99E-02$	(−)
2646	2685	$3.68E-01$	$6.75E-03$	(−)
2646	2691	$3.68E-01$	$1.24E-04$	(−)
2672	2639	$1.93E-01$	$1.22E-03$	(−)
2672	2648	$1.93E-01$	$2.99E-02$	(−)
2672	2685	$1.93E-01$	$6.75E-03$	(−)
2672	2691	$1.93E-01$	$1.24E-04$	(−)
2674	2639	$7.73E+01$	$1.22E-03$	(−)
2674	2648	$7.73E+01$	$2.99E-02$	(−)
2674	2685	$7.73E+01$	$6.75E-03$	(−)
2674	2691	$7.73E+01$	$1.24E-04$	(−)
2686	2639	$5.69E-03$	$1.22E-03$	(−)
2686	2648	$5.69E-03$	$2.99E-02$	(+)
2686	2685	$5.69E-03$	$6.75E-03$	(+)
2639	2691	$1.22E-03$	$1.24E-04$	(−)
2648	2691	$2.99E-02$	$1.24E-04$	(−)
2685	2691	$6.75E-03$	$1.24E-04$	(−)
Result : 27 *trials* 25 (−)'*s* 2(+)'*s*				

(E.3)

Data for floppy shapes validation (Vendor 2)				
Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More severe*	*Metric Value Less severe*	*Sign*
2685	2639	$6.75E-03$	$1.22E-03$	(+)
2685	2648	$6.75E-03$	$2.99E-02$	(−)
2685	2686	$6.75E-03$	$5.69E-03$	(+)
2685	2633	$6.75E-03$	$4.59E-02$	(−)
2685	2641	$6.75E-03$	$2.09E+00$	(−)
2685	2646	$6.75E-03$	$3.68E-01$	(−)
2685	2672	$6.75E-03$	$1.93E-01$	(−)
2685	2674	$6.75E-03$	$7.73E+01$	(−)
2691	2639	$1.24E-04$	$1.22E-03$	(−)
2691	2648	$1.24E-04$	$2.99E-02$	(−)
2691	2686	$1.24E-04$	$5.69E-03$	(−)
2691	2633	$1.24E-04$	$4.59E-02$	(−)
2691	2641	$1.24E-04$	$2.09E+00$	(−)
2691	2646	$1.24E-04$	$3.68E-01$	(−)
2691	2672	$1.24E-04$	$1.93E-01$	(−)
2691	2674	$1.24E-04$	$7.73E+01$	(−)
2639	2633	$1.22E-03$	$4.59E-02$	(−)
2639	2641	$1.22E-03$	$2.09E+00$	(−)
2639	2646	$1.22E-03$	$3.68E-01$	(−)
2639	2672	$1.22E-03$	$1.93E-01$	(−)
2639	2674	$1.22E-03$	$7.73E+01$	(−)
2648	2633	$2.99E-02$	$4.59E-02$	(−)
2648	2641	$2.99E-02$	$2.09E+00$	(−)
2648	2646	$2.99E-02$	$3.68E-01$	(−)
2648	2672	$2.99E-02$	$1.93E-01$	(−)
2648	2674	$2.99E-02$	$7.73E+01$	(−)
2686	2633	$5.69E-03$	$4.59E-02$	(−)
2686	2641	$5.69E-03$	$2.09E+00$	(−)
2686	2646	$5.69E-03$	$3.68E-01$	(−)
2686	2672	$5.69E-03$	$1.93E-01$	(−)
2686	2674	$5.69E-03$	$7.73E+01$	(−)
Result : 31 *trials* 29 (−)′*s* 2(+)′*s*				

(E.4)

