Lean Provisioning of Form Dies for Aircraft Stringers on the 737-800

by
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S.B. Aeronautics and Astronautics, MIT, 1984
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Submitted to the Sloan School of Management and the
Department of Mechanical Engineering
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Master of Science in Management
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Abstract

This thesis studies the external supply chain of Boeing's Tooling Manufacturing Business Unit. A review was conducted of how the form die package for the 737-700 aircraft was provisioned in terms of cost, quality and schedule. A team of Boeing personnel then implemented a preferred supplier approach whereby working more closely with fewer suppliers of form dies resulted in improvements in the same metrics. In general, benefits for both Boeing and a few preferred suppliers result from improved information transfer, knowledge sharing and an alignment of supplier and internal Boeing incentives. In this trial implementation of the use of a preferred supplier on the 737-800 form die package, the specific benefits measured included:

- a reduction in die procurement cost of $32K,
- a reduction in the tool tryout time saving an additional $46K,
- elimination of die rework, and
- an improvement in schedule performance.

In addition, the benefits of increased trust resulted in learning taking place in the supply chain. This approach can be extended to other tooling types and to parts provisioning in general.

The second part of the project involved evaluating the design approach for springback in stringer dies. Die designers currently use a constant 15% overbend to account for springback. A Finite Element Analysis of the stringer forming process showed that larger overbends are appropriate for larger joggles and more slender joggles. Analysis results were correlated with measurement data taken from parts formed using modeled dies. The improved design approach is being implemented on the next die package. The benefit is reduced die rework.

Thesis Advisors:
Professor Charles Fine, Sloan School of Management
Dr. Daniel E. Whitney, Department of Mechanical Engineering

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I would also like to thank those employees at my internship site in the Tooling MBU who took time to either participate in the project or share their ideas and experiences with me. Most importantly, I thank Pat Shanahan for being the inspiration for the project and for pushing me every step of the way. Pat will continue to excel because he expects nothing but the very best out of people working with him. Thanks also to Jim Helland for mentoring me during the project. Jim has run successful businesses outside of Boeing. He brings a great outside perspective to supply chain management that Boeing is now benefiting from. Thanks also go to the team members who did the real work on my project including Ray Plattner, Bob Jacobson, Al Potter, Dave Wagner, Ray Beatty, Wolfgang Demutch, Jon Gabrys and Gerry Young.

Finally, my thanks go to my family and friends in the LFM program that helped me through this two challenging years. I gained a group of friends that will stay with me for my career and life. I won't forget working and having good times with Will Cook, Liana Alvarez, Keith Jackson, Tom Jacob, E.K. Yang, Rob Moeller, and Mike Miller, among others.

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1. Chapter 1 - Introduction

The Tooling Manufacturing Business Unit (MBU) located in Auburn, WA is part of the Fabrication Division of the Boeing Commercial Airplane Group (BCAG). The Tooling MBU is responsible for the majority of the tooling within BCAG. The remaining tooling is either outsourced by Boeing to an existing supplier base or it is designed and manufactured at product divisions such as those in Renton or Everett. Boeing must both make and buy some types of tooling because of limited in-house capacity and the desire to minimize the cyclicality of the factory workforce. Cost savings is one benefit gained by outsourcing in tooling, but often times making schedule is more difficult because of the additional process steps required (e.g. procurement, shipping to Boeing). Since, in tooling, a critical ability is being able to support Boeing's bringing an aircraft product to market on time, there is significant leverage in streamlining the external supply chain. Thus, a core competence of the Tooling MBU is "the coordination of numerable but scarce resources (both internal and external) in a huge development project on a fast development schedule."[1] Although many tooling technologies are mature and widely available in the industry, there is some learning that must take place by suppliers to accommodate Boeing's specific requirements. Others tooling skills such as those related to the design and development of flexible tools are more emerging and proprietary.

While working in the Tooling MBU I have become familiar with tooling development processes in both the internal and external supply chain. The overall goal of my project is to improve the external supply chain portion of the Tooling MBU's processes since: 1) it will represent a larger portion of this MBU's role in the future, and 2) given that the current buy processes for tooling generally require more flowtime than the make processes. While in Auburn, I have extensively reviewed Boeing's performance on the 737-700 die package, a group of nearly 200 form and joggle dies used to make fuselage longitudinal stiffeners. The dies were provisioned from nine sources (two internal shops, seven vendors). Although Boeing saved significant amounts of money overall by outsourcing many of these dies, many of the suppliers delivered dies late and some required significant TTO(tool-tryout) and rework before they could make a good part.

Based on this information, I proposed that the procurement of the next package of dies (737-800) be accomplished differently. We formed a cross-functional team to choose preferred suppliers for the 737-800 dies. Based on inputs from Procurement, Work Transfer Management, Tool Engineering, TTO, and Quality, as well as the cost, quality and schedule information I compiled, we reached consensus on one preferred external supplier. A closer relationship was formed with this vendor, in effect ameliorating the overall flow-time in the buy process in the information and material aspects of the supply chain. By the end of my internship period, I had collected cost, rework, quality, and schedule data from the new process. In this trial implementation of the use of a preferred supplier on the 737-800 form die package, the benefits measured included:

- a reduction in die procurement cost of $32K,
- a reduction in the tool tryout time saving an additional $46K,
- elimination of die rework, and
- an improvement in schedule performance.

In addition, the benefits of increased trust resulted in learning taking place in the supply chain. This approach can be extended to other tooling types and to parts provisioning in general.

Finally, based on part forming trials as correlated with die geometry, it was possible to improve the overall die design process in the area of springback compensation. Both experiments and the use of non-linear Finite Element Analysis were explored as part of this component of the project.

1.1 Thesis Chapter Overview

This thesis contains the following:

- In Chapter 2, a description of the current Tooling MBU processes focusing on the differences between the internal and external supply chain as they exist today.
- In Chapter 3, an evaluation of the data collected in the 737-700 die case study which are used as a baseline case in this project.
- In Chapter 4, the process proposed and used in the 737-800 die package, and an evaluation of the results of this process.

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[1] Professor Charlie Fine during a visit to the Tooling MBU, March 1996.

- In Chapter 5, the results of a study of springback in dies and a proposal for an improved design process.
- In Chapter 6, a proposal for tooling process improvements including: a make/buy strategy in dies, the use of preferred suppliers in other tool types, and the integration of the procurement function into the Tooling MBU.

2. Chapter 2 - Background on Aircraft Tooling

2.1 Introduction

In this Chapter, I will present the background information for my project. Background includes an overview of the Tooling MBU where I spent my internship period. I will discuss the organization and processes used in making and buying tools at Boeing.. I will then describe a survey of how other large tooling users manage their supply chain, and a brief literature survey of supply chain management techniques that apply to this project.

2.2 The Boeing Tooling MBU

The Tooling MBU is responsible for defining, producing and procuring tooling for Boeing products. This tool provisioning is accomplished with the help of both internal and separate functional organizations. The products of the MBU are assembly tools and detail production tools. The services of the MBU include Tool Engineering and Support Services. For reference only, a recent organizational chart for Tooling is shown in Figure 2.1.

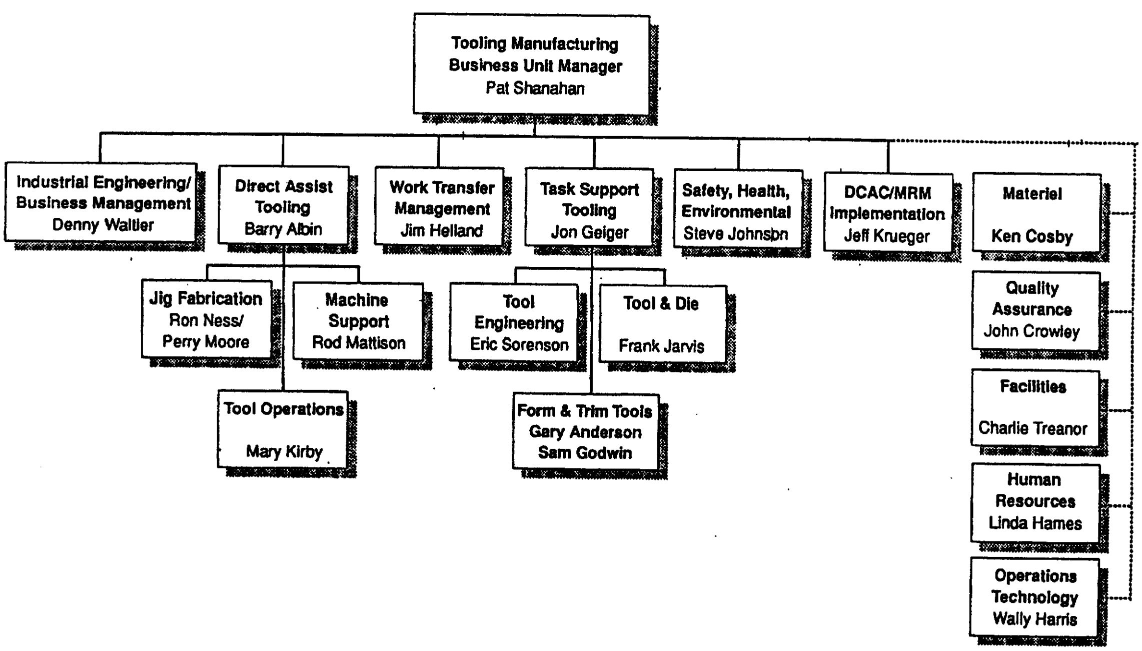

Figure 2.1 Tooling MBU Organizational Chart

2.2.1 Products - Assembly Tools (Direct Assist Tooling)

Assembly Tools are tools used to handle, locate, and assemble one or more parts used in an airplane. Assembly tools include: 1) major jigs, 2) locating jigs, 3) assembly jigs, 4) scaffolding, 5) optical tools, and 6) handling equipment. In general, these tools are used by the Product Divisions such as 777 or 747. Critical skills required to build such tools include welding, large surface machining, and coordinate and optical measurement.

2.2.2 Products Detail Production Tools (Task Support Tooling)

Detail Production Tools are used to form, fabricate, machine or trim parts used in the airplane. Detail production tools include: 1) machine fixtures, 2) trim tools, 3) master and part models, 4) molds, 5) layup mandrels, and 6) forming tools (e.g. dies) These tools are generally used by other MBU's in the Fabrication Division to make parts. For example, the Sheet Metal Center uses form dies made by the Tooling MBU to form stringers used in the assembly of a fuselage. Critical skills required to build these tools include N/C programming, precision machining and tool and die making.

2.2.3 Services - Tool Engineering

Tool Engineering includes Tool Design, Tool Planning, and Tool Numerical Control (N/C). Some assembly tools are designed in the product divisions. However most detail production tools are designed within the Tooling MBU. Tool Planning develops specific process steps and schedules for all tools and the Tool Numerical Control group generates N/C programs which specify cutter types and paths for tools made inside. Critical skills for these groups include CATIA-based design and N/C programming.

2.2.4 Services - Support

There are five support organizations that are part of Tooling and directly support the activities within. These include: 1) Machining, 2) Work Transfer Management (WTM), 3) Tool Operations, 4) Industrial Engineering, and 5) Business Management. I will describe the activities of three of these support organizations as they principally relate to this thesis. In addition, there are two important tooling support groups (Procurement and Quality Assurance) that are organizationally separate that I will describe.

Industrial Engineering - The Industrial Engineering Group within the Tooling MBU is responsible for a number of key steps in provisioning tools. First, they receive the tool orders from the customer, whether they be product divisions or other MBU's. They make a decision on make/buy based primarily on their assessment of factory capacity and loading. For buy orders, they pass the tool order along to WTM. For make orders, they plan and schedule which shops within Tooling will work on the tool and deliver the orders to those shops.

Work Transfer Management - WTM is responsible for receiving a tool order package (including drawings, schedule, requirements) from the Industrial Engineering Group once the buy decision has been made by Industrial Engineering. They prepare the order to be submitted to suppliers (by Procurement) for bid and award. Once the tool order is awarded to a supplier, WTM is then responsible for monitoring and supporting the supplier until the tool is complete. Surveillance members of WTM work closely with suppliers as representatives of Boeing and act as aids in communication and resolution of problems or questions. WTM performs the following functions:

1) **Breakdown** - preparing the tool order to be bid,
2) **Surveillance** - tracking supplier performance on tools, visiting suppliers, assisting in problem resolution,
3) **Squawk Desk** - receiving notification of a vendor problem or question and assisting in disposition,
4) **Analysts** - receiving information from surveillance and updating tracking systems and program managers,
5) **Program Managers** - interfacing with the customer on tool orders.

"We want them(suppliers) to succeed", N. Ramos of WTM (Surveillance)

Business Management - Business Management is responsible for tracking costs within Tooling. They compile and track both direct expenditures on tools and overhead within the MBU. By requesting outside supplier charges from Procurement, they have been able to make some comparisons of Tooling MBU versus supplier costs for similar tools. They have developed a process for making a fair comparison which I use in my assessment of total cost competitiveness for dies. This process modifies costs metrics as follows: 1) supplier cost is increased to account for Q/A inspection, WTM, and Procurement activities (all costs contained in overhead, but real costs to Boeing which must be considered in deciding make/buy), and 2) a make/buy rate for Boeing-made dies is determined by reducing the non-labor (overhead) portion to account for offload support activities and other unfair overhead (such as Boeing General and Administrative) burdening. This make/buy rate is approximately 20-40% below the fully burdened rate.

Procurement - The Procurement Organization (also called Materiel in Boeing) is both located physically and organizationally separate from Tooling. They are responsible for soliciting bids from suppliers and then selecting the supplier. Once an order is placed with a supplier, they communicate with the supplier concerning any contractual changes (including price and terms). They maintain the list of approved suppliers for tooling and production parts. The Procurement Organization has in the past been reluctant to give cost information to others within Boeing because of its potential for being misused in some way. Having Procurement in a separate organization from the Tooling MBU has made it difficult in the past to work together as a team because of different management and reporting structure, performance metrics not aligned with the Tooling MBU and poor communication between the organizations.

Quality Assurance - The Quality Assurance (Q/A) Organization that supports Tooling is organizationally separate (separate management and reporting structure), but it is physically located in the Tooling MBU. They are responsible for inspecting tools, recording tool quality and communication with their customers, whether the tooling is manufactured inside Boeing or at a supplier. Q/A representatives visit suppliers in order to certify supplier Q/A processes and to verify individual tool quality.

2.3 How Boeing procures tooling

2.3.1 Boeing Approach to Satisfying Tooling Demand

Tooling demand occurs at Boeing for two main reasons: 1) for new product development, and 2) for rate requirements (tools that need to be periodically replaced at a fixed "rate"). The majority of tool volume is due to new product development of a new model (e.g. 777, 767) or a new derivative of an existing model (e.g. 737-800, 737-600). A new derivative can create requirements for an entire new tool set for wing, fuselage and empennage components and their assembly. These new products tend to be separated by three to five years and as a result the tooling demand created by new product development is highly cyclical. In the past, Boeing built most tooling inside, and the workforce of the Tooling MBU rose and fell with these demand cycles (Figure 2.2).

More recently, Boeing has tried to maintain a constant level workforce at the MBU in order to create workforce stability, maintain a high skill level, and to concentrate on critical tooling types and emergent (last minute) requirements. This approach results in an increased level of outsourcing when one or more new products are developed. One such program being considered by Boeing is the 747X. Tooling development for the 747X will take place over three years and result in a record level of outsourcing during that period. A recent tooling work statement for the 747X, reflecting the large amount of outsourcing required, is shown in Figure 2.3.

2.3.2 Tool Provisioning Process

The order for a tool tends to occur late in the engineering product (part) definition process. That is, a tool design is only completed when the engineering part design is frozen. Part design is completed by another Boeing division and the order for a tool design is typically the first involvement of the Tooling MBU. Figure 2.4 shows the typical process flow for a tool beginning with the tool design request (TDR). Although most tool designs that the Tooling MBU will provision are completed in Auburn, some designs are completed in product divisions that have separate tool design groups. In those cases, the Tooling MBU only makes or buys the tool. Designers are responsible for translating the part requirements into a tool design that will form the required geometry.

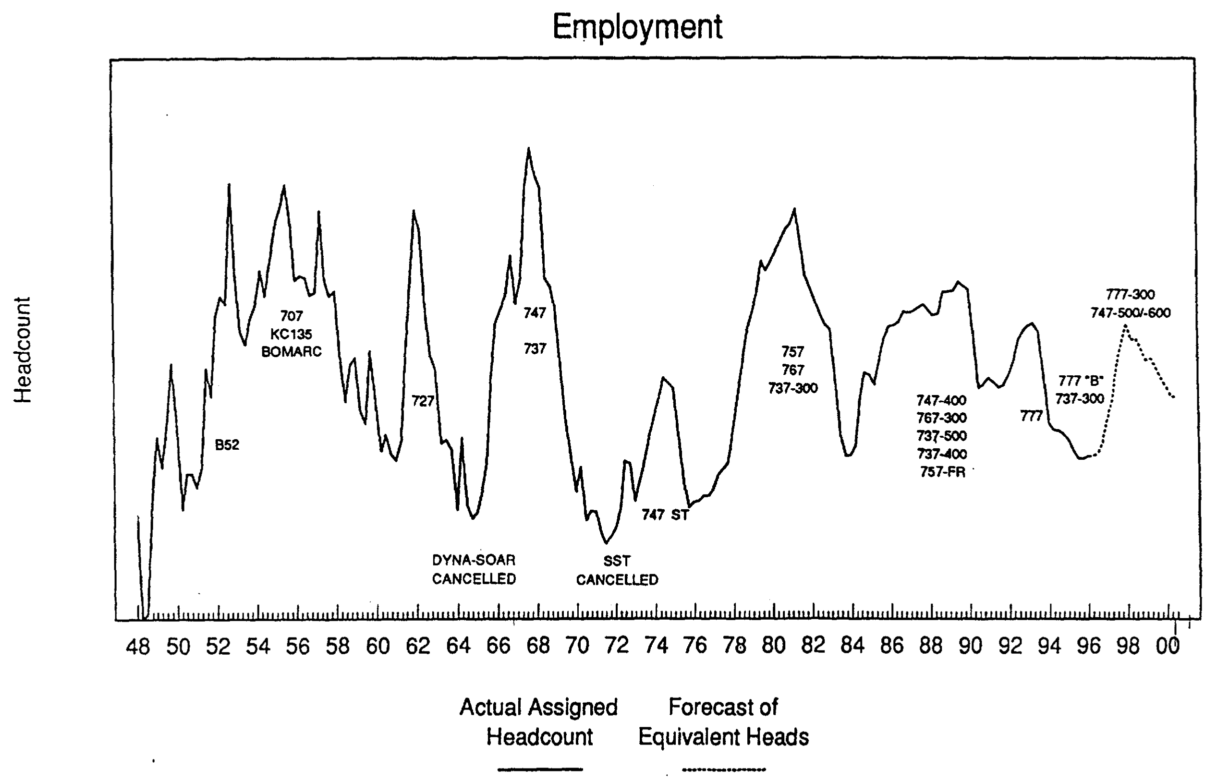

Figure 2.2 Manpower Levels in the Tooling MBU

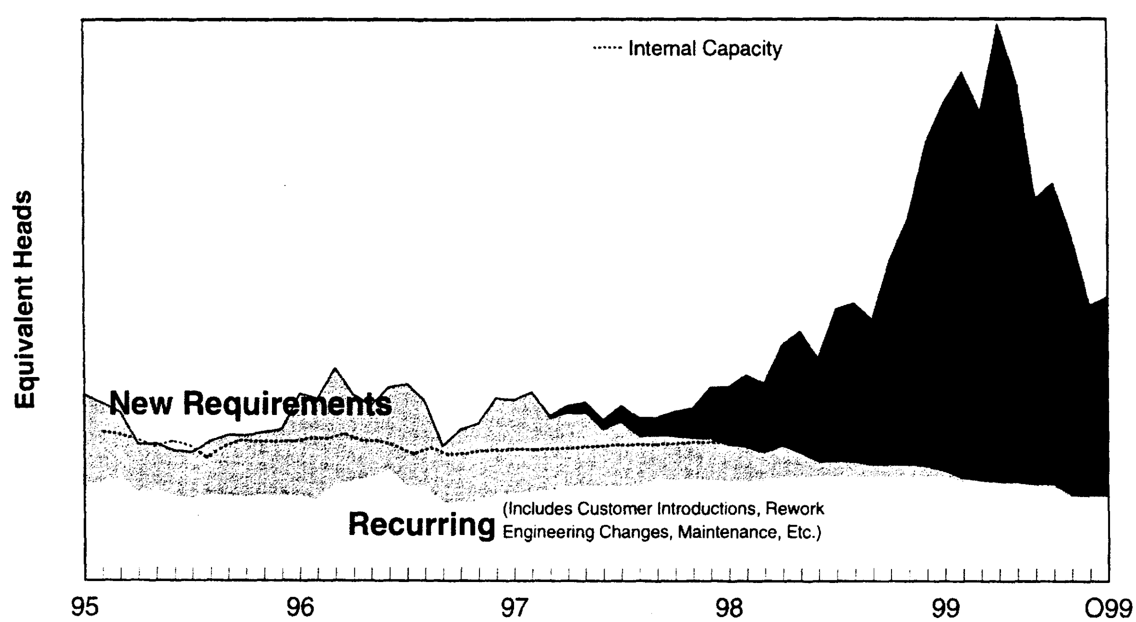

Figure 2.3 Tooling Worklevel Anticipated during the 747X Development

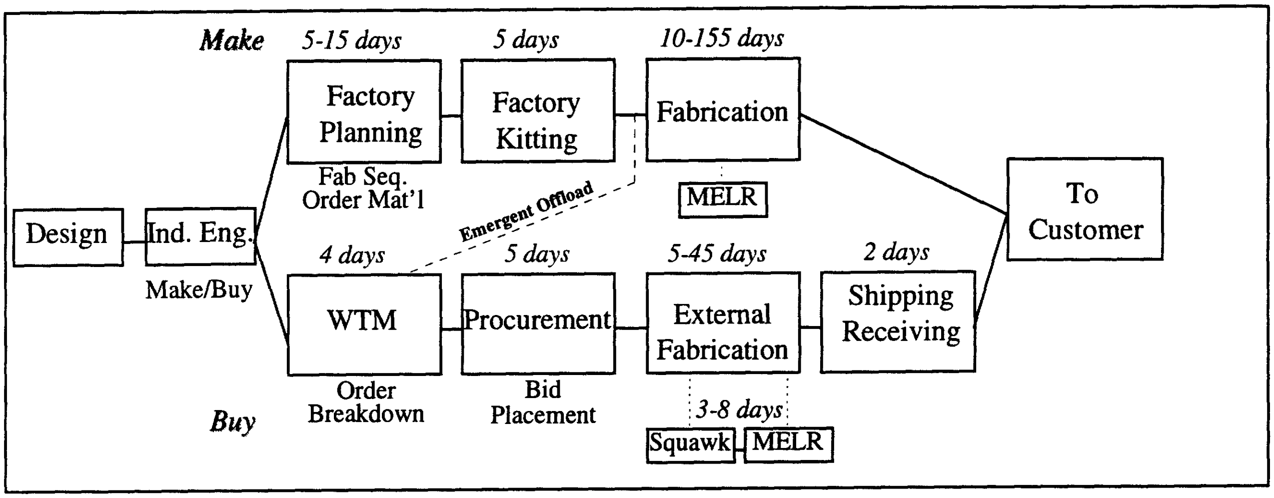

Figure 2.4 Tool Process Flow

An Industrial Engineering group in the company receives each tool design and makes a make/buy decision. In the past the make/buy decision was made primarily on a capability and capacity basis, that is, they have routed it to the factory unless the factory was operating at or near capacity in which case they would make a "buy" decision and route it to the Work Transfer Management Group. More recently, the Tooling MBU has been revising its make/buy strategy to also consider:

- **cost** - having a make preference for tools where Boeing is most competitive,
- **schedule impact** - keeping the most engineering change sensitive,
- **risk to the company** - making the higher risk tooling,
- **emergent requirements** - keeping uncommitted about 20% of internal capacity, and
- **tool criticality** - having a make preference for wing tooling, assembly tooling, and new technology.

Make - For tools that will be made in Boeing, the next step is conducted by Industrial Engineers who plan the fabrication processes, necessary shops, and order materials required. Another group, Tool Operations, then kits the order, bringing together plans, drawings and raw materials and delivering them to the first factory shop in the process. During any processing step, if a machinist has a problem with the drawing, a MELR (Manufacturing Engineering Liaison Request) is written as a request for assistance in resolving a process, design or program related problem in the tool order. Liaison Engineers then communicate with the designer (or other responsible party)to solve the problem. Typical flow time is three days for a MELR. Recently, this process has been expedited in that the machinist, instead of writing a MELR, simply calls the designer who walks down to the factory floor to solve the problem.

In some cases, the Industrial Engineering group miscalculates the shop load and the order, after planning and kitting, has to be sent to an outside supplier to be completed in time. This is called emergent offload. Emergent offload occurs between 5 and 20% of the time and about half an order's scheduled flow time has been used up by the time it occurs. As a result, emergent offload can result in impacted schedules and a tool being late.

Buy - WTM is responsible for receiving a tool order package (including drawings, schedule, requirements) from the Industrial Engineering Group once the buy decision has been made. They first prepare the order to be submitted to suppliers (by Procurement) for bid and award. This preparation includes insuring that it is complete and has everything necessary for the supplier to complete the order. WTM also recommends a supplier. Procurement then sends the package out to three suppliers for quotes and then selects a supplier, usually the lowest bidder qualified. Once the tool order is awarded to a supplier, WTM is then responsible for monitoring and supporting the supplier until the tool is complete. Surveillance members of WTM work closely with the suppliers as representatives of Boeing and act as aids in communication and resolution of problems or questions. A Squawk Desk exists within WTM that receives notification of a vendor problem or question. When a "squawk" is received, WTM determines who can solve the problem and makes the necessary disposition. One action that can result from a squawk is a MELR (previously described). This MELR results in the correct group within Boeing being contacted to resolve the outstanding issue and WTM assists in this resolution, notifying the supplier of the MELR response and "closing out the squawk ".

"Vendors know they can manipulate schedule", J. Helland, WTM Manager

2.3.3 Boeing Tooling Suppliers

Boeing uses approximately 120 tooling suppliers for the 122 different types of tools they need throughout the company. These suppliers each have different capabilities that are useful in various tool types. Broadly, the key capabilities that categorize a tooling supplier are as follows:

- **5-Axis Machining** - Necessary for tools with complex geometry and high dimensional accuracy. Approximately 20 suppliers have this capability.
- **3-Axis and Conventional Machining** - Most tools can be made with this capability and 70 suppliers have some ability in this area
- **Medium to Large Fabrication Capability** - Welding and assembly skills are necessary for jig fabrication. 35 suppliers have this capability
- **CATIA Design** - Boeing outsources some tool design to these six suppliers.
- **Volumetrically Certified** - 25 suppliers have certified coordinate measurement machines or others with verified performance accuracy.
- **Load Test/ NDT** - 30 suppliers have the ability to perform required tests on tools to verify strength or performance capability.

These 120 suppliers are located near Boeing facilities or in other areas such as Southern California or Detroit. Suppliers of tooling to Boeing tend to have other customers because: 1) Boeing's tooling demand is somewhat cyclical, and 2) the procurement strategy has been to reduce risk by spreading the work around rather than concentrating work in a few suppliers. As a result, suppliers have either broadened their customer base, taking on additional tooling business, or they have taken on Boeing production parts business, smoothing their work load throughout the Boeing product cycle.

"I can make you promises I know I can't keep", Boeing Tooling Supplier

Supplier Relationships - In other areas of Boeing (e.g. production parts) steady demand for large quantities of the same item has made it fruitful for Boeing to establish long term relationships with suppliers in order to capture economies of scale. These relationships often involve some form of fixed pricing on the suppliers part and a guaranteed work level on Boeing's part. Procurement of tooling has not benefited from the same relationships. Tooling is like an extreme mass customization exercise in that there are a large number of variations of a number of tool types making it more difficult to capture economies of scale. As a result, tooling has been procured using the competitive bid process.

"What job is Boeing holding us up on now?" Boeing Tooling Supplier

The Procurement Organization in Boeing has principally used the competitive bid process to choose among (typically) three qualified suppliers. Suppliers have to bid low to win each job and they generally agree to the indicated need date. However, two things often happen in this procurement process: 1) squawks (and resulting MELR's) resulting from incomplete instructions or materials result in the supplier requesting more time or money, and 2) Boeing requested changes occur resulting in the supplier requesting additional time and money. Little learning has taken place between Boeing and its suppliers because of these "arms-length" relationships. On the supplier's part, there is little interest in sharing information with Boeing, because there are no agreements that it will be safeguarded (e.g. not shared with another supplier). On Boeing's part, there has been little sharing of process information with the supplier because factory personnel feel that suppliers are "taking their jobs away". In addition, the large number of suppliers would make it difficult to educate all in tool manufacturing processes.

2.4 Large Tooling users (Industry and literature review)

Large scale tooling users tend to be part of the aircraft or automotive industries. Because of this I wanted to look at how some companies within these two industries provision tools. I organized a fact finding trip to Detroit and Connecticut to investigate such issues as:

1) How much tooling is made internally,
2) How supplier selection is performed,
3) What kinds of relationships are formed with suppliers, and
4) How the supplier's performance is monitored.

We learned much from this trip. Furthermore, I was able to bring members of the Tooling MBU and Procurement Organizations and their respective management along. Thus we learned the same things through equivalent "lenses". We also noticed an improvement in the personal relationships between members of these organizations, directly resulting from the trip. Generally we found that other large tooling users are: 1) moving towards outsourcing more of their tooling,

2) forming closer relationships with their suppliers, 3) working with fewer suppliers. We found evidence that the competitive bid process for tooling is not the preferred method of supplier selection.

2.4.1 Chrysler

"You don't want to squeeze your suppliers" D. Hurd, Chrysler

We talked with the Tooling and Facilities Procurement Organization and Stamping Tools Manufacturing representatives. We found that Chrysler makes the least tooling of any organization we visited. They outsource approximately 95% of their tooling. Procurement representatives have a dual reporting role; within their own organization and "dotted line" to the Platform Teams. They also seemed to have the strongest supplier relationships. Competitive bid is not used. Rather, they use target costing in tooling, where Estimating (Industrial Engineers), Platform (Design Engineers), and Procurement representatives jointly develop what tools should cost using past experience as a guide. Chrysler then has core suppliers for all tools (and facilities). They ask the following questions in order to determine core suppliers:

1) Who is the best? (benchmarking them)
2) Who do we use now?
3) How many of the best do we need?

They make sure that they are using only the best few suppliers (based on their needs) and they annually review their status. Furthermore, they have a significant program designed to learn from their suppliers called SCORE (Supplier Cost Reduction Effort). They seek inputs from their suppliers on how Chrysler might reduce costs (perhaps through design changes). SCORE allows the suppliers to participate in any savings and they expect participation in it as part of their annual review. Finally rather than have complicated written agreements which must be followed, Chrysler believes in the use of oral agreements made at higher levels of management (e.g. committing to use a single supplier as long as their costs remain reasonable). They believe that "squeezing the last dollar" out of a supplier is counterproductive; it will prevent the supplier from having the resources to innovate and improve capabilities.

2.4.2 Ford

"We have nobody up above (in management) that knows a god-damn bit about tooling"

Ford representative at PICO

We talked with Ford assembly tooling personnel at one of their full-service suppliers (PICO). Ford makes approximately 20% of their tooling needs and outsources the remaining 80%. Ford concentrates its outsourcing of tooling at five major suppliers, a number which is down from approximately 120 in 1985. These full service suppliers manage the provisioning of tooling from design to installation in a Ford factory. Ford also uses target costing for tooling, and the price paid to a full-service supplier may be a bit higher than paid previously but it includes the tooling program management that Ford previously performed itself. In the past, Ford paid for tool design changes or schedule delays. Now Ford only pays for product changes which impact a tool. This has resulted in a significant reduction in the 35-40% change cost that occurred in the past using competitive bid. It was clear that Ford also has close relationships with their tooling suppliers. In reducing the number of suppliers, they have helped the few grow tremendously. Ford management had to change along the way, adopting a more coaching position rather than performing "tool follow-up" (checking on the progress of individual tools).

2.4.3 GM

GM is scrambling.....they have no (supplier) relationships", PICO representative

We spoke with Tool Engineering representatives for assembly tools at General Motors. GM satisfies approximately 50% of their tooling needs internally. Besides tool manufacturing, they have significant tool design efforts at outside design suppliers. Most tool design and fabrication locations tend to be physically separate. Rather than focus on improving supplier relationships, GM has been focusing efforts on standardization of tooling and using simulation to reduce tooling cost. They use the competitive bid process to choose suppliers and award tool orders. At our meeting with Ford and PICO representatives, we were shown Figure 2.1, which indicates how GM requires significantly more time than Chrysler or Ford to install the assembly tooling needed to reach full production of a similar vehicle, supposedly because of GM's use of competitive bid to procure tooling.

At some point your suppliers don't want to do business with you at any price", D. Hemberg, PICO

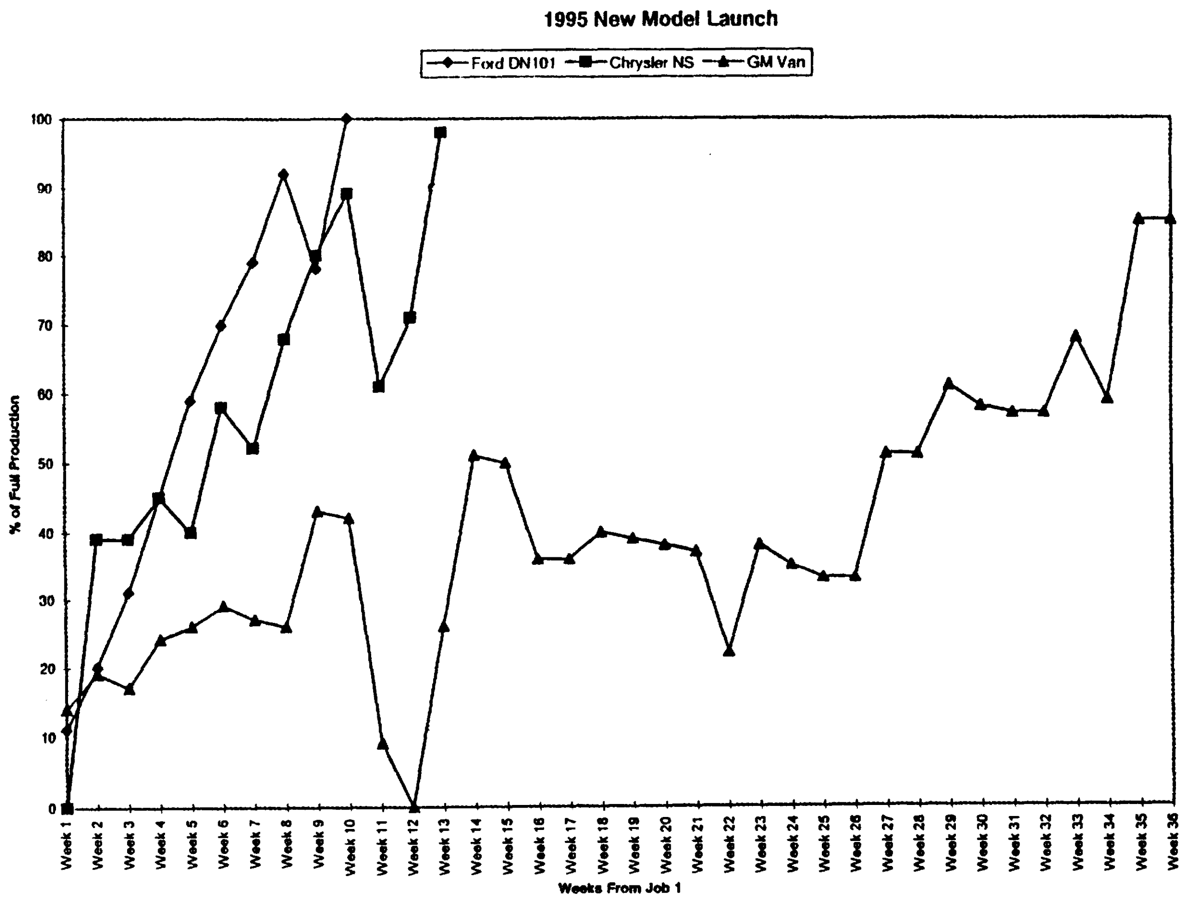

Figure 2.1 Time Required to Reach Full Scale Production (from Job 1)

2.4.4 Pratt & Whitney

We spoke with tooling and procurement representatives at the Turbine Airfoils Product Center near Hartford, CT. Pratt is trying to maintain a significant level of capacity in-house for tooling. Currently, they make approximately 90% of their needs. By becoming a lean manufacturer internally, they believe they are competitive with suppliers. They are trying to establish "preferred agreements" with a few suppliers whereby two suppliers bid for work against one another. There is no specific guarantee of work even though rates are set. Part and tool design takes place concurrently. Procurement representatives are located within the tooling organization. Procurement did express concerns that they were not viewed as fully participating team members; that their engineering and manufacturing teammates were driving the real decisions and that they were being asked to simply "take care of the paperwork" once the decisions had been made.

2.4.5 Pertinent Literature

We learned on our industry review trip about many of the concepts that US industry is now applying to supply chain management. I wanted to mention a few of the principal literature sources for these methods and simply demonstrate that the ideas we saw implemented are not new, but merely new implementations of what has been talked about for almost two decades.

I first saw the concept of lean supplier relations in The Machine that Changed the World.[2] Toyota, and other Japanese automobile companies have had lean supplier relationships with their first tier suppliers which are long term relationships including trust, information sharing, joint quality responsibility, and CQI (Continuous Quality Improvement). Womack, et.al. contrasts this with the mass production supply systems at General Motors which are focused on mutual mistrust, price, and many suppliers of each item.

In Dynamic Manufacturing,[3] Hayes et. al. compares two contrasting industrial factories called Factory A. Factory A was organized by process and was more like mass production, whereas Factory B was organized by cells and was more like a lean manufacturing example. In the area of supplier relations, Factory A focused on reducing the price paid for each part and they maintained a large supplier database to choose from. Factory B focused on fewer suppliers and formed long term relationships with the few. Factory A suppliers were forced to take the short term view and thus firefighting became a major skill set, reducing their ability to develop capabilities that might help their customer (Factory A) be more competitive in the long term. Supplier relations are contrasted nicely in Table 2-1. The Hayes book stated that the Comaker (Factory B) approach leads to a competitive advantage. Experiences at Mazda and HP Vancouver are some of their evidence of Factory B being the best strategy. Table 2-1 provided

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[2] James Womack et.al., The Machine that Changed the World, Harper Collins, 1990, Page 140.

[3] Robert Hayes, et.al., Dynamic Manufacturing, Macmillan Inc., 1988, Page 185.

me with a framework for evaluating the state of Tooling at Boeing and some ideas as to how supplier relations there might be improved.

Table 2-1 Contrasting Views of Vendor Relations

	Traditional (mass production)	**Comaker** (lean supplier relationship
Selection/qualification criteria	multiple sources suppliers compete price is primary criterion	few sources best are sought out and retained nonprice criteria given weight
Vendor's production process	arm's length relationship focus on final test stability is goal	works closely with buyer focus on process control improvement is the goal
Pricing	buyer wants lowest price leverage based short term agreements	fair return expected trust based long-term agreements
Schedules	extreme flexibility expected constant changes in schedules	realistic commitments that must be met credible promises
Quality expectations	vendor's responsibility acceptance levels	joint effort continued improvement
New Products	late vendor involvement no supplier design content	early vendor involvement vendor design skills valued
Information transfers	minimal: exceptions only no news is good news single buyer-vendor contact points	substantial and regular problem solving info. constantly passed back and forth multiple levels, 2-way contacts

2.4.6 Industry and Literature Review Summary

From our industry review trip and a review of the literature, I learned that Boeing is behind other large tooling users in managing their external supply chain. Themes that I saw repeatedly on the trip concerning tooling supply chains are similar to those of other (parts) supply chains. These themes include:

- Increased dependency on outsourcing of tooling,
- Movement away from the competitive bid process,
- Use of fewer tooling suppliers,
- Team oriented approach to procuring tooling (Procurement and Manufacturing),
- Recognition that working more closely with your suppliers is critical, and
- Less rigid supplier agreements, more trusting being practiced.

2.5 What makes form dies different

I chose dies for this evaluation primarily because there is significant make and buy activity. That is, Boeing has decided that regardless of cost differences, it is important to keep some level of die manufacturing in house to handle emergent requirements, but that it does not intend to increase this in-house capacity. Thus, when a new product is developed, the spike in die demand will always require some supplier involvement.

Form dies (and the form die provisioning process) have a few other characteristics that also make them unique among tool types and possibly more likely to benefit from a long term supplier relationship. These characteristics are: 1) having Tool Tryout in-house and 2) the presence of significant levels of "tribal knowledge" in Boeing and at suppliers.