Data for die wear validation (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2641	2633	6.05	22.0	(+)
2641	2639	6.05	29.0	(+)
2641	2646	6.05	12.5	(+)
2641	2648	6.05	22.0	(+)
2641	2691	6.05	29.0	(+)
2641	2685	6.05	12.5	(+)
2641	2686	6.05	22.0	(+)
2672	2633	8.96	29.0	(+)
2672	2639	8.96	12.5	(+)
2672	2646	8.96	22.0	(+)
2672	2648	8.96	29.0	(+)
2672	2691	8.96	12.5	(+)
2672	2685	8.96	22.0	(+)
2672	2686	8.96	29.0	(+)
2674	2633	10.29	12.5	(+)
2674	2639	10.29	22.0	(+)
2674	2646	10.29	29.0	(+)
2674	2648	10.29	12.5	(+)
2674	2691	10.29	22.0	(+)
2674	2685	10.29	29.0	(+)
2674	2686	10.29	12.5	(+)
2633	2685	26.08	39.84	(+)
2639	2685	23.46	39.84	(+)
2646	2685	16.74	39.84	(+)
2648	2685	18.40	39.84	(+)
2691	2685	28.55	39.84	(+)
2633	2686	26.08	32.84	(+)
2639	2686	23.46	32.84	(+)
2646	2686	16.74	32.84	(+)
2648	2686	18.40	32.84	(+)
2691	2686	28.55	32.84	(+)
Result : 31 *trials* 31 (+)'*s* 0(−)'*s*				

(E.5)

Data for die wear validation (Vendor 2)				
Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More*	*Metric Value Less*	*Sign*
2685	2633	39.8	26.10	(+)
2685	2639	39.8	23.50	(+)
2685	2646	39.8	16.70	(+)
2685	2648	39.8	18.40	(+)
2685	2672	39.8	8.96	(+)
2685	2674	39.8	10.30	(+)
2685	2691	39.8	28.60	(+)
2686	2633	32.8	26.10	(+)
2686	2639	32.8	23.50	(+)
2686	2646	32.8	16.70	(+)
2686	2648	32.8	18.40	(+)
2686	2672	32.8	8.96	(+)
2686	2674	32.8	10.30	(+)
2686	2691	32.8	28.60	(+)
2633	2641	26.10	6.05	(+)
2639	2641	23.50	6.05	(+)
2646	2641	16.70	6.05	(+)
2648	2641	18.40	6.05	(+)
2672	2641	8.96	6.05	(+)
2674	2641	10.30	6.05	(+)
2691	2641	28.60	6.05	(+)
2685	2641	39.80	6.05	(+)
2686	2641	32.80	6.05	(+)
Result : 23 *trials* 0 (−)'*s* 23(+)'*s*				

(E.6)

Data for hot shortness validation (Vendor 1)				
Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More severe*	*Metric Value Less severe*	*Sign*
2633	2641	26.08	6.05	(+)
2639	2641	23.46	6.05	(+)
2646	2641	16.74	6.05	(+)
2686	2641	32.84	6.05	(+)
2691	2641	28.55	6.05	(+)
2685	2641	39.84	6.05	(+)
2633	2648	26.08	18.40	(+)
2639	2648	23.46	18.40	(+)
2646	2648	16.74	18.40	(−)
2686	2648	32.84	18.40	(+)
2691	2648	28.55	18.40	(+)
2685	2648	39.84	18.40	(+)
2633	2672	26.08	8.96	(+)
2639	2672	23.46	8.96	(+)
2646	2672	16.74	8.96	(+)
2686	2672	32.84	8.96	(+)
2691	2672	28.55	8.96	(+)
2685	2672	39.84	8.96	(+)
2633	2674	26.08	10.29	(+)
2639	2674	23.46	10.29	(+)
2646	2674	16.74	10.29	(+)
2686	2674	32.84	10.29	(+)
2691	2674	28.55	10.29	(+)
2685	2674	39.84	10.29	(+)
2885	2633	39.84	26.08	(+)
2885	2639	39.84	23.46	(+)
2885	2646	39.84	16.74	(+)
2885	2686	39.84	32.84	(+)
2885	2691	39.84	28.55	(+)
Result : 29 *trials* 28 (+)*'s* 1(−)				

(E.7)

Data for hot shortness validation (Vendor 2)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2641	2639	6.05	23.5	(+)
2641	2672	6.05	8.96	(+)
2641	2674	6.05	10.3	(+)
2641	2691	6.05	28.6	(+)
2641	2633	6.05	26.0	(+)
2641	2646	6.05	16.7	(+)
2641	2648	6.05	18.4	(+)
2641	2685	6.05	39.8	(+)
2641	2686	6.05	32.8	(+)
2639	2633	23.50	26.0	(+)
2639	2646	23.50	16.7	(−)
2639	2648	23.50	18.4	(−)
2639	2685	23.50	39.8	(+)
2639	2686	23.50	32.8	(−)
2672	2633	8.96	26.0	(+)
2672	2646	8.96	16.7	(+)
2672	2648	8.96	18.4	(+)
2672	2685	8.96	39.8	(+)
2672	2686	8.96	32.8	(+)
2674	2633	10.3	26.0	(+)
2674	2646	10.3	16.7	(+)
2674	2648	10.3	18.4	(+)
2674	2685	10.3	39.8	(+)
2674	2686	10.3	32.8	(+)
2691	2633	28.6	26.0	(−)
2691	2646	28.6	16.7	(−)
2691	2648	28.6	18.4	(−)
2691	2685	28.6	39.8	(+)
2691	2686	28.6	32.8	(+)
Result : 29 *trials* 23 (+)*'s* 6(−)*'s*				

(E.8)

Data for bending validation (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2633	2641	0.0020	0.060	(+)
2633	2646	0.0020	0.169	(+)
2633	2672	0.0020	1.260	(+)
2633	2674	0.0020	0.040	(+)
2633	2685	0.0020	0.216	(+)
2633	2686	0.0020	0.906	(+)
2639	2641	11.180	0.060	(−)
2639	2646	11.180	0.169	(−)
2639	2672	11.180	1.260	(−)
2639	2674	11.180	0.040	(−)
2639	2685	11.180	0.216	(−)
2639	2686	11.180	0.906	(−)
2648	2641	0.2510	0.060	(−)
2648	2646	0.2510	0.169	(−)
2648	2672	0.2510	1.260	(+)
2648	2674	0.2510	0.040	(−)
2648	2685	0.2510	0.216	(−)
2648	2686	0.2510	0.906	(+)
2691	2641	0.0897	0.060	(−)
2691	2646	0.0897	0.169	(+)
2691	2672	0.0897	1.260	(+)
2691	2674	0.0897	0.040	(−)
2691	2685	0.0897	0.216	(+)
2691	2686	0.0897	0.906	(+)
Result : 24 *trials* 12 (+)*'s* 12(−)*'s*				

(E.9)

Data for bending validation (Vendor 2)

Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More*	*Metric Value Less*	*Sign*
2641	2639	$1.42E-01$	$1.99E+00$	(−)
2641	2646	$1.42E-01$	$2.07E-01$	(−)
2641	2633	$1.42E-01$	$5.06E-03$	(+)
2641	2674	$1.42E-01$	$7.02E-02$	(+)
2641	2685	$1.42E-01$	$5.25E-01$	(−)
2641	2686	$1.42E-01$	$6.73E-01$	(−)
2641	2691	$1.42E-01$	$1.21E+00$	(−)
2648	2639	$5.79E-01$	$1.99E+00$	(−)
2648	2646	$5.79E-01$	$2.07E-01$	(+)
2648	2633	$5.79E-01$	$5.06E-03$	(+)
2648	2674	$5.79E-01$	$7.02E-02$	(+)
2648	2685	$5.79E-01$	$5.25E-01$	(−)
2648	2686	$5.79E-01$	$6.73E-01$	(−)
2648	2691	$5.79E-01$	$1.21E+00$	(+)
2672	2639	$2.22E+00$	$1.99E+00$	(+)
2672	2646	$2.22E+00$	$2.07E-01$	(+)
2672	2633	$2.22E+00$	$5.06E-03$	(+)
2672	2674	$2.22E+00$	$7.02E-02$	(+)
2672	2685	$2.22E+00$	$5.25E-01$	(+)
2672	2686	$2.22E+00$	$6.73E-01$	(+)
2672	2691	$2.22E+00$	$1.21E+00$	(+)
2639	2633	$1.99E+00$	$5.06E-03$	(+)
2639	2674	$1.99E+00$	$7.02E-02$	(+)
2639	2685	$1.99E+00$	$5.25E-01$	(+)
2639	2686	$1.99E+00$	$6.73E-01$	(+)
2639	2691	$1.99E+00$	$1.21E+00$	(+)
2646	2633	$2.07E-01$	$5.06E-03$	(+)
2646	2674	$2.07E-01$	$7.02E-02$	(+)
2646	2685	$2.07E-01$	$5.25E-01$	(−)
2646	2686	$2.07E-01$	$6.73E-01$	(−)
2646	2691	$2.07E-01$	$1.21E+00$	(−)