2.5.1 TTO (Tool Tryout)

"We get some real junk here", Wolfgang D., TTO lead

A small group of experienced factory machinists is dedicated to receiving all form dies, whether they are made in Boeing or by a supplier. They are located near the customer, the Sheet Metal Center at Boeing. They first evaluate whether the die meets the drawing and then form a part using the die to see whether the part meets the engineering drawing requirements. In many cases, the dies need some additional work before they make a "good" part. This may include: 1) additional grinding, 2) additional milling, and 3) hand polishing of the dies. In some cases, significant work (greater than 50 man-hours (MH)) would be required to get a "good" die. In these cases, a rework order is written and the die is sent back to the Tooling MBU to be machined correctly. TTO then would tryout the die again. Rework orders are an uncommon occurrence. Regardless, once the die makes a good part, it is delivered to the Sheet Metal Center.

"Vendor cost does not reflect total cost to Boeing", T. Van Cleave, TTO Manager

2.5.2 Tribal Knowledge

I classify tribal knowledge as being either drawing related or process related. First, concerning drawing related, Boeing had been manufacturing form dies completely internally until the industry downturn in the late 1980's when significant factory downsizing occurred. The factory became experienced at making good dies, regardless of what was on the drawing. The tool designer did not always specify what was required to make a good part beyond overall dimensional requirements. For example, such features as corner radius requirements and the surface finish of the die (among other features) were left unspecified. In the past, such key requirements of the die were understood by the factory so they were not always put in the engineering drawing. Factory machinists "simply knew" how to complete these features.

The second form of tribal knowledge is related to manufacturing process. I learned that process improvements are taking place in Boeing and at suppliers to reduce the time it takes to make a die. For example, within the Tooling MBU machinists are now using a Knee Mill with a carbide wheel cutter in arbor set-up to make a rough cut of the die stock in one pass, saving time in rough machining dies. At one supplier, New Tech, the use of advanced equipment, Wire EDM, is reducing the amount of grinding necessary and improving the surface finish of the dies. Regardless of where this process tribal knowledge exists, it remains tribal because the relationship Boeing has with its suppliers does not promote learning in the supply chain.

2.6 Chapter Summary

I learned that other large tooling users in the automotive industry are moving towards developing lean supplier relationships for tooling and parts. The ones that are closer to this goal have reduced cost and product development time. These relationships are modeled after the lean factories adopted by the Japanese at Toyota and similar companies. These relationships include: 1) Use of longer term contracts (commitments) with fewer suppliers, 2) Sharing of "best practice" process information between user and supplier, 3) Supplier taking responsibility for quality control of their product, (alleviating the need for receiving inspection) 4) Focus on value rather than just purchase cost, and 5) Participation in customer design teams. The tooling supply chain at Boeing is still managed using the traditional or mass production model, where the focus is on short term relationships with suppliers and where price is the main factor determining who gets the business. Form dies are one tool type where this traditional model did not allow the required learning (of tribal knowledge) to take place in the external supply chain. Procurement of form dies is accomplished using the competitive bid process with many suppliers. As such, it is a valid tool type to focus on for implementing lean supply chain management concepts.

3. Chapter 3 - Form Die Development and Procurement on the 737-700

3.1 Introduction

The 737-700 was launched in November 1993 on the strength of Southwest Airlines order for 63 airplanes. The -700 is the first of the new generation of 737's, incorporating a new wing, new engines and new systems. The -700 will have the same size fuselage as the -300, still in production. However, changes to systems and interiors, as well as concurrent production of the older -300 model, resulted in the need for an entire new form die set for manufacturing -700 fuselage stringers.

In order to support the January 1996 assembly of the first -700 fuselage section, form dies had to be designed in early 1995 so that the full set would be complete in time to support stringer production by the end of 1995. Approximately 215 dies were needed to form fuselage stringers on the -700. Because this die package was complete, that is, all dies manufactured, successfully through the TTO process and delivered to the customer, it presented a rich source of data to learn about form dies and Boeing's current process for provisioning tools. In this Chapter, I describe what I learned using this data, which I collected from three sources: 1) Boeing's shop tracking system (OTIS), 2) the Procurement Organization, and 3) TTO records. Data for individual dies is contained in Appendix 1.

3.2 Introduction to Die Types

3.2.1 Elements of Complexity

Although cross sections are similar in all -700 stringers, the dies that form them have different features that, according to factory machinists and suppliers (specifically die estimators) I interviewed, make the dies that form them either simple or complex to manufacture. Based on these interviews, I learned that these complexity feature are:

- **size (length)** - larger dies tend to have more individual blocks that must be precisely aligned to prevent markoff (undesirable impressions) in the part. These individual blocks result in additional machine setups during manufacture.

- **number of features (joggles or crushes) per die** - a joggle is needed in a stringer when an the entire stringer cross section (hat and flanges) must travel around an obstruction; a crush is needed when only the hat portion height needs to be changed (crushed) to travel around an obstruction. Each joggle or crush results in additional manufacturing steps (setups and machining), and the transitions between these features and the rest of the die must be smoothly ground. Dies with more features tend to be longer.
- **joggle or crush depth** - deeper features require more material to be removed from both die halves.
- **use of spring loaded mechanisms** - springs are used in dies to prevent stringer wrinkling during the forming process. They are generally included in the design when features are either deeper or occur over a longer length (larger joggle ratio).
- **use of die base sets** - a die base set is a fixture manufactured to be used with a large die with many features that must be precisely located within the press, maintaining both lateral and longitudinal dimensions.

I learned from discussions that there is significant interaction in these key features and that some are more important in determining manufacturing cost and complexity than others. First, number of features is most important and rises with die size. Second, the springs tend to drive the cost in the deeper featured dies more than that specific feature's additional machining time itself. Based on this information, I decided to review the 737-700 data using five candidate categories of dies formed from these three principal complexity features: 1) number of features, 2) presence of springs, and 3) presence of die set. These five die types are shown in Figure 3.1.

3.2.2 Effects of Complexity

I used both internally fabricated dies and outsourced dies in looking at the effects of complexity. A summary of this data is shown in Table 3-1. Manufacturing hours are either bid hours (supplier provided dies) or actual clocked (internally fabricated dies). I collected die length from drawings and TTO hours from actually clocked hours (OTIS).

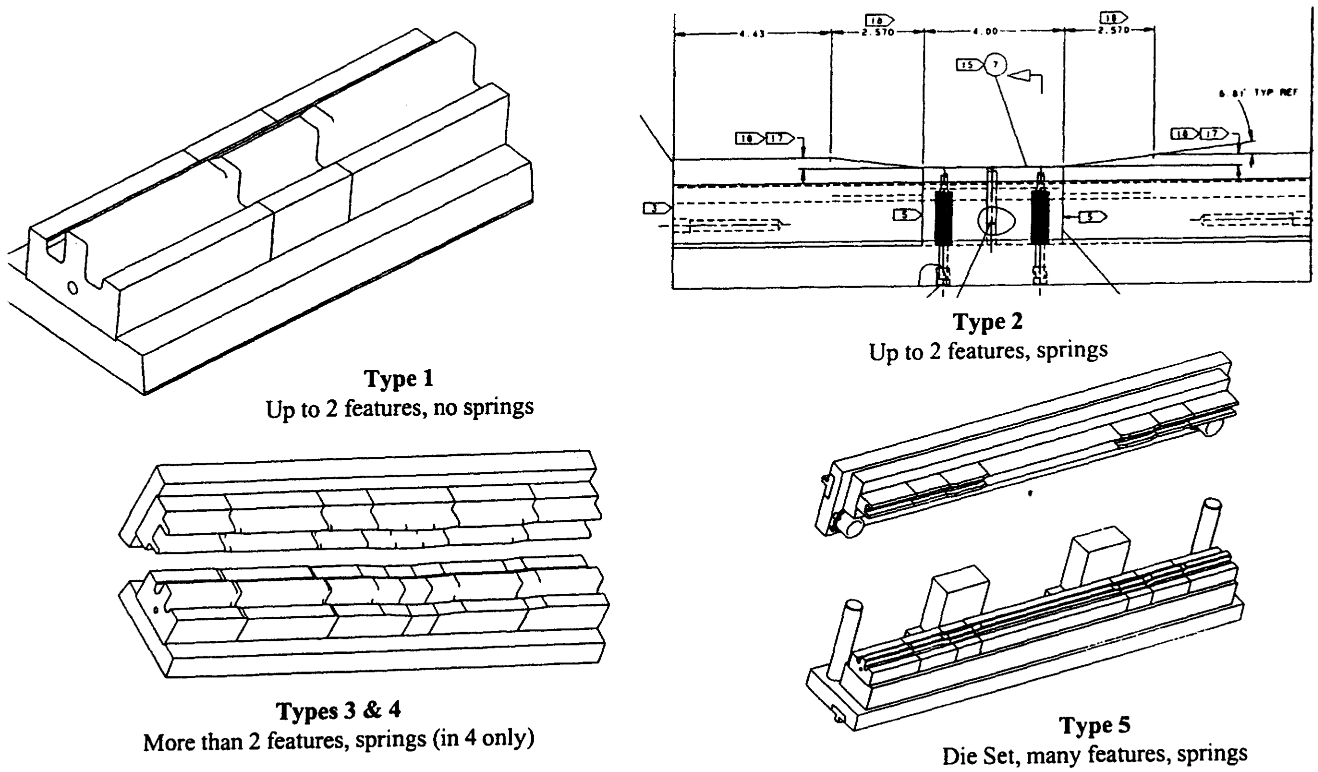

Figure 3.1 Form Die Types

Table 3-1 Average Results Based on Die Complexity

Type	Quantity	MH/die	length	MH/inch	TTO/die
1	66	115.5	16.8"	6.88	25.7
2	60	117.5	14.6"	8.02	26.1
3	39	136.7	19.2"	7.13	31.2
4	36	167.2	20.8"	8.02	33.8
5	13	307.0	34.8"	8.83	44.7

I have selected fabrication time per die and length to be shown graphically in Figure 3.2. As expected:

1) There is some rise in total manufacturing time with an increase in complexity, (The average length of each die type must also be considered in making a fair comparison),
2) Dies that have more features are longer than those with few features, and
3) Springs don't appear to correlate with die length.

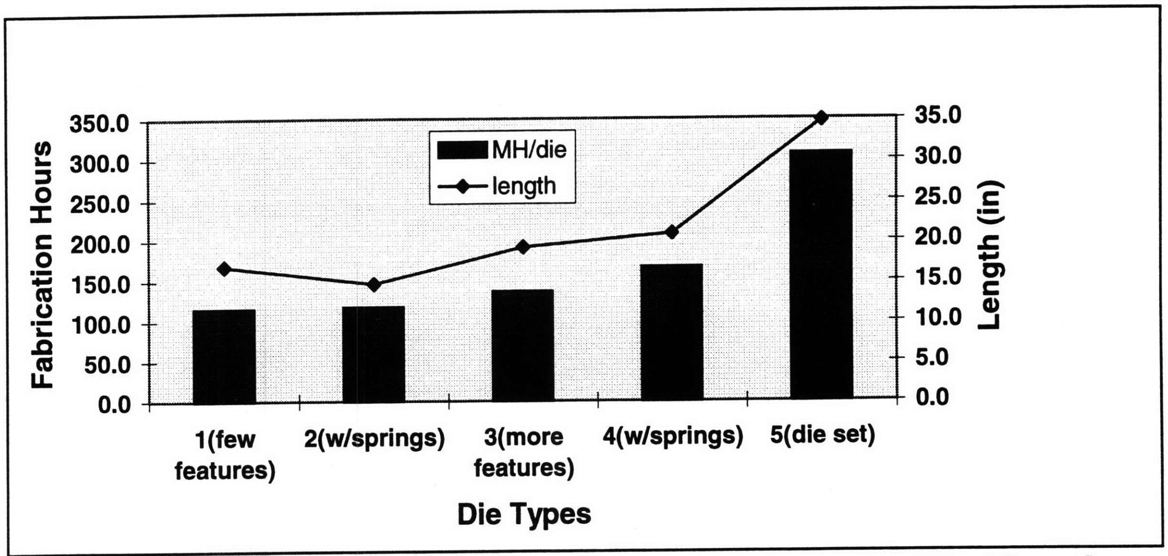

Figure 3.2 Effect of Die Complexity on Fabrication Time and Length

The largest increase in total manufacturing time is when a die uses a die set, which also tends to occur in longer dies with many features. I normalized the data by the average length and have compared this with average TTO hours (an indication of how much modification is necessary to get the die to make a good part) in Figure 3.3. As shown, this comparison indicates that:

1) Springs have a large effect on cost/inch, adding to manufacturing complexity,
2) Springs seem to have little effect on TTO hours, and
3) Dies with more features tend to have higher TTO hours and therefore be more difficult to get to work properly.

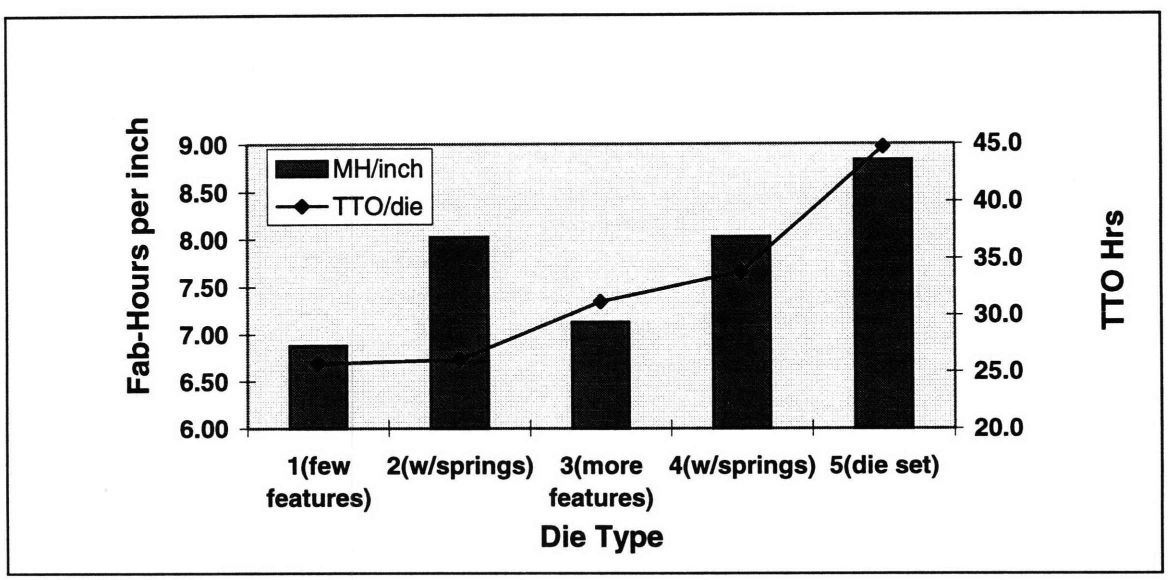

Figure 3.3 Effect of Die Complexity on Fabrication Time and TTO

3.3 Procurement Process

As with other tool types, Procurement used the competitive bid process to choose suppliers for the 737-700 die package. Nine past suppliers of form dies to Boeing were asked to bid for some portion of the 118 dies Boeing outsourced. Six suppliers were successful in winning a portion of the package. Two internal Boeing shops (A3755 and A3720) made the remaining 96 dies. These dies were distributed as shown in Table 3-2.

Table 3-2 Distribution of Dies on 737-700

Source	Type 1	Type 2	Type 3	Type 4	Type 5	Total
A3720	2	6	6	3	3	20
A3755	26	18	9	13	8	74
AVI	9	1	1	0	0	11
ADI	4	2	2	3	0	11
Barnes	1	3	2	1	0	7
New Tech	16	19	14	8	2	59
Oregon Tool	3	2	1	0	0	6
EPS	3	8	3	7	0	21

3.4 Results

3.4.1 Total Cost Comparison

The total cost to Boeing for form dies is the sum of the cost of manufacturing, cost of TTO and any rework performed on the dies. For Boeing-made dies, I present the total man-hours expended and then determine a cost equivalent. In order to make a fair comparison between Boeing and its suppliers, I used the make/buy cost comparison process developed by Business Management (previously described) as follows:

1) adding approximately 15% to supplier costs to account for additional costs to Boeing when outsourcing, and
2) using a make/buy rate with internal fabrication hours (having reduced overhead).

In addition I made the following assumptions:

1) to account for materials cost, I reduced supplier costs by $25 per inch of die (materials are not included in the Boeing-made die costs, being a part of overhead). This $25/inch estimate was provided by New Tech and confirmed as a reasonable average by Procurement.
2) in order to come up with total cost to Boeing, I added the TTO and any rework hours to the fabrication hours and used the same make/buy rate.

The total man-hour comparison is shown in Figure 3.4. For Type 1 dies (the simplest), Boeing and its suppliers(on average) have essentially the same productivity (within 2%). For Types 2 and three dies, (with springs and more features, respectively), suppliers have a productivity advantage of 15% (in total man-hours). Finally, for Type 4 dies, this advantage rises to 27%. I have chosen not to compare Type 5 dies in most regards because of the small number outsourced.

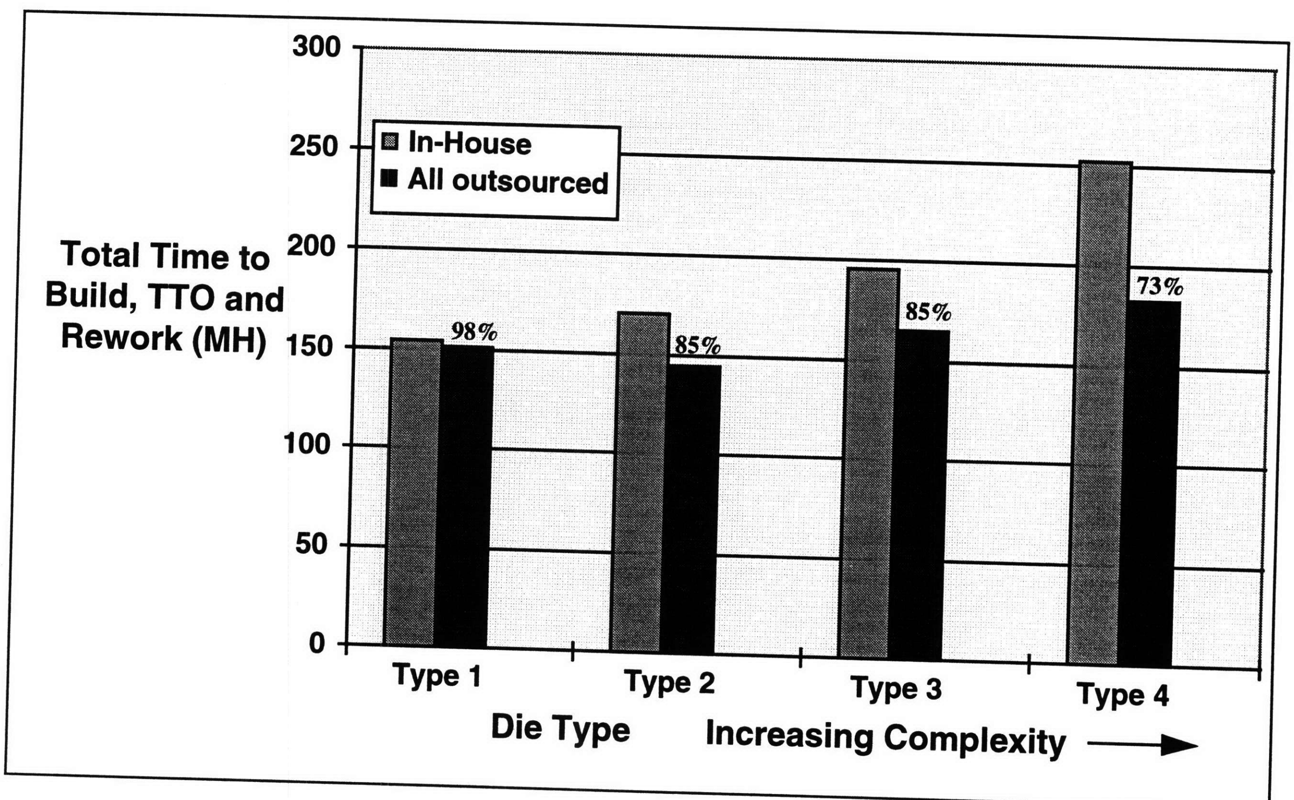

Figure 3.4 Total Time Comparison for 737-700 Form Dies

There is a belief within Boeing that MH are not a fair way to compare competitiveness, because the Boeing hours are actuals recorded while the supplier hours are based on a bid provided to

Boeing. Also MH do not include the effect of hourly rate differences between Boeing and its suppliers (hourly rate differences include the difference in the rate paid to the machinist and differences in total overhead applied). Boeing rates are higher than supplier rates (by at least 20%) so comparing dollar cost does tend to increase competitive differences. Because of this, I show the same comparison using total dollar cost in Figure 3.5. Based on my examination of individual supplier data, one supplier (New Tech), appeared more cost effective on the Type 3 and 4 dies. I have separately shown New Tech's average cost data (they are also included in the overall outsource averages). When rates are taken into account, an approximate 20% savings resulted from outsourcing the simplest dies (reflecting this rate difference). Springs don't change these numbers dramatically. However, Boeing appears to save more (36%) by outsourcing the most complex (Type 4) dies to New Tech. (Note: When New Tech is removed from the outsourced average, there appears to be much less of a complexity effect).

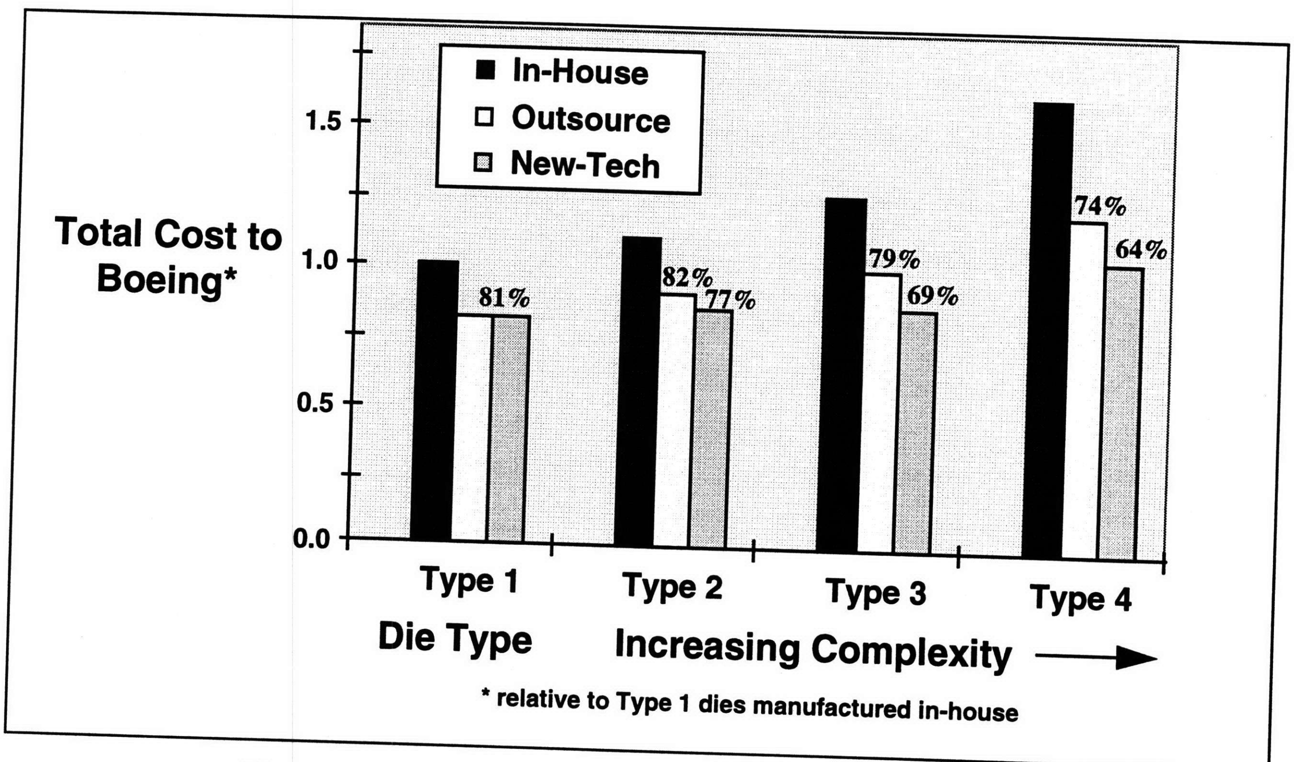

Figure 3.5 Total Cost Comparison for 737-700 Form Dies

3.4.2 TTO and Rework Results

I collected TTO and rework hours for all dies and separated the data by fabrication source. All dies go through the TTO process but only some have to be reworked. Figure 3.6 shows the average of TTO and rework hours for all dies. As shown, Boeing builds dies that require less TTO and less rework than any of their suppliers of 737-700 dies. In addition, some suppliers are much better than others at providing good dies (those requiring little TTO and rework).

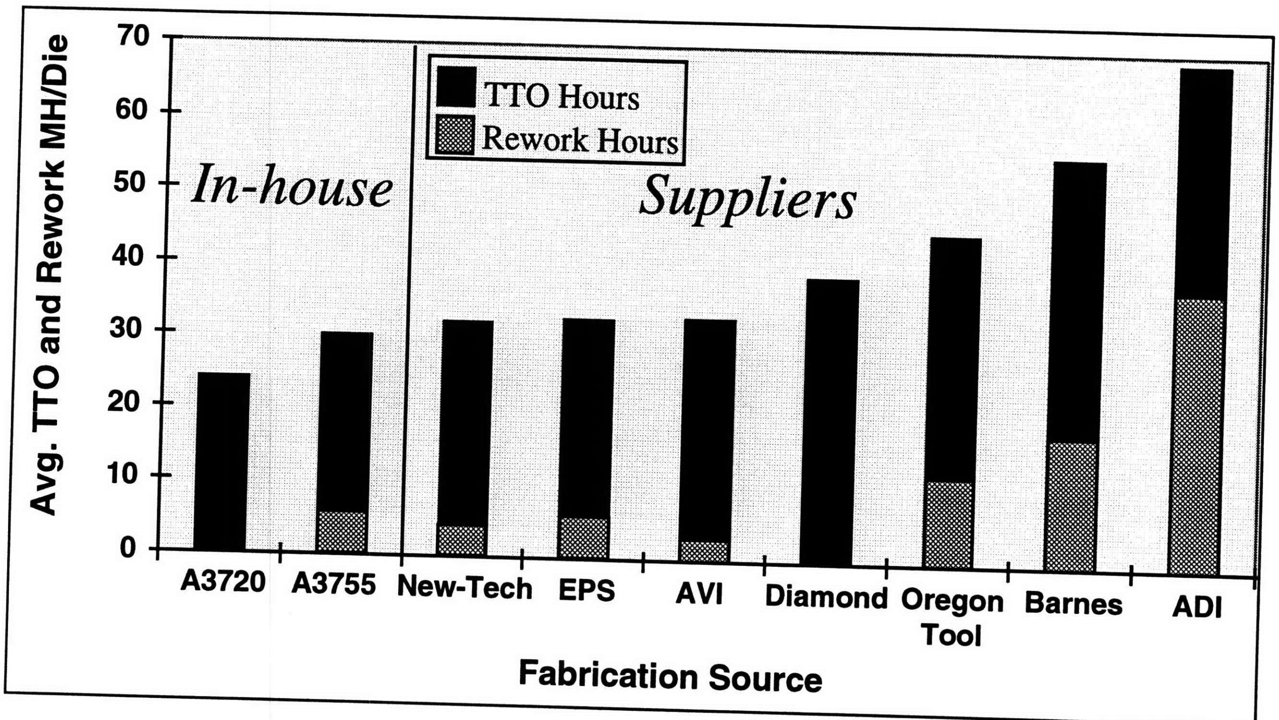

Figure 3.6 TTO and Rework Hours by Fabrication Source

I also looked at TTO and Rework hours as a function of complexity to see whether die type affected getting a good die from the fabrication source. This result is shown in Figure 3.7. As die complexity increases, there is an increase in TTO and rework hours both internally and in the external supply chain as a whole. New Tech appears to be less sensitive to the effects of complexity in this regard, although their simple dies require more TTO than in-house dies.

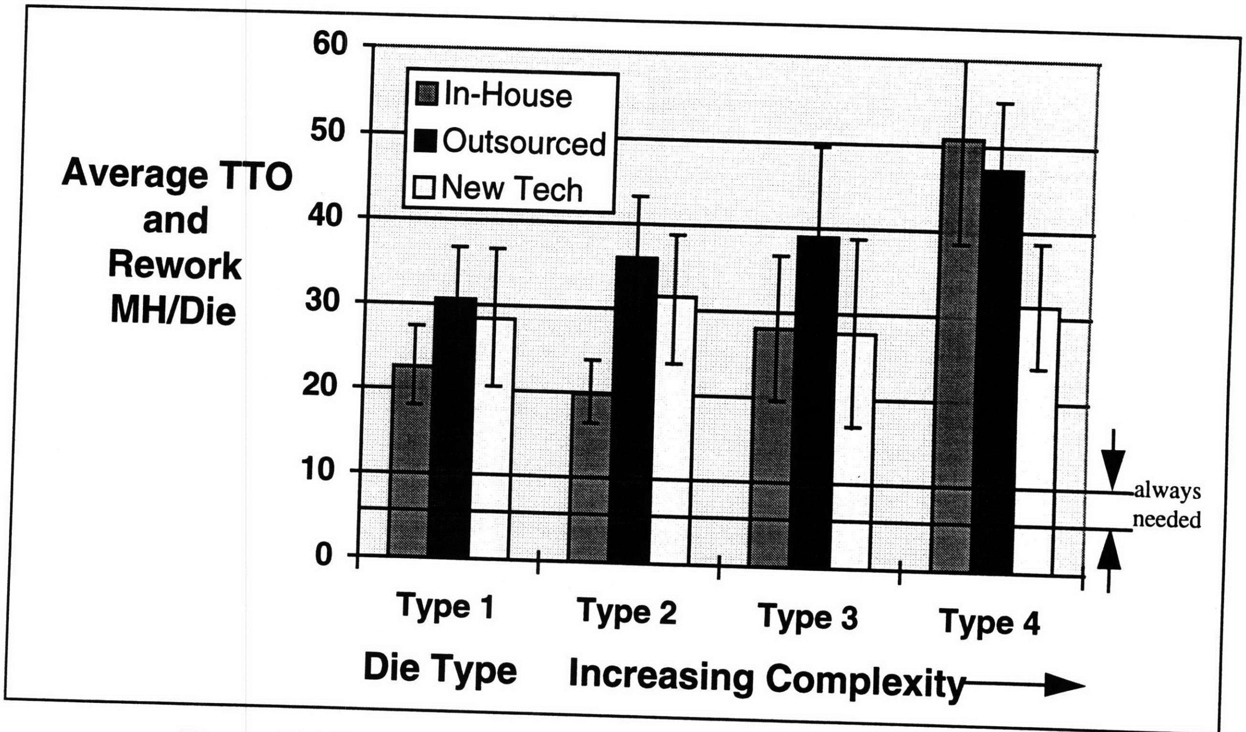

Figure 3.7 TTO and Rework Hours by Complexity and Source

3.4.3 Causes of Defects

In talking with TTO machinists, I learned a great deal about the causes of die problems and their resolution. If a die is "perfect", some TTO hours are still required to receive the die, inspect it, and form a trial part. Depending on the individual die, this can take 6-10 hours per die. Additional time, what I refer to as "excess TTO" and rework, is required to make modifications to the die, and verify that these modifications result in a die that makes a good part (through further part trials). TTO lead machinist Wolfgang Demutch has taken some data on each die that has passed through TTO in the past few years. Little has been done with the data; it simply acts a permanent record of each individual die's condition upon receipt and the date it completes the TTO process.

I acquired a copy of these written records and reduced the 737-700 data by recording:

- each defect type,
- the fabrication source of the die,
- total numbers of each defect (by source and type).

The types of defects recorded by TTO are listed along with their typical resolution in Table 3-3. Some of these defects are due to Boeing design or engineering deficiencies (e.g. overbend or engineering change). Others are due to the tribal knowledge I discussed earlier; that is, that all features are not specified on the drawing as being critical and only the internal Boeing shops have the experience to make a good die (e.g. radius, surface finish, die straps).

Table 3-3 Causes and Resolution of Die Excess TTO and Rework

Defect	Description	Resolution
Overbend	Trial part is not within tolerance due to springback	Machine features of punch or die and regrind sections
Radius	Radius within tolerance may still mark part or not allow sufficient material flow during forming	Grind radius
Poor Fit/Gaps/Not Ground	Variance in (within tolerance)dimensions can result in poor die half match	Machine and/or grind die surfaces
Poor Finish	Poor surface finish prevents adequate material flow	Finish grind all surfaces
Dimensions	Not all part dimensions checked by supplier or Q/A	Machine and regrind necessary surfaces
Poor Quality/Workmanship	Transitions not smooth or die surface damaged	Regrind surfaces or transitions
No Die Straps	Used to carry and protect die and punch	Fabricate and attach die straps
Engineering Change	Change in dimensions after manufacturing order placed	Machine and regrind necessary surfaces

Figure 3.8 shows the number of occurrences recorded for each type of defect listed in the previous table. As shown, overbend is the most commonly occurring defect. Of the over 200 dies manufactured for the 737-700, 51 dies had to be modified because the design did not incorporate the correct amount of springback, even though the die met all drawing specifications. Overbend was responsible for 30% of all defects. However, with the exception of engineering change, the other defects (nearly 70% of the total) are supply chain management related. That is, many of the occurrences could be prevented by better education of (or communication with) either the Boeing shop or supplier responsible for manufacture.

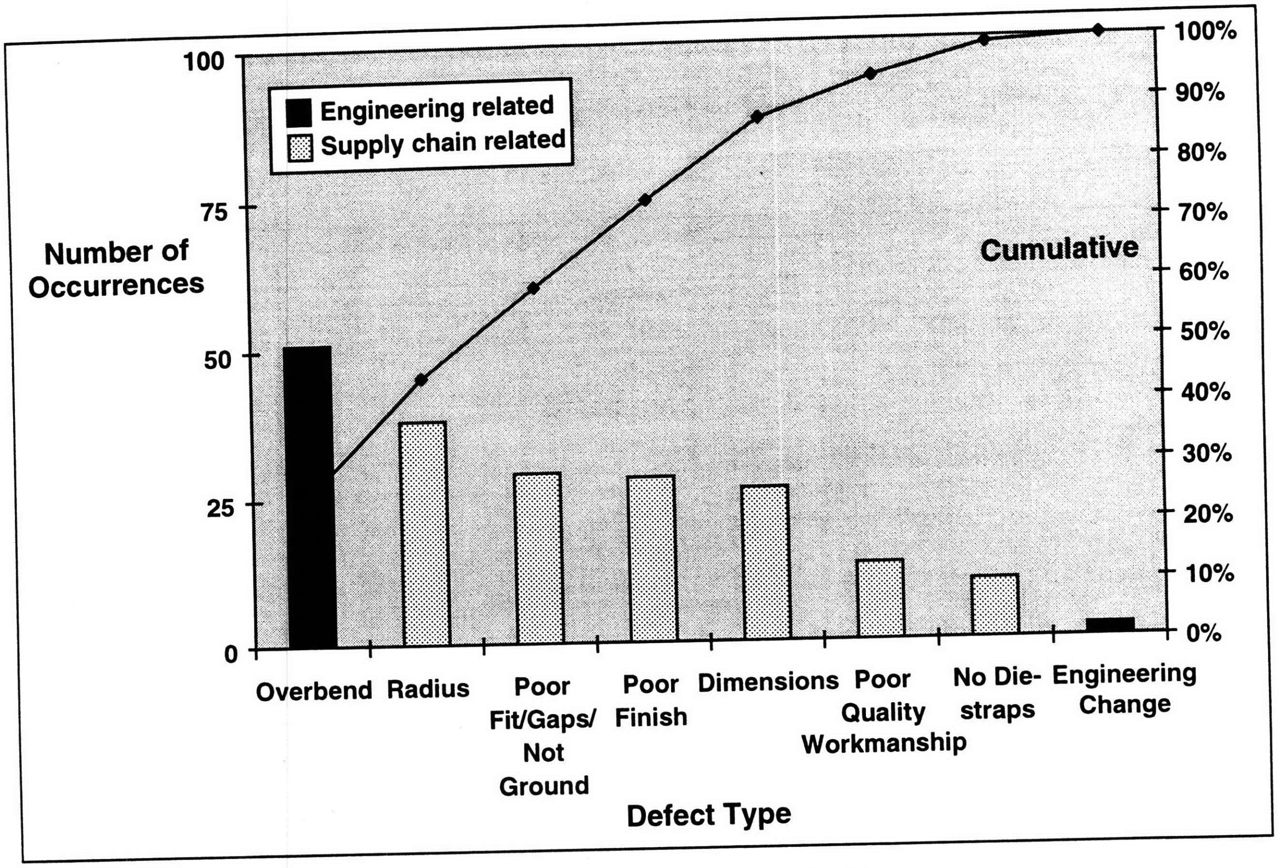

Figure 3.8 Defect Occurrences by Type

3.4.4 Schedule

The Tooling MBU has had a reputation of not meeting customer schedules for tools. In past years, the overall percentage of tools meeting their committed customer need dates was under 50% (varying by month). This has improved recently. In the external portion of the tooling supply chain, outsourcing and the competitive bid process is one cause of schedule performance being worse than in house. In addition, suppliers looking for ways to delay the job (e.g. through the MELR process) are another. I reviewed the performance of die fabrication sources (internal Boeing and supplier), believing that a new process might result in some improvement. These results are summarized in Table 3-4. Number of days late or early is defined as the difference in when a supplier actually committed to deliver the die and when they actually did deliver it. Engineering changes would result in a Boeing allowed change in the supplier committed date and are therefore not factored in schedule performance. As the table shows, outsourced dies tend to be later (by six days on average) than those made in-house.

Table 3-4 Schedule Performance on the 737-700 Die Package

Die Fabrication Source	Boeing	Supplier
Number of Dies	108 dies	123 dies
Number On time	41 dies	26 dies
On Time Performance	38%	21%
Average Performance	**5.5 days late**	**11.6 days late**

3.5 Chapter Summary

In my discussions with Boeing and suppliers, I learned a tremendous amount about die design and manufacture. More importantly I came to understand enough about the process that I knew which data to seek out. From analyzing this data, I learned that:

- Number of features and to a lesser extent the presence of springs affect die complexity (Figures 3.2 & 3.3, interviews),
- Boeing is more cost effective on simpler dies than complex dies (Figure 3.5),
- New Tech is most competitive on complex dies (Figure 3.5),
- Boeing builds better dies (less TTO and rework) than most suppliers (Figure 3.6),
- Some suppliers build better dies (less TTO and rework) than others (Figure 3.6),
- Overbend is the most common design/engineering defect (Figure 3.8),
- Most other defects are supply chain related, and constitute 70% of all defects (Figure 3.8), and
- Outsourced dies require approximately six additional manufacturing flow days (Table 3-4).

This information was used in the work described in Chapter 4 to evaluate the effects of process changes initiated on the 737-800 die package.

4. Chapter 4 - Use of a Preferred Supplier for the 737-800

4.1 Introduction

The 737-800 was launched in September 1994 with customer commitments for more than 40 airplanes. The -800 became the second of the new generation of 737's, having a stretched fuselage in order to carry 162 to 189 passengers. This fuselage stretch resulted in the need for a partial new die set for manufacturing -800 fuselage stringers. In order to support the February 1997 assembly of the first -800 fuselage section, form dies had to be designed in early 1996 so that the full set would be complete in time to support stringer production by the end of 1996. 52 new dies were needed to form fuselage stringers on the -800.

When I started my internship at Boeing in the Tooling MBU, the -800 die design was underway and manufacturing was scheduled to begin in the middle of my internship. Although the approximate number of dies to be made in-house had been decided, suppliers had not been selected as of yet. In this Chapter, I describe what changes I helped make to the die provisioning process and then present the results of these changes. I did not make these changes myself. I give full credit to the team of Boeing personnel that together developed this process and the supplier that worked with us. The challenge was not in developing this approach, but in implementing it in an environment where functional barriers still exist and suppliers are forced to compete with Boeing factory shops. Data for individual 737-800 dies discussed herein is contained in Appendix 2.

4.2 Preferred Supplier Process

I learned from my first LFM readings in The Machine that Changed the World[1] that managing the external supply chain is critical to a company's performance in outsourcing. My overall approach in improving the provisioning of dies at Boeing was as follows:

1) form a cross-functional team to jointly develop and implement process improvements,
2) decrease the number of suppliers of form dies to Boeing,

3) work closer with those suppliers to decrease supply chain related causes of excess TTO and rework, and
4) investigate design improvements to decrease the design-based causes of excess TTO.

This approach would be implemented first on the 737-800 die package. However, in the back of my mind, I wanted to demonstrate a process which could be utilized in similar fashion on other tool types. The savings we might demonstrate on form dies could thus be multiplied many times over.