Result : 31 *trials* 11 (−)'s 20(+)'s

(E.10)

Data for heat treat distortion validation (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2633	2646	0.90	0.2033	(−)
2639	2646	0.05	0.2033	(+)
2641	2646	0.70	0.2033	(−)
2648	2646	790.00	0.2033	(−)
2674	2646	7.35	0.2033	(−)
2691	2646	0.028	0.2033	(+)
2633	2672	0.90	0.1490	(−)
2639	2672	0.05	0.1490	(+)
2641	2672	0.70	0.1490	(−)
2648	2672	790.00	0.1490	(−)
2674	2672	7.35	0.1490	(−)
2691	2672	0.028	0.1490	(+)
2633	2685	0.90	64.000	(+)
2639	2685	0.05	64.000	(+)
2641	2685	0.70	64.000	(+)
2648	2685	790.00	64.000	(−)
2674	2685	7.35	64.000	(+)
2691	2685	0.028	64.000	(+)
2633	2686	0.90	0.0600	(−)
2639	2686	0.05	0.0600	(+)
2641	2686	0.70	0.0600	(−)
2648	2686	790.00	0.0600	(−)
2674	2686	7.35	0.0600	(−)
2691	2686	0.028	0.0600	(+)
Result : 24 *trials* 11 (+)*'s* 13(−)*'s*				

(E.11)

Data for heat treat distortion validation (Vendor 2)

Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More*	*Metric Value Less*	*Sign*
2641	2639	4.39E − 02	6.80E − 03	(+)
2641	2691	4.39E − 02	2.70E − 03	(+)
2641	2633	4.39E − 02	2.84E − 01	(−)
2641	2648	4.39E − 02	9.80E − 03	(+)
2641	2674	4.39E − 02	2.70E − 01	(−)
2641	2685	4.39E − 02	1.59E − 01	(−)
2641	2686	4.39E − 02	3.90E − 02	(+)
2646	2639	2.56E − 02	6.80E − 03	(+)
2646	2691	2.56E − 02	2.70E − 03	(+)
2646	2633	2.56E − 02	2.84E − 01	(−)
2646	2648	2.56E − 02	9.80E − 03	(+)
2646	2674	2.56E − 02	2.70E − 01	(−)
2646	2685	2.56E − 02	1.59E − 01	(−)
2646	2686	2.56E − 02	3.90E − 02	(−)
2672	2639	2.30E − 02	6.80E − 03	(+)
2672	2691	2.30E − 02	2.70E − 03	(+)
2672	2633	2.30E − 02	2.84E − 01	(−)
2672	2648	2.30E − 02	9.80E − 03	(+)
2672	2674	2.30E − 02	2.70E − 01	(−)
2672	2685	2.30E − 02	1.59E − 01	(−)
2672	2686	2.30E − 02	3.90E − 02	(−)
2639	2633	6.80E − 03	2.84E − 01	(−)
2639	2648	6.80E − 03	9.80E − 03	(−)
2639	2674	6.80E − 03	2.70E − 01	(−)
2639	2685	6.80E − 03	1.59E − 01	(−)
2639	2686	6.80E − 03	3.90E − 02	(−)
2691	2633	2.70E − 05	2.84E − 01	(−)
2691	2648	2.70E − 05	9.80E − 03	(−)
2691	2674	2.70E − 05	2.70E − 01	(−)
2691	2685	2.70E − 05	1.59E − 01	(−)
2691	2686	2.70E − 05	3.90E − 02	(−)

Result : 31 *trials* 21 (−)'s 10(+)'s

(E.12)