4.2.1 Team Oriented Approach

As a relative outsider to the Tooling MBU and Boeing Commercial Airplane Group in general, I believe I was able to take a relatively unbiased viewpoint in this project. Very early in my internship, I sensed some very functional perspectives on the part of many of the groups involved in die provisioning. I knew that we could only get past these functional barriers by working together towards the right answer for Boeing as a whole. Once I understood the tool provisioning process, I invited key personnel to a meeting where I explained the goals of my project and asked them for their support. I will not say that they embraced the project whole-heartedly; all invited groups agreed to cooperate and participate but they did have reservations which they shared with me individually. I next describe the group members and their initial feelings on my project approach.

4.2.2 Team Members

Procurement - Ray Plattner, Lead Buyer for Tooling, was their representative on our team. Procurement is a key group in making any outsourcing-related process change work. They were also the only functional group on the team yet organizationally separate from the Tooling MBU. They were the most reluctant, at first insisting that they have sole responsibility for selecting vendors and managing the external supply chain. They strongly believed that they are: 1) saving the company money by picking the lowest cost bidder and 2) reducing risk by spreading the work among several suppliers. Procurement was concerned that the team-based approach would relegate their role to one of an order "clerk" carrying out the instructions of others making the real decisions. I tried to assure Ray that their role of assisting in supplier selection and cost management in the external supply chain was a valuable one.

Tool Design - Two Tool Designers (Al Potter and Dave Wagner) participated on our team. They believed that their die designs were excellent and that "anybody" (within Boeing or external suppliers) should be able to manufacture these relatively simple dies. They believed that New Tech provided dies with superior surface finish, resulting in better parts being formed the first time.

Work Transfer Management - Bob Jacobson, from Surveillance, participated in our team. I sensed a bit of friction between WTM and Procurement, based on the fact that Procurement often does not take WTM's recommendation on which supplier to select for a job. Bob strongly felt that New Tech made superior dies and that all work should go to New Tech.

TTO - Wolfgang Demutch, Lead TTO machinist, participated and fully supported the idea of reducing the number of suppliers. He felt that New Tech's dies were as good as those made in-house.

Factory - Die machinists and their first line management were also a bit reluctant to participate in our team. They have always been sensitive to outsourcing, thinking that the eventual Boeing goal was to eliminate internal capability. I assured them that Boeing management intended to maintain a level die capacity internally and that my main goal was to improve the way we do the required outsourcing.

There was a general reluctance on everyone's part to participate, thinking that the team would require additional work from them. I agreed that I would do most of the team's "dirty work"; collecting data and presenting findings to them. I also stressed that some process improvements (e.g. reducing the number of suppliers) would decrease their workload. We agreed to meet every other week during the design and manufacture of all 737-800 form dies.

4.2.3 Team Process

Supplier Selection - At our next meeting, I presented the data collected and analyzed in Chapter 3. The main decision facing us was which supplier(s) to select for the -800 die package. Based on the total number of dies to be outsourced (approximately 40), we knew that one supplier would be sufficient. There was consensus that the first supplier should be New Tech because of the following:

1) having the lowest TTO hours of any supplier on the 737-700 (Figure 3.6),
2) having lower total cost on complex dies,
3) a past history of working on a large number of dies for Boeing,
4) expressing a willingness to improve their working relationship with the Tooling MBU,
5) having a manufacturing process that resulted in significantly better surface finish,
6) being located geographically close to the Tooling MBU.

We selected Diamond and EPS as backup suppliers for the -800 dies. Procurement agreed to solicit bids from all three suppliers and to place the work with New Tech as long as their bid cost was "reasonable". As a team, we agreed to use only New Tech in view of their demonstrated abilities on the -700, as long as they did not fall behind on delivery dates as the outsourcing proceeded.

Make/Buy Determination - We decided to outsource more of the complex dies to New Tech to capture some of the savings we saw on the -700 dies. Out of a total of 14 Types 3,4 and 5 dies, we decided to keep four inside and to outsource the remaining 10. Four was believed by the Factory to be the minimum number necessary to preserve the "skill level" of die machinists. Breakdown of dies by complexity is shown in Table 4-1.

Table 4-1 737-800 Breakdown by Complexity and Fabrication Source

Source	Type 1	Type 2	Type 3	Type 4	Type 5	MJD[1]	Total
New Tech	10	10	0	8	2	9	39
Boeing	7	6	0	4	0	8	25

[1]MJD(mass joggle dies) are a new die type similar to Type 1 with increased tolerance requirements

Supplier Interaction - I visited New Tech in the same week along with representatives of Procurement and WTM. This was one of the first times that both organizations talked to the supplier at the same time. We first shared our objectives with New Tech. There were no formal written agreements made. Instead, we verbally committed to having New Tech manufacture all -800 dies to be outsourced, as long as their costs were reasonable, quality was unchanged, and they met commitment dates. In the past, low bid cost had been stressed and date often was viewed by the supplier as "subject to change". Together, we told New Tech that meeting the schedule was the number one priority and the main metric they would be evaluated on.

While at New Tech, I was told by the lead Machinist that they would like to review advance copies of -800 die drawings, because they had previously had problems understanding design requirements. In the following week, I visited New Tech with Dave Wagner, the die designer. Before we left, New Tech had Dave's phone number and were told to call him whenever they had a question or problem. This type of interaction was repeated throughout the -800 die program. 15 minute discussions replaced MELR's that in the past took days to complete.

4.3 Results

I used the same methodology described in Chapter 3 to calculate total cost for dies made in-house and at suppliers. Individual results are given in Appendix 2. I have compared Boeing and supplier's performance on similar die types where possible.

4.3.1 Cost

A make versus buy comparison is shown in Figure 4.1. Type 3 dies were not manufactured in the -800 and all Type 5 (having die sets) were manufactured at New Tech because of the small total number. As shown, for the simplest dies having few features and no springs (Type 1 and

MJD's) the total cost of in-house dies is within 14-16% of outsourced dies. This is in agreement with previous comparisons made on the 737-700 die package. The Type 2 dies (few features with springs) were 44% less in total cost when outsourced. This is 23% less than in the 737-700 die package, a significant difference. Finally, the Type 4 dies were 41% less costly when outsourced, similar to the 36% difference in the 737-700 Type 4 dies.

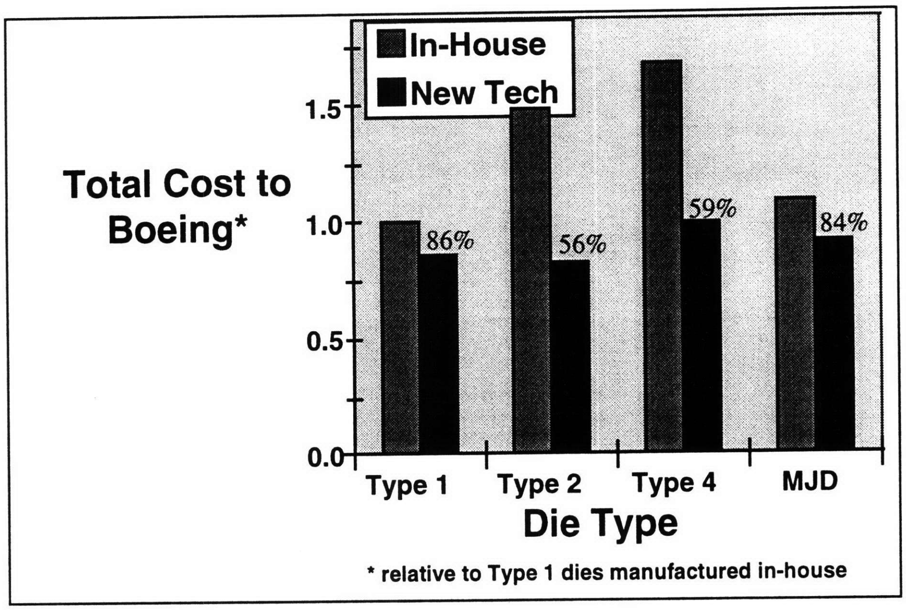

Figure 4.1 Average Cost of 737-800 Dies by Complexity and Fabrication Source

The increase in Type 2 die cost (in-house) was of concern and I looked into it further. The increase was driven by manufacturing hours (not TTO or rework) and occurred partially due to some bad material encountered by the factory. After machining the rough profile of "a small number of dies" according to the factory, the material had to be scrapped due to it having been improperly heat treated. Three of the six Type 2 dies manufactured in Boeing took in excess of 200 hours to manufacture. Regardless, total cost comparisons shown here supported the assertion that internal Boeing die fabrication sources are more competitive on the simplest dies.

In the 737-700 die package, fewer complex dies had been outsourced (51%). The 737-800 die make/buy policy was modified here to take advantage of the outsourcing advantage on complex dies. We increased the percentage of complex dies outsourced to 71%. Based on using the more efficient manufacturer of complex dies and the increase in outsourcing of those dies, a $32K savings was achieved.

4.3.2 TTO and Rework

I next reviewed the TTO and rework hours on the 737-800 die package. As shown in Figure 4.2, for in house dies, the average amount of TTO hours expended per die did not change significantly (26.9 vs. 25.3 MH/die) For supplier provided dies, the average number of TTO hours went from 36.7 to 28.3 MH/die, a significant reduction. This was not a surprise. In choosing New Tech as the preferred supplier, we knew that they were closest to Boeing in providing dies requiring little TTO. New Tech improved a slight amount (to 28.2 from 29.7 MH/die) and this decrease in TTO hours over all outsourced dies corresponds to a $46K savings to Boeing.

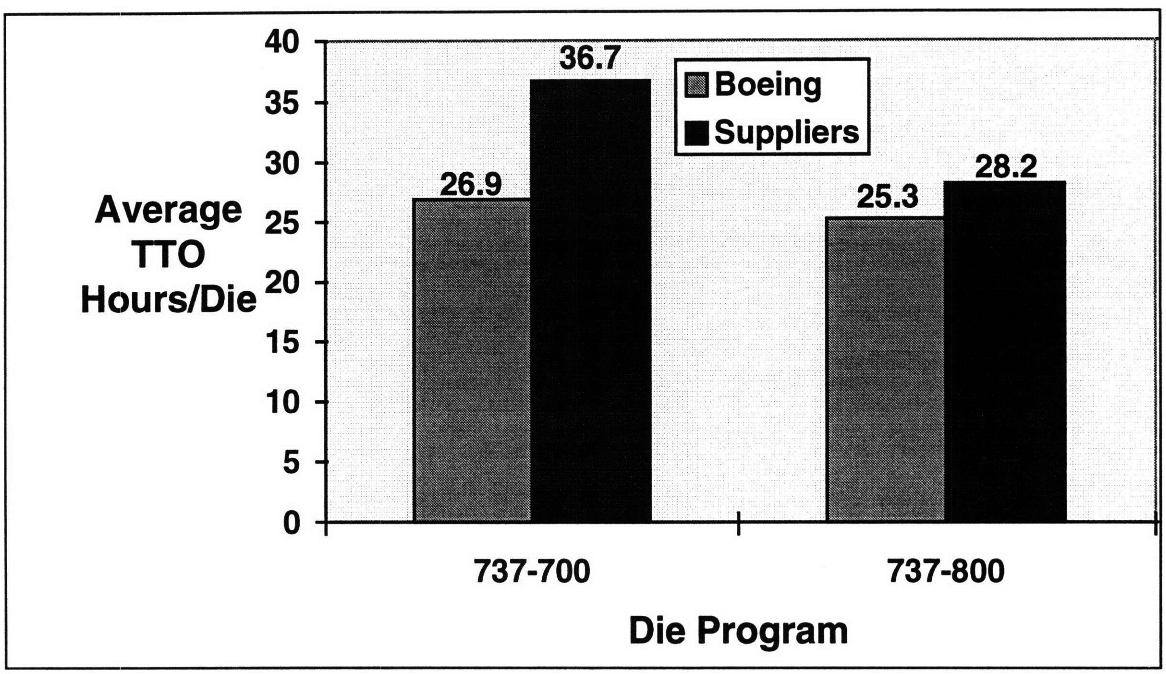

Figure 4.2 Average TTO Hours of 737-700 and -800 Dies by Fabrication Source

Next, a note on rework is appropriate. Both in-house and New Tech dies had a very low incidence of rework on the 737-700 die package. However, when rework was required (15 dies total), it took an an average of 57 MH per die. On the 737-800 dies; not one die required rework. This constitutes a $33K savings on the 737-800 die package.

4.3.3 Schedule

I reviewed the schedule performance of Boeing and New Tech and these results are summarized in Table 4-2. Number of days late or early is defined as the difference in when a supplier actually committed to deliver the die and when they actually did deliver it. A dramatic improvement in schedule took place in both in-house dies and outsourced dies.

Table 4-2 Schedule Performance on the 737-800 Die Package

Die Fabrication Source	**Boeing**	**New Tech**
Number of Dies	25 dies	39 dies
Number On time	17 dies	35 dies
On Time Performance	68%	90%
Average Performance	**2.8 days late**	**1.1 days late**

I attribute this improvement in schedule to the following:

1) an increased focus within the Tooling MBU on schedule,
2) our Team's communication with the supplier of the importance of making the committed date, and
3) a decrease in the number of order delays caused by squawks and MELR's.

I believe that part of the improvement in New Tech's schedule performance is due to the fact that they knew they were being "watched" and evaluated on schedule performance. I cannot say with certainty that this kind of performance can be maintained. However, for the first time, they had one "team" voice asking them to improve schedule, where as in the past, Procurement berated them on cost and they heard little criticism when they didn't make the committed date.

4.3.4 Learning and Information Transfer

There are additional but less tangible benefits to the preferred supplier process we implemented at the Tooling MBU. These benefits are difficult to quantify, yet they may result in significant savings to Boeing in the long term. I would like to describe three such benefits relating to learning and information transfer that resulted from this project.

Supplier to Factory Learning - New Tech was willing to share their form die manufacturing process once we agreed not to share detailed cost and process information with other suppliers. I was curious as to why they were more productive than Boeing and other suppliers on complex dies (having the most features). I have listed both New Tech and the Tooling MBU's die process steps in Appendix 3. New Tech's process has been simplified to protect their proprietary information.

Figure 4.3 summarizes the key steps in the Boeing process that are different than New Tech's. The conventional machining approach takes a squared-off block of material and rough mills the entire profile. Then the entire length is ground. The length is then cut into individual segments used in a Type 3, 4 or 5 die. Each of those segments is then milled and ground individually to form the correct crush or joggle feature. Finally, the ends of each segment and the feature transitions are ground.

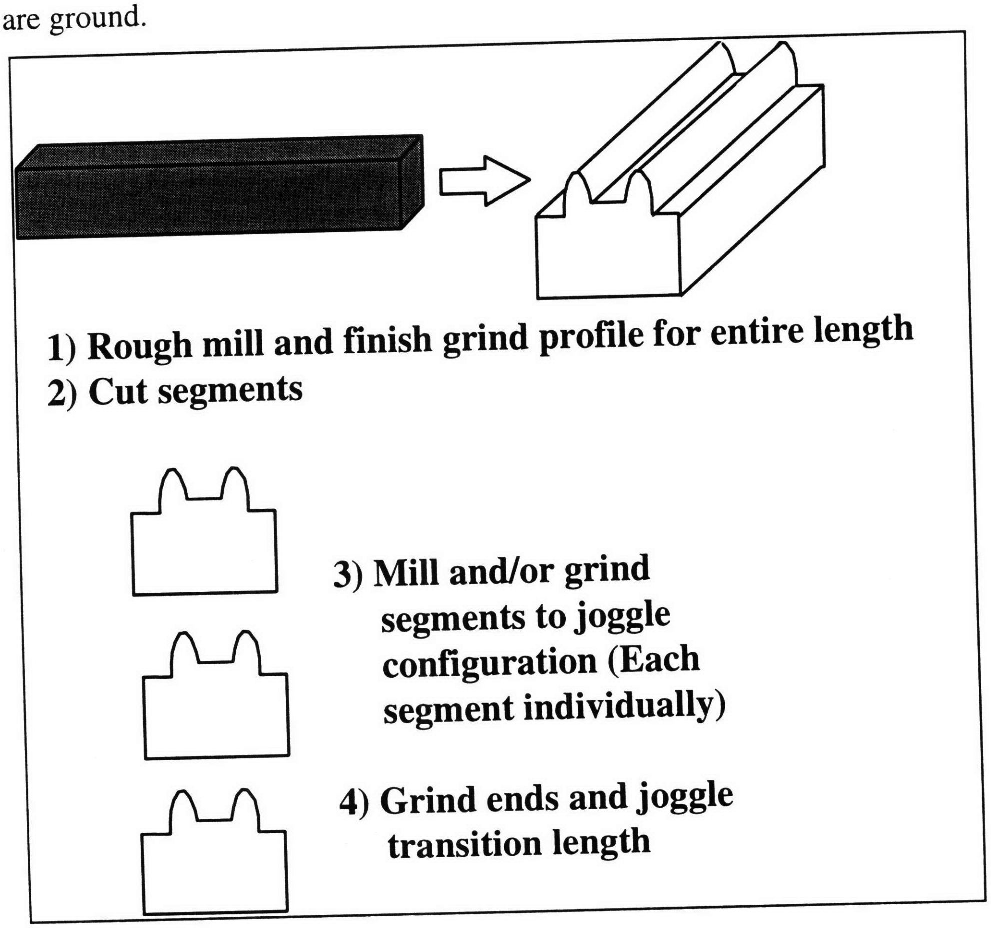

Figure 4.3 Conventional Form Die Key Process Steps

New Tech uses a Wire EDM machine in place of a conventional mill. Wire EDM is a relatively new process (compared with conventional milling) that uses an electric-discharge wire that slowly moves along a computer prescribed path, cutting a workpiece, with the discharge sparks acting like cutting teeth. New Tech first cuts a squared-off block into segments. They then Wire EDM the profiles and feature transitions of all segments at one time using a platen with all segments set-up at once (Figure 4.4). They then do a limited amount of grinding of transitions and ends of segments.

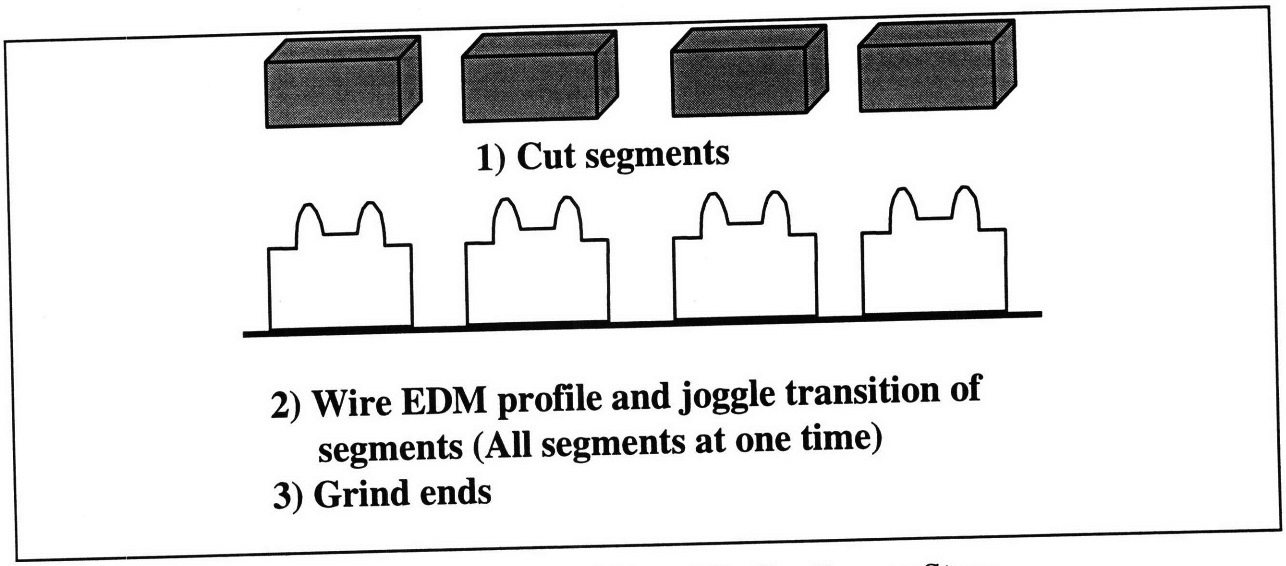

Figure 4.4 Wire EDM Form Die Key Process Steps

There is little difference in process time in simple dies because they have few segments. However, in dies with more segments, there are many fewer set-ups needed in the Wire EDM process because: 1) multiple segments are Wire-EDM'd at once and 2) the Wire EDM process leaves a surface finish that requires less grinding. Finally, New Tech occasionally runs its Wire EDM machine overnight or over a weekend, without an operator present. As an aside, current Boeing-Union rules would prohibit a machine from being operated unattended. Boeing learned how they could improve their process for complex dies (by acquiring a Wire EDM capability).