Data for revised section balance (Vendor 1)				
Extrusion Number Less severe	*Extrusion Number More severe*	*Metric Value Less severe*	*Metric Value More severe*	*Sign*
2633	2641	$2.32E-04$	$2.96E-01$	(+)
2633	2646	$2.32E-04$	$7.65E-02$	(+)
2633	2672	$2.32E-04$	$4.47E-01$	(+)
2633	2674	$2.32E-04$	$6.30E-02$	(+)
2633	2685	$2.32E-04$	$3.74E-03$	(+)
2633	2686	$2.32E-04$	$6.38E-03$	(+)
2639	2641	$1.38E-02$	$2.96E-01$	(+)
2639	2646	$1.38E-02$	$7.65E-02$	(+)
2639	2672	$1.38E-02$	$4.47E-01$	(+)
2639	2674	$1.38E-02$	$6.30E-02$	(+)
2639	2685	$1.38E-02$	$3.74E-03$	(−)
2639	2686	$1.38E-02$	$6.38E-03$	(−)
2648	2641	$1.89E-02$	$2.96E-01$	(+)
2648	2646	$1.89E-02$	$7.65E-02$	(+)
2648	2672	$1.89E-02$	$4.47E-01$	(+)
2648	2674	$1.89E-02$	$6.30E-02$	(+)
2648	2685	$1.89E-02$	$3.74E-03$	(−)
2648	2686	$1.89E-02$	$6.38E-03$	(−)
2691	2641	$1.92E-04$	$2.96E-01$	(+)
2691	2646	$1.92E-04$	$7.65E-02$	(+)
2691	2672	$1.92E-04$	$4.47E-01$	(+)
2691	2674	$1.92E-04$	$6.30E-02$	(+)
2691	2685	$1.92E-04$	$3.74E-03$	(+)
2691	2686	$1.92E-04$	$6.38E-03$	(+)
Result : 24 *trials* 20 (+)*'s* 4(−)*'s*				

(E.13)

Data for revised section balance (Vendor 2)

Extrusion Number More severe	*Extrusion Number Less severe*	*Metric Value More*	*Metric Value Less*	*Sign*
2641	2639	$2.96E-01$	$1.38E-02$	(+)
2641	2646	$2.96E-01$	$7.65E-02$	(+)
2641	2633	$2.96E-01$	$2.33E-04$	(+)
2641	2674	$2.96E-01$	$6.30E-02$	(+)
2641	2685	$2.96E-01$	$3.74E-03$	(+)
2641	2686	$2.96E-01$	$6.38E-03$	(+)
2641	2691	$2.96E-01$	$1.92E-04$	(+)
2648	2639	$1.89E-02$	$1.38E-02$	(+)
2648	2646	$1.89E-02$	$7.65E-02$	(−)
2648	2633	$1.89E-02$	$2.33E-04$	(+)
2648	2674	$1.89E-02$	$6.30E-02$	(−)
2648	2685	$1.89E-02$	$3.74E-03$	(+)
2648	2686	$1.89E-02$	$6.38E-03$	(+)
2648	2691	$1.89E-02$	$1.92E-04$	(+)
2672	2639	$4.47E-01$	$1.38E-02$	(+)
2672	2646	$4.47E-01$	$7.65E-02$	(+)
2672	2633	$4.47E-01$	$2.33E-04$	(+)
2672	2674	$4.47E-01$	$6.30E-02$	(+)
2672	2685	$4.47E-01$	$3.74E-03$	(+)
2672	2686	$4.47E-01$	$6.38E-03$	(+)
2672	2691	$4.47E-01$	$1.92E-04$	(+)
2639	2633	$1.38E-02$	$2.33E-04$	(+)
2639	2674	$1.38E-02$	$6.30E-02$	(−)
2639	2685	$1.38E-02$	$3.74E-03$	(+)
2639	2686	$1.38E-02$	$6.38E-03$	(+)
2639	2691	$1.38E-02$	$1.92E-04$	(+)
2646	2633	$7.65E-02$	$2.33E-04$	(+)
2646	2674	$7.65E-02$	$6.30E-02$	(+)
2646	2685	$7.65E-02$	$3.74E-03$	(+)
2646	2686	$7.65E-02$	$6.38E-03$	(+)
2646	2691	$7.65E-02$	$1.92E-04$	(+)

Result : 31 *trials* 28 (+)'*s* 3(−)'*s*

(E.14)

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