When my internship was complete, Tooling MBU management was deciding whether it made sense to purchase a Wire EDM machine to manufacture these dies. I believe they are leaning toward not making the investment in view of the cyclicality of form die demand and the ability to simply have New Tech manufacture the majority of these dies and still capture the advanced process savings. While Boeing may not improve its manufacturing process as a result of this learning, it has caused the factory management to be more focused on their own competitiveness than in the past (now that they have total cost data).

TTO to Procurement information sharing- Through our team, information was shared across organizational boundaries. The Procurement Organization was not aware of the existence of TTO data; their metric on vendor performance had always been bid cost alone. We were able to correct their cost metric, in effect, by adding the cost of TTO and rework to determine total cost to Boeing.

Tool Design to Supplier learning - By putting the designer of form dies in direct contact with the supplier's machinists, we removed non-value added steps such as the MELR along with their flow times. In effect, we made the same improvement in the external supply chain that has already been accomplished internally in the Tooling MBU, whereby the Boeing machinist simply calls the designer when he has a question or problem. We expedited New Tech's learning of Boeing's form die requirements and this same degree of learning might not have been possible had we been working with many suppliers.

I don't want to imply that New Tech is unique in all ways. They did have a better manufacturing process for complex dies. However, we would have seen some of the benefits of this preferred supplier process had we picked any one or two of the other competitive suppliers. Because of the increased learning and information transfer that would take place with any such supplier, TTO and rework hours should decline. By getting "closer" to the supplier in terms of information transfer, as we did with New Tech, any supplier should be able to build dies as good as Boeing's factory, while capturing the rate-related benefits of outsourcing.

4.4 Chapter Summary

As I have said before, the challenge of this internship was not in discovering what to do, but in its implementation in a large tooling organization with a somewhat functional environment. The following summarizes the basic steps that we took and that will be repeated by the Tooling MBU with other tool types:

1) Work as a team consisting of Procurement, WTM and the Factory,
2) Choose a supplier(s) based on past performance considering total cost (putting competitive bid aside),
3) Share objectives with the supplier (including the importance of schedule), and
4) Streamline the transfer of information between design and the supplier.

By implementing this preferred supplier process on the 737-800 die package, we were able to demonstrate a manufacturing savings of $32K, a dramatic improvement in schedule performance, and a reduction in TTO and rework hours (saving an additional $79K).

5. Chapter 5 - Springback in Form and Joggle Dies

When I collected the data shown in Figure 3.8, it was clear that overbend was the most commonly occurring die defect that required "excess TTO" or rework within Boeing. Overbend occurred in both dies made in-house and those made by suppliers and was clearly a design and not supply chain related defect. A group exists within Boeing Defense & Space Group (D&SG), that has significant expertise in analyzing forming processes. I was able to lead a cooperative effort between the Tooling MBU and this group. Using Finite Element Analysis (FEA) and comparisons with die measurements, we made a design process improvement to more accurately account for this springback. This process improvement is now being implemented on the 737-600 die package.

5.1 What is Overbend

Overbend occurs when the die feature depth, whether it be a joggle or a crush depth, is not increased by the correct amount to account for the springback which occurs after the die set is opened following the forming process. As shown in Figure 5.1, an elastic-plastic material such as aluminum, exhibits first linear and then non-linear stress-strain behavior. During the forming process, aluminum is typically loaded into the non-linear region of this stress-strain curve, resulting in both elastic and plastic deformation. Upon opening of the die (releasing the load on the part), the elastic strain (ε_e) is recovered (returns to zero). The springback is caused by the elastic portion of total strain in the part returning to zero. The plastic strain (ε_p), however, remains in the part. Thus, the part is formed to a different shape than that prescribed by the die geometry alone.

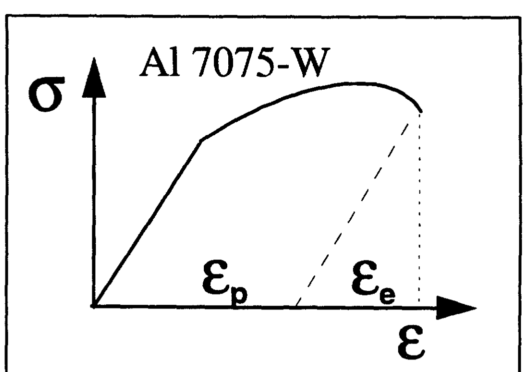

Figure 5.1 Typical Metal Stress-Strain Behavior

The amount of springback (and thus the necessary overbend to be designed in a die) is dependent on a number of material and structural parameters including:

- elastic modulus (E_e),
- yield stress (σ_y),
- plastic modulus (E_p and shape of the non-linear portion of the stress strain curve),
- part geometry (e.g. thickness, length),
- loading type (rate, direction, concentration), and
- boundary conditions.

5.2 Current Process

Because the plastic strain is non-linear deformation that occurs during the forming process, there is no closed-form solution to the springback in a given part. As a result, a design guideline (rule-of-thumb) has been used for years by the Tool Designers to account for springback in dies. All dies incorporate a joggle or crush depth as follows:

$$D_{die} = (D_{part} \times 1.15) + .01''$$

This "15% plus 10-mil." rule was believed to be a good rule which would not overestimate the die depth required. When the die depth needed is underestimated (the part springs back too much), additional die machining is necessary and easily accomplished, incurring some additional cost. However, if the die depth is overestimated, material cannot be "added" as easily. The die is then either shimmed or needs to be remanufactured (a costly situation).

I reviewed many drawings on the 737-700 and 737-800 and found that this rule-of-thumb was generally applied as stated. However, in some designs, it was incorrectly applied as just 15%, by inexperienced designers. In other cases, some variation of the rule was applied (e.g. 15%+5-mil, 20%+10-mil) with no particular reason given or pattern of use.

5.3 Use of Finite Element Analysis

5.3.1 Background

The purpose of this portion of my internship was to investigate the use of Finite Element Analysis (FEA) as a scientific tool to find a better rule than "15% plus 10-mil" in order to reduce rework on joggle dies. The automotive industry has had similar problems as the aerospace industry, except that there are requirements for higher production rates and the material used is generally steel (generally a more formable material). Since 1993, the automotive industries and ALCOA have published a significant amount on the use of FEA to solve metal forming problems. The basic conclusion is that approximately 25% of the time necessary to implement a forming process (basically through trial and error, like TTO) can be cut out using FEA.

The process steps involved in FEA are shown in Figure 5.2. Steps include the building of a finite element model (FEM), the performance of the analysis, and a review of the analysis; all of which can be summarized as the pre-processing, analysis and post-processing. The pre-processing phase requires a digital definition for the tooling and part, plus a mathematical definition of the forming process. The digital definition was provided by the CATIA software. The analysis was performed by two non-linear FEA programs (in this case Dyna3D and Nike 3D). A non-linear code was used because, during the forming process, enough strain is caused in the aluminum part to cause the material to get well into the plastic region of the stress-strain curve. I will next describe each of these steps in a bit more detail.

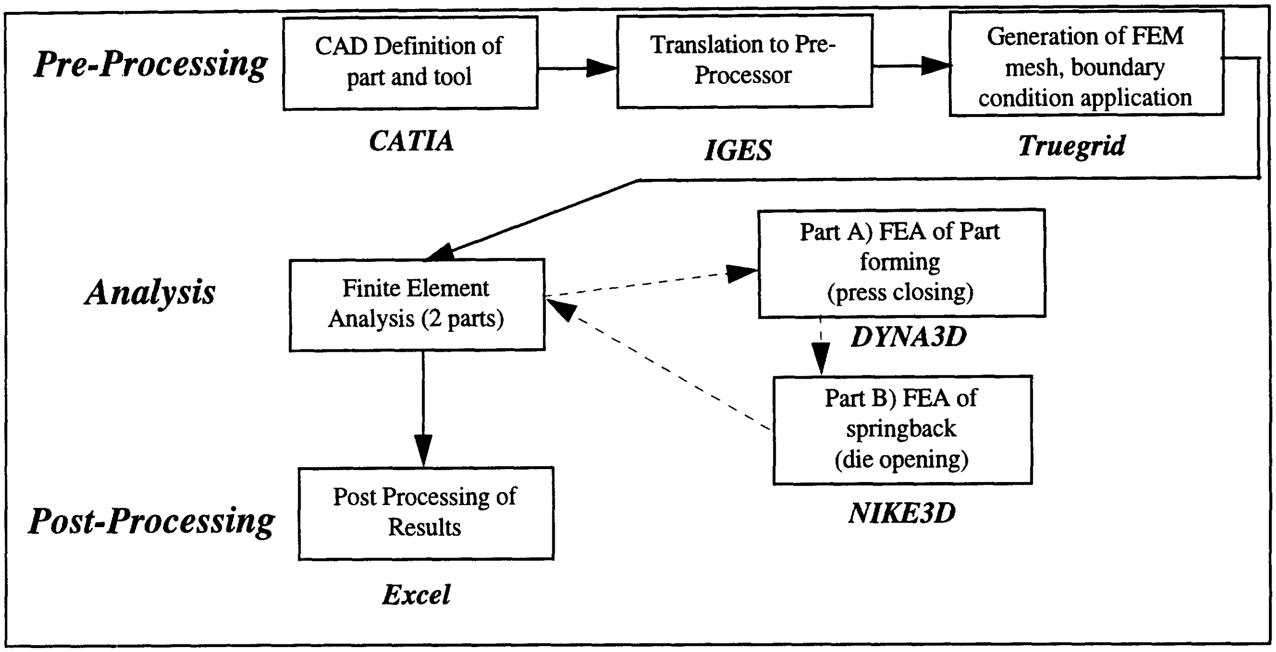

Figure 5.2 FEA Process and Software Tools Used

5.3.2 Pre-Processor

Pre-processing is the step where the physical elements of the forming problem are defined. The elements of the forming problem are the part blank and the die sections (punch and die) that will form the part. CATIA generates surface elements which cannot be used by the analysis program. Boeing and much of industry uses an IGES (Initial Graphics Exchange Standard) translator to convert the CAD drawing from CATIA into a standard format that can be read by a mesh generator. The mesh generator is called Truegrid. It converts the IGES dataset into usable finite elements. Each die-part model utilized approximately 16821 shell-type elements, connected through 17,280 nodes defined in the die and part. The die and part model is shown in Figure 5.3.

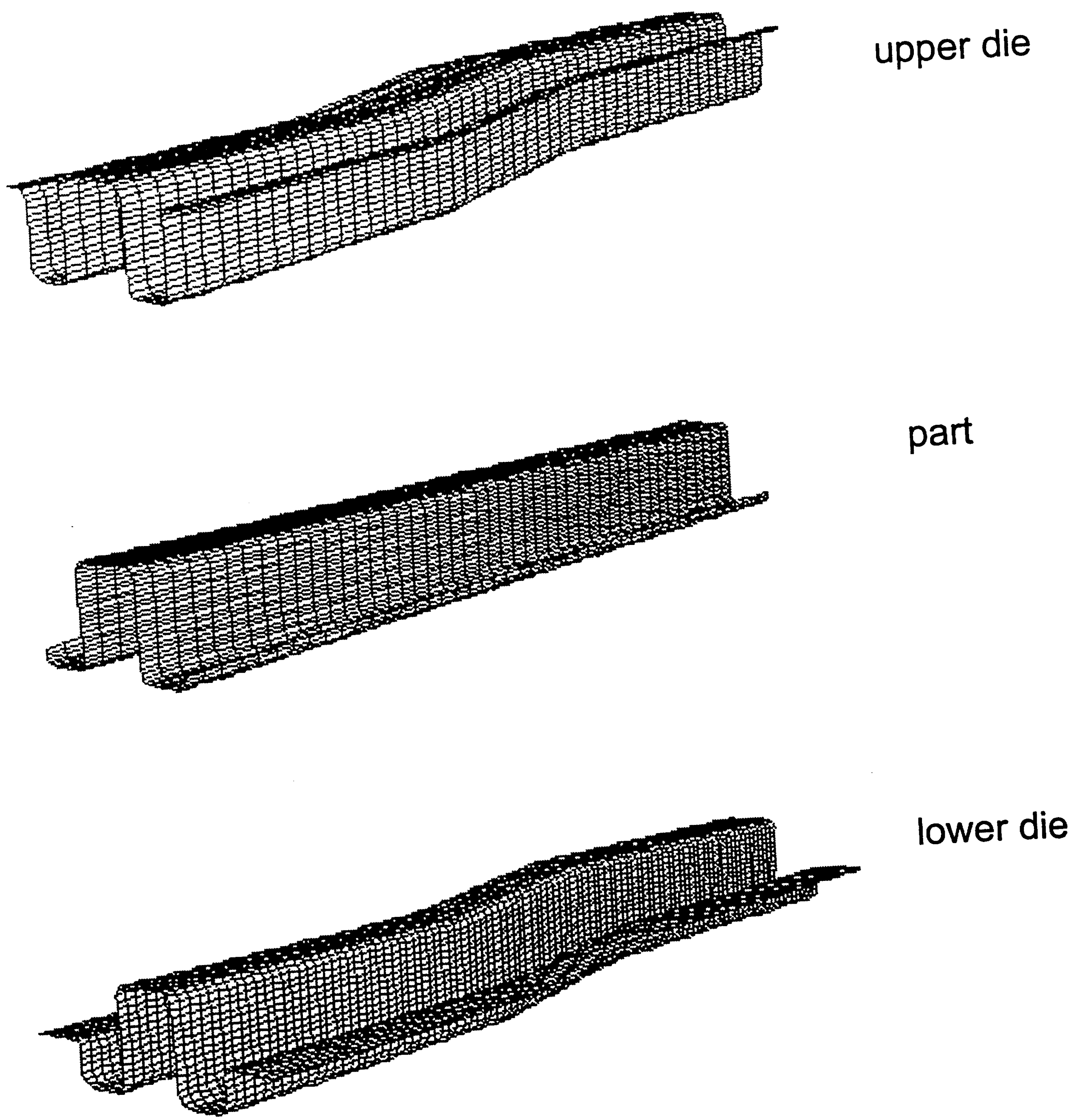

Figure 5.3 Die and Part Finite Element Model

Assignment of boundary conditions is the next step performed in pre-processing. Boundary conditions describe how the tooling and part elements move, the amount of friction between parts, and the relationship between stress and strain in the materials used. In this forming analysis, the top punch was constrained to move up and down, and the bottom die was completely constrained from moving. The part was left unconstrained. Finally the loading is defined in this step (including its rate, whether pressure or concentrated, the load direction and application points). The loading "curve" used corresponded to the actual press loading and was a ramp-up to 900 psi (lasting 1 second) applied over the entire part. This is an idealization of the actual press loading.

5.4 Model Description

There are two types of non-linear FEA software codes, implicit and explicit, as described below in 5.4.1 and 5.4.2. They have application in different types of problems and their correct use is a process that depends on the experience of the analyst. I relied on the experience of Defense & Space Group (Jon Gabrys and Gerry Young) in analyzing the die-part model I provided them with. These capable analysts have developed a process of marrying an implicit code and an explicit code to solve springback problems. That is, the explicit code was found most suitable for modeling the forming process through to when the press is closed. The implicit code was then used to model the part of the process when die is then opened and the part relaxes, springing back by some amount.

5.4.1 Implicit Codes

Implicit analysis codes have the ability to take large time steps into account when applying a load curve to a part. This time step can also be adjusted. This time step is on the order of tenths of a second. An implicit code can have convergence problems; therefore an answer does not always result. Troubleshooting of failed implicit models can be a lengthy process and requires experience. However, once a solution is reached, the answer is usually a good one. Nike3D is an implicit code used by Boeing D&SG. It was developed by Livermore Software Technologies Corporation and is utilized widely in industry.

5.4.2 Explicit Codes

Explicit codes use a time step approximately 100-1000 times smaller than the implicit codes. They do not allow adjustment in the time step. Explicit codes require less memory and less time to solve each iteration but they take many more steps to arrive at a solution than an implicit code. Although the explicit codes always arrive at an answer, they can calculate an erroneous solution, so care must be taken in evaluating the validity of solution from explicit codes. D&SG has used Dyna3D, another Livermore developed code, with much success.

5.5 Model Results

The models were run on an HP C110 workstation. Each run required approximately two hours. The post-processing of the analysis results consisted of examining the part geometry data after forming and recording the deflection of the hat portion of the part along its length (the origin being the left end of the part). This deflection as a function of distance along the part was copied into an Excel spreadsheet so that it could be compared with experimental results.

5.5.1 Die Geometries Analyzed Using FEA

A total of six dies were analyzed using FEA. In past years, only dies with smaller joggles (<.075") having steeper slopes (6 to 1 ratio) were designed. More recently, larger joggles and those with more slender ratios have been designed. Tool Designers felt they knew less about the springback of these type parts. As a result, we decided to investigate larger joggles and more slender joggles. The first die analyzed had a 10 to 1 joggle ratio and a .287" die joggle (.25" part joggle plus 15% for springback). Each of the remaining five dies was simply a modification of the original die as shown in Table 5-1. For the modified cases, the CATIA model was altered to yield the given geometry before entering the IGES translator.

Table 5-1 Die Part Model Configurations Analyzed

Run	Ratio	Desired Part Joggle	Die Joggle Depth
1	10 to 1	.25"	.287"
2	6 to 1	.25"	.287"
3	15 to 1	.25"	.287"
4	10 to 1	.1"	.115"
5	6 to 1	.1"	.115"
6	15 to 1	.1"	.115"

5.5.2 Die Springback Data Collection

In order to correlate the FEA results and increase confidence in their accuracy, measurements were taken of parts pressed from dies in their "out-of-the-box" condition. That is, no modifications were made to the die after it was received by TTO. Thus, the dies had the geometry represented by the drawing (within its tolerances). Data was generally taken from at least two dies having a particular joggle depth and ratio configuration that was analyzed. It is not intended that this data be statistically significant; merely that it give an indication as to the overall accuracy of the analysis and trends indicated by the analysis. For each part measured, the following process was followed:

1) a 15" constant cross-section (blank) was removed from the freezer,
2) the part was allowed to come to room temperature for 30 minutes,
3) the part was pressed in the trial press,
4) the part was measured in a Digital CMM (coordinate-measurement machine), and
5) data was taken at 0.5" intervals at two locations both on the hat and each of the flanges (6 locations total).

In the CMM, the part was constrained from moving by c-clamps and a clamping block. A part being measured is shown in Figure 5.4. The left side top edge of the part was defined as the origin and measurements made with respect to this origin. The data was then copied into Excel and compared with the FEA results. This CMM data is given in Appendix 5.

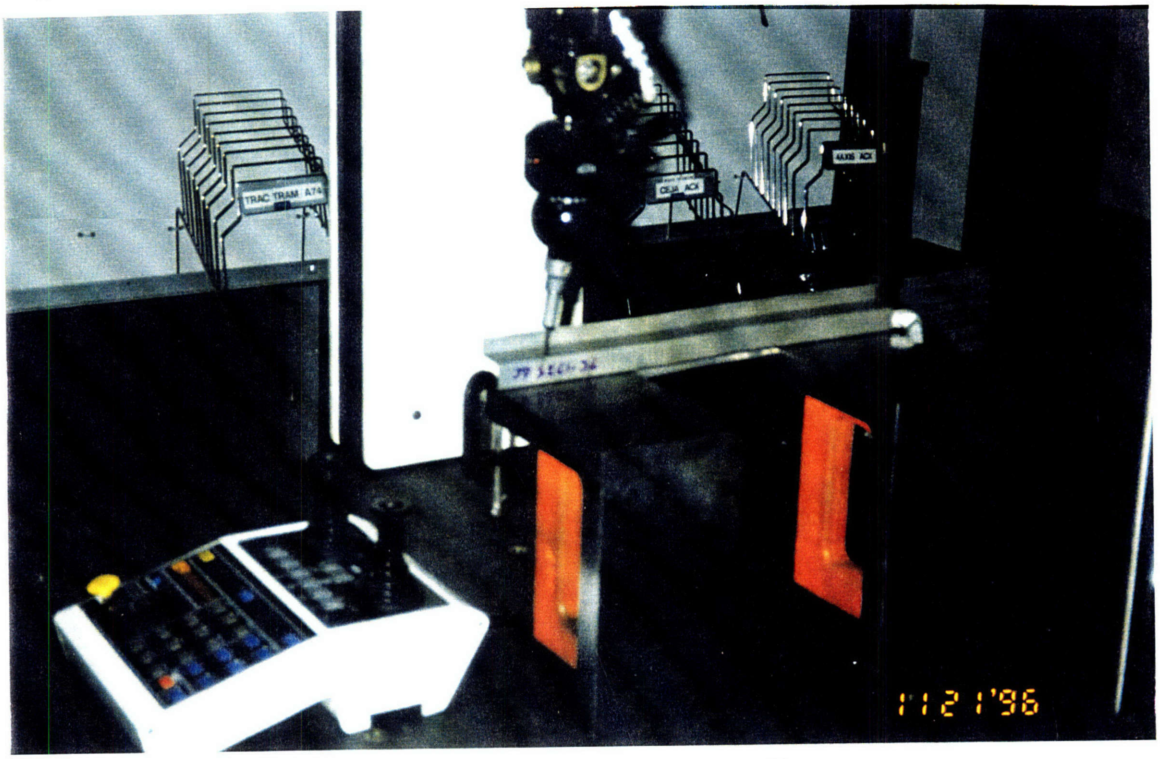

Figure 5.4 CMM Part Measurement Process

5.5.3 Results - Larger Joggles

The first FEA run was for a larger joggle and a 10 to 1 joggle ratio. The FEA results for this design are shown in Figure 5.5. The model predicts that a die joggle of .287" will cause the part to springback to .173", corresponding to 40% springback. The data taken using the CMM shows an actual part springback to .20" corresponding to a 30% springback. The FEA model thus overpredicts the springback by 11%. Both the FEA results and the CMM data indicate that the 15% design for springback (or even 15% +.01") underestimates the overbend required in a die with a larger (.250") joggle.

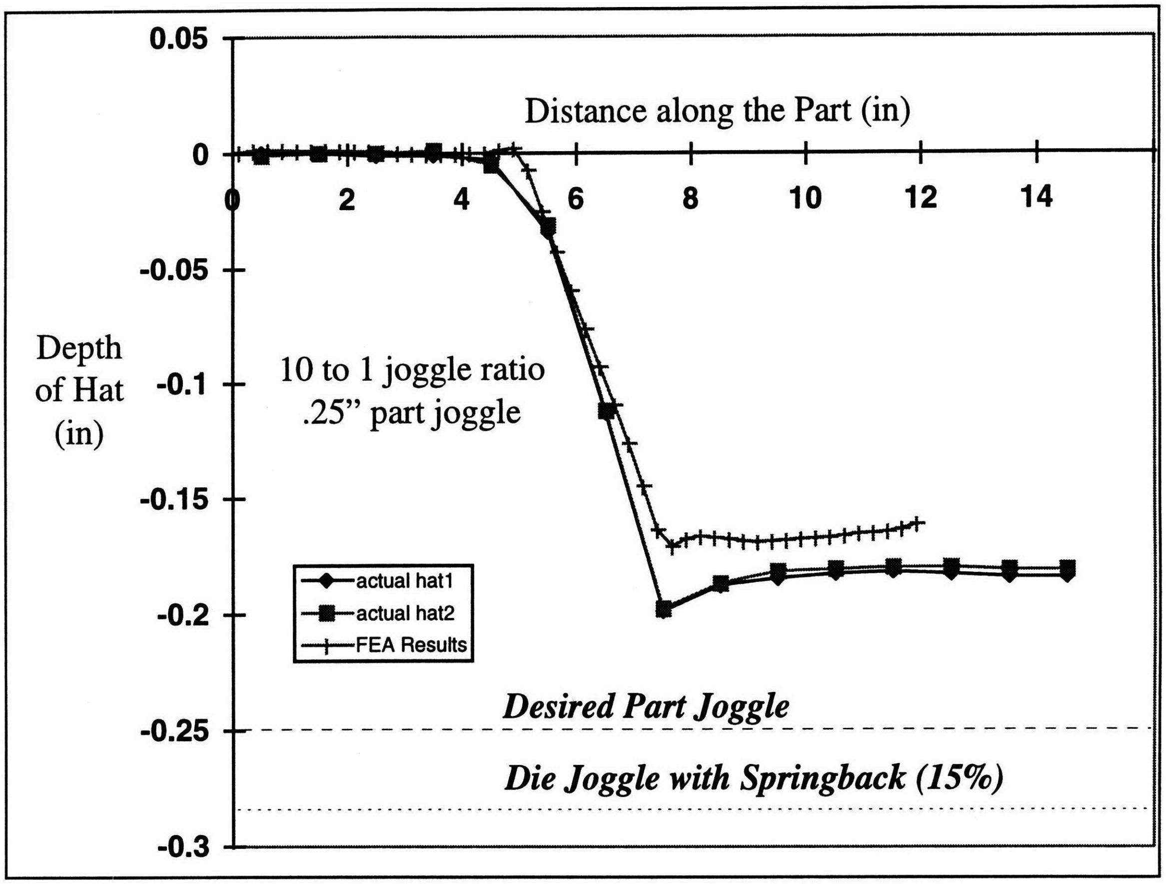

Figure 5.5 FEA Results for a Large Joggle

5.5.4 Results - Effects of Joggle Ratio

The CATIA data was then modified for two series of additional runs to investigate the effects of joggle ratio. The first series (two additional runs) examined the same joggle depth with a more slender (15 to 1) and then a steeper (6 to 1) joggle ratio. As shown in Figure, a 6 to 1 joggle ratio results in the smallest amount of springback. The 15 to 1 joggle ratio results in the largest amount of springback. All FEA results for the .25" joggle depth and their corresponding TTO measurements are given in Table 5-2. Deflection versus distance along the part is shown in Figure 5.6. As shown, the 6 to 1 ratio joggle exhibits less springback than the 10 to 1 joggle, and the 15 to 1 joggle exhibits more springback.

Table 5-2 Results for .25" Joggle Depth

Joggle Ratio	Current Design (15%+.01")	FEA Result	FEA %	CMM Data %	Difference
6 to 1	19%	.200"	30%	23%	+7%
10 to 1	19%	.172"	40%	36%	+4%
15 to 1	19%	.145"	49%	39%	+10%

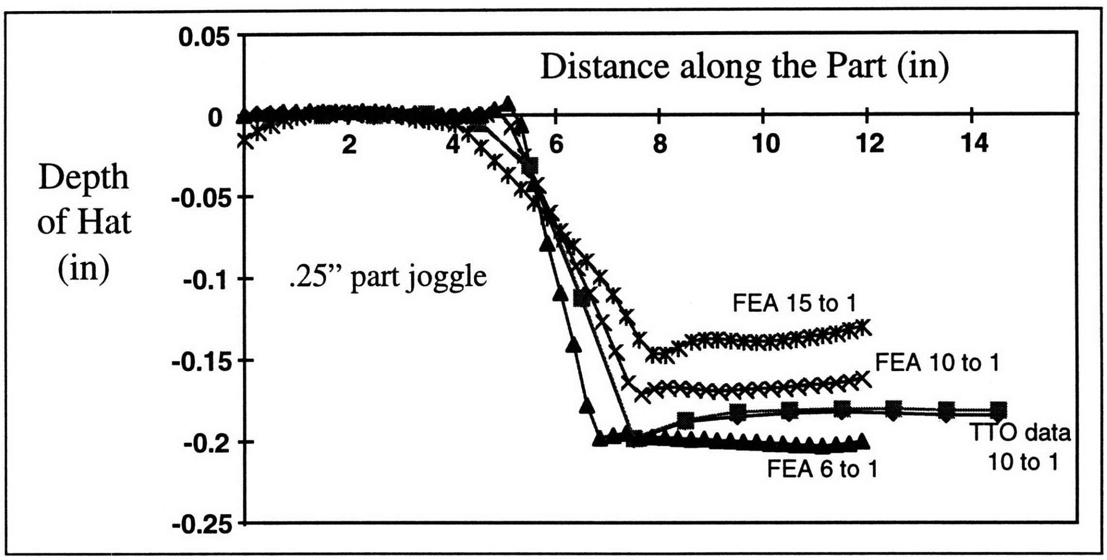

Figure 5.6 FEA Springback Results for three Joggle Ratios (.25" joggle)

As shown in Figure 5.7, the analysis tends to overpredict the springback recorded in the actual dies. Regardless, at all joggle ratios, current design practice (15%+.01"), corresponding to 19% springback compensation, is significantly below what either the CMM data or FEA indicates.

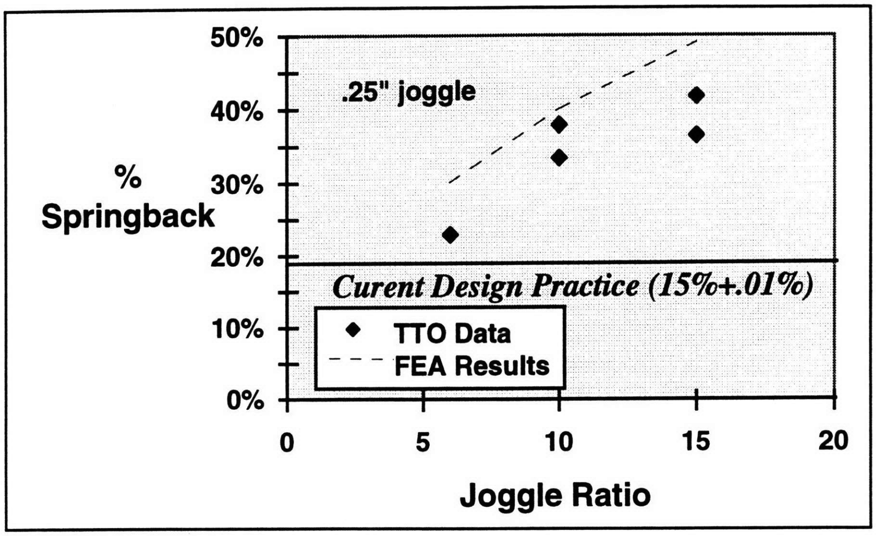

Figure 5.7 Springback vs. Joggle Ratio for Large Joggles

Results for the final three FEA runs (.10” joggle depth) are listed in Table 5-3. CMM data was also taken for these size joggles. The analysis shows the same increasing springback % with joggle ratio. However, the increase is less dramatic with the .10” joggle depth. The maximum springback predicted is 39% and occurs with a 15 to 1 joggle ratio. Deflection versus distance along the part is shown in Figure 5.8.

Table 5-3 Results for .10” Joggle Depth

Joggle Ratio	Current Design (15%+.01”)	FEA Result	FEA %	CMM Data %	Difference
6 to 1	23%	.074”	36%	26%	+10%
10 to 1	23%	.072”	37%	33%	+4%
15 to 1	23%	.070”	39%	35%	+4%

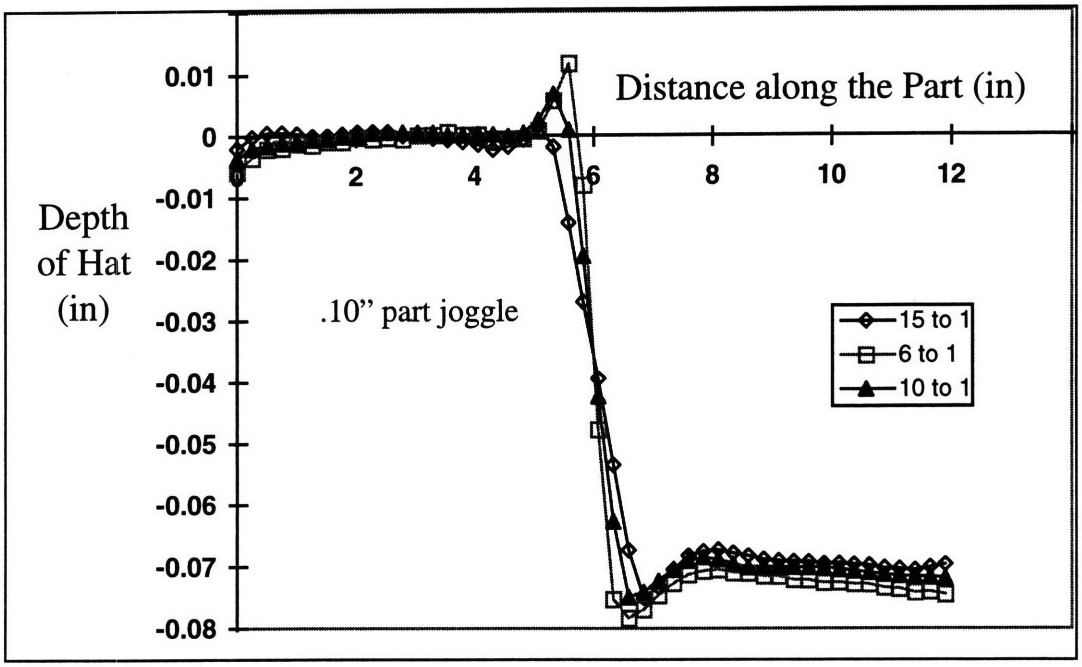

Figure 5.8 FEA Springback Results for three Joggle Ratios (.10" joggle)

As shown in Figure 5.9, the analysis tends to overpredict the springback recorded in the actual dies. Regardless, at all joggle ratios, current design practice, corresponding to 23% springback compensation, is significantly below what either the CMM data or FEA indicates.

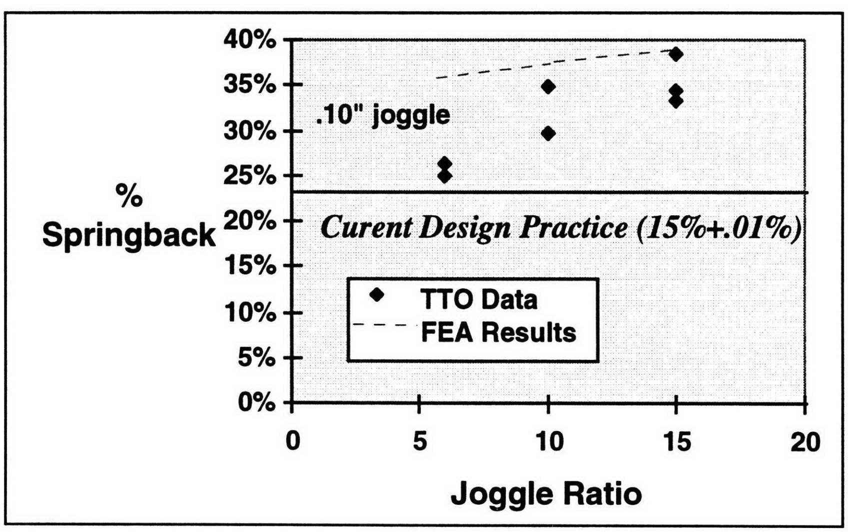

Figure 5.9 Springback vs. Joggle Ratio for Medium Depth Joggles

5.5.5 Causes of Error and Variation

The FEA analysis tends to overpredict the springback recorded in actual part forming trials. This deviation or error between analysis and experimental data was as much as 10% of the FEA amount. In addition, there is variation in the CMM data, even for dies of the same geometry. There are a number of causes of this error and variation in experimental data and it is important to understand some of the reasons.

First, concerning the FEA, a main contributor to possible error in the results is the material properties. Small changes in material properties (stress-strain behavior) can lead to large changes in strain results and the corresponding springback predicted. In this case, the part material used is Aluminum 7075-W. "W" indicates that it is has not been heat-treated prior to forming. This material must be stored in the freezer. Once it is removed from the freezer (and comes to room temperature), the material slowly ages and approaches a final condition. Its material properties are constantly changing as it ages. This is the reason why we tried to form the part after allowing the blank to come to room temperature for 1/2 hour. One cannot look up the material properties for 7075-W; even ALCOA could not provide us with the information. We used our best available information based on previous analytical efforts which indicated that for 7075-W, aged for 30 minutes:

Elastic modulus $E = 10.62$ msi,

Tangent modulus $E^T = 5$ msi,

Yield Stress $\sigma_y = 22.3$ ksi, and

Poisson's Ratio $\nu = .33$

Another key parameter used in the analysis is the friction coefficient between the part and the die. A water based lubricant is used when forming joggles. Experimental tests at ALCOA have shown that the coefficient is typically $\mu = 0.15$ for water based lubricants. This value was used in this analysis. However, it does vary along the interface based on die/part interface quality (primarily depending on surface finish of the die).

Concerning variation in the CMM data, there is one likely cause besides the two already mentioned as also driving error in the FEA results. Thickness of the part being formed did vary between individual dies being measured. Preliminary FEA runs showed only a small effect of part thickness on springback (compared with the effects of joggle depth and ratio) and this led to part thickness being ignored as a significant driver of springback percent.

Finally, the FEA analysis was performed on dies having .115" and .287" die joggles (intended to create .100" and .250" part joggles, respectively). The CMM data was taken from dies designed to form parts having .120"-.128" and .253"-.350", respectively. Thus one would expect there to be some difference in the FEA results and experimental data if springback percent depends on joggle depth (which I propose it does).

5.6 Design Process Improvement

Regardless of the variation in experimental data and any possible error in the FEA results, it was clear that the current design methodology for accounting for springback was inadequate for some dies. The incorporation of 15% plus .01" (or just 15%) overbend may have been adequate for smaller dies and those having a 6 to 1 ratio, those predominant in the past. Larger die ratios and larger joggles clearly require more overbend in their die designs. In coming up with a recommended design approach, I was aware of the desire to not overcompensate for springback. We want to err on the low side in our recommendation to allow material to be removed (if necessary) to increase the overbend to an acceptable value. As a result, the CMM data played a significant role in determining the final design guideline. In general, the die designers will be using a value corresponding to the lower end of the CMM data range recorded for that die design. The modified design approach for springback is given in Table 5-4.

Table 5-4 Improved Design for Springback

Joggle Type		**Joggles under .075"**		**Joggles .076-.175"**		**Joggles .176-.300"**	
Ratio	**Current Methodology**	**Current Effective %**	**New %**	**Current Effective %**	**New %**	**Current Effective %**	**New %**
6	**15%+.01**	28%	same	23%	**same**	19%	**23%**
10	**15%+.01**	28%	same	23%	**30%**	19%	**33%**
15	**15%+.01**	28%	same	23%	**35%**	19%	**36%**

5.7 Chapter Summary

This improved design approach will be used in the next die package. The 737-600 dies are currently being designed at Boeing. An evaluation will be conducted following the completion of all 737-600 die TTO to insure that the occurrence of overbend as a defect has been reduced and to evaluate the magnitude of this reduction. This same approach can be utilized to evaluate design approaches used in crush features for dies (which this project did not address) and to evaluate springback challenges in other tool types.

6. Chapter 6 - Tooling Process Improvements and Lessons Learned

6.1 Introduction

In this chapter, I would like to make several recommendations that result from my experience in the Tooling MBU at Boeing. Some, such as how to perform make/buy, result from my internship project directly, from data that I collected and analyzed. Others result from my observations of the organization and the challenges faced by a large Tooling provisioner that is part of a functionally organized business in a cyclical product development environment. The last idea is not my own. The integration of the Procurement Organization into Tooling has been discussed and its implementation is planned. My contribution is the extent to which I believe that integration should take place. I believe it to be an important step towards the improvement of external supply chain management in Tooling. Finally, I will describe a few lessons learned from my experience, reflecting back on my time spent in the organization.

6.2 Make/Buy in Form Dies

Boeing will always have emergent requirements in form dies and thus must keep some capability in house. However, they cannot make all dies because of capacity requirements during new product development cycles. Thus, they will always have make/buy decisions to make for these tools. Based on my internship experience, we learned that:

1) Boeing is more cost competitive on the simpler dies,
2) Dies differ in difficulty by key features of complexity, and
3) Some vendors are more cost competitive at complex dies.

Based on these results, I propose that the make/buy policy for form dies be as shown in Figure 6.1. The majority of the simple dies, those part of a new product development program (such as for the 737-800) should be made in house. Other simple dies that are emergent or airplane rate requirements, should also be made in house and only outsourced to a partner supplier if Boeing does not have sufficient capacity. All new product development complex dies should be made at a partner supplier (such as New Tech). A few complex dies (emergent and rate requirements) should be made in house to serve the function of maintaining the skills of Boeing's machinists. Emergent and rate requirement dies serve this function well since they have more continuous (less cyclical) die demand than new product developments. New Tech is an ideal preferred supplier of dies because they can survive the cyclicality of die demand with their diversified work statement which includes both tooling and production parts (which are less cyclical). If demand warrants it, Boeing should explore the use of other similar preferred suppliers of dies or those diversified across industries (e.g. supplying dies to the automotive industry).

	Emergent/Rate *10-15% of all dies*	**New Product Development** *85-90% of all dies*
Simple (Types 1,2,MJD)	*Make/Partner*	*Make/Partner*
Complex (Types 3,4,5)	*Make*	*Partner*

Figure 6.1 Make/Buy Policy for Form Dies

6.3 Use of Preferred Suppliers in other Tool Types

I believe that the process used in this project to partner with a form die supplier is usable with many other tool types provisioned by Boeing. In the same way that Chrysler asks these questions of all its core suppliers, Boeing should be asking:

1) Who is the best? (benchmarking them),
2) Who should we use?, and
3) How many do we need?

The resulting concentration on fewer preferred suppliers will certainly strengthen Boeing's external supply chain by committing work to that supplier (making them healthier), making the supplier willing to share their processes (learning), and reducing Boeing transaction costs (i.e. by concentrating surveillance, Q/A and Procurement on fewer suppliers). One additional benefit that can occur concerns emergent demand. Boeing pays a premium when it outsources tooling having a shorter than standard lead time. I believe they could reduce or even eliminate this premium paid for emergent requirements using a partner supplier; the partner should be willing to substitute an emergent tool for a long lead tool without charging a premium since Boeing has committed to paying for a fixed amount of that supplier's efforts.

One negative often mentioned in using this approach is risk. If a partner should fail, the Tooling MBU would have difficulty either making or buying those tools in time to meet customer demand. However, this approach should result in fewer but stronger suppliers. I would recommend maintaining a minimum of two preferred suppliers for each tool type. This will maintain some competitive spirit between the suppliers and act as a check and balance on pricing when required.

6.4 Integration of Procurement Function

"We don't want to become clerks just placing orders with suppliers based on Tooling's instructions" (R. Plattner, Procurement)

When I came to the Tooling MBU, I saw two "walls" existing between organizations. The first wall was between the Tooling MBU and Work Transfer Management, which previously was part of a separate organization located away from the factory. Early in my internship, WTM was integrated into the Tooling MBU. Once their objectives became clearly aligned and they were part of the same organization, I saw a drastic change in the working relationship between WTM and the rest of the Tooling MBU. In a few words, the "us versus them" mentality went away and the attitude under Jim Helland became "what can we do together to provision tools on time".

The second and remaining wall is between the Tooling MBU and Procurement. In past years Procurement was kept separate from the operating divisions in order to avoid any conflict of interest; it was felt that the personnel responsible for monitoring the supplier should not make supplier selection decisions since they might be unfairly influenced by the supplier (e.g. bribes or other more subtle favorable treatment). Procurement has become proud and protective of their unique role in supplier selection. They have remained focused on reducing the cost of tools purchased from suppliers, the metric by which they are evaluated. The Tooling MBU, on the other hand, has always been evaluated on schedule, rather than cost. In fact, the cost of tools purchased from suppliers is generally only known to Procurement.

I believe that the reasons for this separation have diminished. First of all, the current environment, where many people review the performance of a supplier on a job, is less conducive to an inferior supplier being allowed to be selected. Many people review the performance on a job including: 1) WTM (surveillance, program managers, and analysts), 2) Q/A personnel, and 3)Procurement. My recommendation is that a team approach to supplier selection and management be adopted. The team would consist of the WTM, Q/A and Procurement personnel, and it would result from the integration of Procurement into the Tooling MBU. A team approach would allow checks and balances to exist in the supplier selection and management process. Both cost and schedule (in addition to Quality) would be monitored by the same Boeing personnel, allowing for a more meaningful evaluation of suppliers. Procurement personnel would not become "just clerks" as they feared, but valuable members of the external supply chain management team within the Tooling MBU.

6.5 Lessons Learned

I learned many things about Boeing and its suppliers of tooling while in Auburn. Some of the lessons were not the result of specific data I took, but rather my overall experience there in Manufacturing. Two of the three lessons learned that I wish to share could apply to almost any large manufacturing company other than Boeing. The third is unique to the aircraft industry (as well as some others). These lessons learned are that:

1) There is no substitute for good data,
2) Functional smokestacks still exist, and
3) Tooling should be considered a core competency within Boeing.

The first lesson learned results from the importance I attribute to the data I collected during my internship. Before I knew what data was needed, different organizations involved in my project (e.g. Procurement, Factory, WTM) were ready with explanations of what the data would say. Procurement thought they were buying the cheapest dies. The Factory thought they were most competitive in complex dies. Change is difficult to accomplish when hearsay rules and all sides think they are doing what's best. The data I collected and shared with my team had a big impact in getting their support for process improvement. Hearsay can be argued, but once the data and its origin are understood, it is difficult to dispute.

Next, the lesson that functional smokestacks still exist, was apparent in my project. Boeing has gone far in implementing cross-functional teams to develop products. However, the development of tooling has still been hampered by the need to have different organizations with separate management structure and distinct incentives cooperate in provisioning tooling. In this project, the Procurement organization was a separate organization from the others. Although Q/A was also a separate organization, they had integrated their personnel in the Tooling MBU and as a result were effectively integrated. The lack of common direction has held up progress in the area of supply chain management as each organization wrestles for control of the chain. When I had left, Procurement had agreed reluctantly to co-locate in the Tooling MBU. Hopefully, they will be willing to integrate with Tooling and travel a common road.

Finally, I became impressed with the magnitude of the tooling challenge while at Boeing. Tooling doesn't often get much respect at Boeing although it is the second largest non-recurring portion of airplane development. Tooling is last to get its requirements defined in the development of an airplane. Its no wonder why they're often late in meeting customer need dates. When they're late, significant costs can be incurred if assemblies cannot be completed on time. It's easy to get blamed if you're in Tooling. On the other hand, each tool is different so economies of scale are hard to come by. Tooling demand is extremely cyclical so it's difficult to keep the same people busy on the same tool types. Learning is often lost between cycles, yet this learning is so important because if a machinist simply builds the tool to the drawing, it may not work without his modifications based on his (tribal) knowledge of the tool requirements. Tooling development is critical to the development of airplanes and because of these reasons should be elevated to the status of a core competency within Boeing.

7. Chapter 7 - Summary and Recommendations

While working in the Tooling MBU I became familiar with tooling development processes in both the internal and external supply chain. The overall goal of my project was to improve the external supply chain portion of the Tooling MBU's processes since it would play an larger portion of this MBU's role in the future and given that the buy processes for tooling generally require more flowtime than the make processes.

7.1 Summary

I reviewed Boeing's performance on the 737-700 die package, a group of nearly 200 form and joggle dies used to make 737-700 fuselage longitudinal stiffeners. The dies were provisioned from 9 sources (two internal shops, seven vendors). Although Boeing saved significant amounts of money overall by outsourcing many of these dies, many of the suppliers delivered dies late and some required significant TTO and rework before they could make a good part. From this data, I learned that:

- the number of features and to a lesser extent the presence of springs affects die complexity,
- Boeing is more cost effective on simpler dies than complex dies,
- New Tech is most competitive on complex dies,
- Boeing builds better dies than most suppliers,
- Some suppliers build better dies than others,
- Overbend is the most common design/engineering defect,
- most other defects are supply chain related, and constitute 70% of all defects, and
- Outsourced dies require approximately six additional manufacturing flow days.

Based on this information, I proposed that the procurement of the next package of dies (737-800) be accomplished differently. We formed a cross-functional team to choose preferred suppliers for the 737-800 die package. Based on inputs from Procurement, Work Transfer Management, Tool Engineering, TTO, and Q/A, as well as the cost, quality and schedule information I compiled, we reached consensus on one external supplier (New Tech). A closer relationship was formed with New Tech, resulting in an increase in trust between them and Boeing and an increase in the learning between the two. By the end of my internship period, I had collected cost, rework, quality, and schedule data from the new process. By implementing this preferred supplier process on the 737-800 die package, we were able to demonstrate:

- Manufacturing savings of $32K,
- Dramatic improvement in schedule performance (10 days), and
- A reduction in TTO and rework hours (saving an additional $79K).

Finally, I felt it was possible to improve the overall die design process. Both experiments and the use of non-linear Finite Element Analysis were explored as part of this component of the project. It was clear that the current design methodology for accounting for springback was inadequate. The incorporation of 15% plus .01" (or just 15%) overbend may have been adequate for smaller dies and those having a 6 to 1 ratio, those predominant in the past. The analysis showed that parts with larger joggle ratios and larger joggle depths clearly require more overbend in their die designs. The improved design approach developed will be used in the 737-600 die package currently being designed at Boeing. An evaluation will be conducted following the completion of all 737-600 die TTO to insure that the occurrence of overbend as a defect has been reduced and to evaluate the magnitude of this reduction.

7.2 Recommendations

My main recommendations were discussed in Chapter 6 but are repeated here for emphasis. My experience at the Tooling MBU leads me to believe that the way Boeing manages its external Tooling supply chain needs to be changed. First, the make/buy process should be understood for each tool type and be based on complexity, factory capabilities, supplier capabilities and total cost to Boeing. Tooling should be partnered with a few key suppliers for each tool type and work closer with these suppliers, sharing process information, while committing to provide those suppliers with some level of effort if they maintain reasonable cost, schedule and quality. Finally, the Procurement Organization or some members of it, should be integrated with the

Work Transfer Management Group within Tooling. The integrated WTM group should conduct supplier selection and management as a group, collectively responsible for the same performance metrics of cost and schedule. Their incentives aligned in this way, they should recognized as a team for their success in managing the external supply chain.

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737-700 Die Package									
Outsourced									
P/N	**Type**	**Supplier**	**Bid hrs**	**Size**	**Features**	**Springs**	**Complx.**	**Rework**	**TTO**
141A3120-12	2FD	427	91	12	2 cr	n	1		28
141A3340-15	JD	427	100	18	2 cr	n	1		20.5
141A3340-41	FD	427	90	15	2 cr	n	1		26
141A3341-5	FD	427	80	12	2 off	n	T		15.8
141A3341-6	FD	427	80	12	2 off	n	1		20.5
141A3531-1	FD	427	100	15	2 cr	n	1	41.6	51.2
146A3234-1	2FD	427	100	18	2 cr	n	1		33.8
146A3234-1	FD	427	120	18	2 cr	n	1		35.5
147A3200-9	JD	427	87	9	off	n	1		26.9
147A3210-3	FD	427	80	12	2 offs	n	1		30.6
147A3214-5	JD	427	80	12	off	n	1		16.8
147A3287-1	FD	427	100	15	2 cr	n	1		58.9
147A3287-19	FD	427	100	15	2 cr	n	1		8.2
147A3287-2	FD	427	102	15	2 cr	n	1		59.6
148A3370-2	2FD	427	77	9	2 offs	n	1		3.2
148A3370-2	FD	427	77	12	2 cr	n	1		18.4
141A3320-23	JD	8A1	57	18	2 cr	n	1		16
147A3215-15	JD	992		33	2 cr	n	1		21.6
147A3211-9	JD	1EP	110	18	2 cr	n	1		32.4
147A3210-29	JD	1EP	110	12	2 off	n	1		22.4
146A3254-10	JD	1EP	110	18	2 cr	n	1		28.9
146A3204-2	JD	457	140	27	2 cr	n	1		51.2
146A3204-1	JD	457	140	28	2 cr	n	1		16
144A3522-3	JD	457	115	12	2 cr	n	1		20.1
143A3241-9	JD	992		30	2 cr	n	1		13.9
143A0061-6	JD	AVI	125	12	off	n	1		31
143A0061-3	JD	AVI		15	2 cr	n	1		16.9
143A0061-1	JD	AVI		15	2 cr	n	1		42
141A3532-8	JD	AVI	125	17	2 cr	n	1		25
141A3532-7	JD	AVI	125	15	2 cr	n	1		17.5
141A3532-5	JD	992		12	2 cr	n	1		20.4
141A3532-3	2JD	AVI	125	15	2 cr	n	1		24
141A3532-3	FD	992		15	2 cr	n	1		
141A3532-12	FD	AVI		15	2 cr	n	1		41.1
141A3532-11	FD	AVI		15	2 cr	n	1		35.8
141A3532-1	FD	AVI	125	15	2 cr	n	1		34.1
141A3340-17	FD	1OT	131	15	2 cr	n	1	56.0	26.6
141A3340-13	FD	1OT	121	15	2 cr	n	1	18.6	24.1
141A3340-1	FD	1OT	120	15	2 cr	n	1		36.2
143A3221-10	JD	427	66	18	2 cr	y	2		42.9
143A3221-9	JD	427	69	18	2 cr	y	2		34.1
143A3241-11	JD	427	108	18	2 cr	y	2		23
143A3241-13	JD	427	108	18	2 cr	y	2		80.2
143A3261-14	JD	427	66	19	2 cr	y	2		28.1
143A3261-16	JD	427	66	18	2 cr	y	2		14.5
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147A3215-2	FD	427	100	15	2 offs	y	2		33.8
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147A3210-8	FD	1EP	110	12	2 off	y	2		18.3
147A3210-32	FD	1EP	110	12	2 off	y	2		27.5
147A3210-31	FD	1EP	110	12	2 off	y	2		32.3
147A3210-30	FD	1EP	114	12	off	y	2		70.4
147A3210-23	FD	789	75	12	2 off	y	2		39.7
147A3210-14	2FD	1EP	110	12	2 off	y	2		23.2
147A3210-13	FD	1EP	110	12	2 off	y	2		20.9
147A3210-10	2FD	1EP	110	12	2 off	y	2		18.5
146A3234-11	FD	1EP	112	33	1 cr,1 off	y	2		37.5
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143A3261-18	FD	1OT	130	15	off	y	2		38.2
141A3532-6	FD	992		15	2 cr	y	2		48.8
141A3531-4	FD	AVI	125	15	2 cr	y	2		40.9
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141A3341-16	FD	427	120	18	3 off	n	3		
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147A3210-38	2FD	427	110	18	2 off,2 cr	n	3		14.5
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147A3287-8	FD	427	110	18	3 cr	n	3		27.7
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147A3211-4	FD	1OT	166	15	3 off	n	3		31.9
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147A3211-4	FD	427	90	15	3 offs	y	4		27.4
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147A3210-22	FD	1EP	110	18	3 cr	y	4	49.9	26.5
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141A3532-6	2FD	992		24	5 cr	y	4	146.5	31
141A3531-3	FD	992		24	4 cr	y	4		56
141A3531-3	FD	992		24	5 cr	y	4	54.9	61.6
141A3120-8	2FD	8A1	94	18	3 cr	y	4		10.8
In-House									
PN	**TYPE**	**Fab Hrs**	**Size**	**Feature**	**Springs**	**Complx.**	**Rework**	**TTO**	
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141A3340-19	FD	107.1	15	2 cr	n	1		24	
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143A3241-4	FD	107.8	22	2 cr	n	1			
143A3241-7	FD	116.6	22	2 cr	n	1			
143A3261-4	FD	172.6	32	2 cr	n	1		18.6	
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146A3204-7	FD	58	12	2 cr	n	1		19.9	
146A3204-8	FD	42	6	2 cr	n	1		34.3	
146A3234-12	FD	163.2	21	2 cr	n	1		19.5	
146A3234-6	FD	151	6	2 cr	n	1		16.9	
147A3211-41	FD	110.2	12	2 offs	n	1		32.6	
147A3215-11	FD	272.3	33	2 cr	n	1		44.9	
147A3215-17	2FD	231.8	12	2 off	n	1		4.6	
147A3287-10	FD	70.1	15	2 cr	n	1		31.6	
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147A3287-25	FD	88	15	2 cr	n	1		30.8	
147A3287-32	FD	57.9	15	2 cr	n	1		21.1	
147A3287-38	FD	111	15	2 cr	n	1		21.1	
147A3211-14	FD	223.4	33	2 cr	n	1		15.1	
141A3120-21	2FD	338.7	15	off	y	2		22.5	
141A3120-21	3FD	117.7	12	1 off	y	2		22.9	
143A3221-6	JD	241.2	18	2 cr	y	2		8	
143A3241-15	JD	77.1	18	2 cr	y	2		32.3	
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143A3241-4	JD	80.8	18	2 cr	y	2		26.4	
143A3241-7	JD	85.8	18	2 cr	y	2		22.5	
143A3261-12	JD	229.1	18	2 cr	y	2		9.6	
143A3261-12	2JD	395	13	2 cr	y	2		18.8	
143A3261-6	JD	172.8	19	2 cr	y	2			

143A3261-6	2JD	149.5	18	2 cr	y	2		9.5	
144A3521-1	FD	100.8	7.5	2 cr	y	2		17	
144A3521-5	FD	105.7	8	2 cr	y	2		19.6	
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144A3521-7	FD	87.8	11	2 cr	y	2		20.4	
146A3204-7	JD	243.1	12	off	y	2			
146A3234-14	JD	152.3	12	off	y	2		18.5	
146A3234-14	2JD	85.1	12	off	y	2		21.4	
146A3234-2	JD	165	12	off	y	2		31.1	
146A3234-5	JD	161.6	12	off	y	2		23.3	
146A3234-6	JD	69.1	12	off	y	2		16	
146A3254-6	JD	100.4	21	2 cr	y	2		8	
147A3211-40	JD	197.9	12	off	y	2			
147A3211-8	2FD	71	18	1 off,1 cr	y	2		35.5	
141A3340-23	FD	122.1	18	3 cr	n	3		19.1	
144A3522-1	FD	192.7	25	4 offs	n	3		75	
144A3522-3	FD	312.8	18	5 cres	n	3		42.8	
146A3234-2	FD	224.4	15	2 cr,1 off	n	3		23.3	
146A3234-4	FD	94.4	15	2 cr,1 off	n	3		13	
147A3211-6	2FD	188.8	33	6 off	n	3		27	
147A3214-6	FD	136.3	18	3 off	n	3		41.8	
147A3215-17	3FD	188.6	21	5 off	n	3		5.2	
147A3215-17	FD	196.8	18	4 off	n	3		12.5	
147A3287-14	FD	116.7	18	3 cr	n	3		31.3	
147A3287-29	FD	142.2	18	3 cr	n	3		46.1	
147A3287-40	FD	165.3	18	3 cr	n	3		19.9	
147A3287-41	FD	145.7	18	3 cr	n	3		23.2	
148A3380-5	2FD	112.3	12	2 cr(legs)	n	3		14.5	
148A3380-5	FD	167.6	12	2 cr(legs)	n	3		26.6	
141A3120-11	2FD	161.2	21	2 cr/2off	y	4			
141A3340-40	FD	172.1	21	4 cr	y	4		37.4	
143A3221-2	FD	281.1	18	3 cr	y	4		8	
143A3221-3	FD	129.5	15	3 cr	y	4		8	
147A3200-9	FD	198.6	9	1 cr(legs)	y	4		22.9	
147A3211-11	2FD	84.9	27	2 cr,2 off	y	4	209	14.7	
147A3211-11	FD	244.6	21	2 cr,1 off	y	4	36	51.8	
147A3211-12	FD	250.6	21	1 off,2 cr	y	4		112.4	
147A3211-28	2FD	255.2	30	5 off	y	4		26	
147A3211-28	FD	264.4	24	3 off,2 cr	y	4		33.8	
147A3211-3	2FD	275.3	30	5 off	y	4		36.1	
147A3211-3	FD	364.1	24	4 off	y	4		59	
147A3211-5	FD	194.2	27	5 off	y	4		34.8	
147A3211-6	FD	211.6	21	3 off	y	4		42.6	
147A3211-8	FD	163.4	18	1 off,3 cr	y	4		21.7	
147A3215-3	FD	205.1	18	3 off	y	4		23.5	
143A3241-2	FD	430.4	33	4 cr	y(die set)	5	21.7	59.7	
144A3521-8	2FD	804.3	52	2 cr/4 off	y(die set)	5		61.8	
146A3234-10	FD	201.6	33	1 cr,2 off	y(die set)	5	28.8	45	
146A3234-5	FD	299.6	44	2 cr	n(die set)	5	4.6	34	
147A3211-12	2FD	564.5	48	4 cr,2 off	y(die set)	5		61	
147A3214-8	2FD	325.6	40	2 cr	n(die set)	5			
147A3214-8	FD	43.2	40	2 cr	n(die set)	5			

147A3214-8	FD	365.8	40	2 cr	n(die set)	5				
147A3215-15	FD	347.7	44	2 cr	n(die set)	5	4.8	17.4		
148A3380-11	JD	231.4	33	2 cr	n(tapering)	5		23.7		
148A3380-6	JD	160.9	6	off	n(tapering)	5		34		

737-800 Die Package							
New-Tech							
P/N	**Type**	**Size**	**Feature**	**Springs**	**Compl.**	**M/H**	**TTO Hrs**
143A3221-20	FD	30	2 cr	n	1	140	29.1
143A3221-20	2FD	33	2 cr	n	1	140	25.5
143A3221-23	JD	12	off	n	1	90	11.5
143A3221-23	FD	33	2 cr	n	1	140	41.1
143A3261-32	JD	21	2 cr	n	1	110	39.8
143A3261-34	JD	18	2 cr	n	1	110	20
146A3204-10	JD	30	2 cr	n	1	140	19.6
146A3204-15	FD	18	2 cr	n	1	110	14
146A3204-16	FD	18	2 cr	n	1	110	2
146A3204-16	2FD	12	2 cr	n	1	95	26.3
143A3221-29	JD	12	off	y	2	90	21.4
143A3221-30	JD	15	off	y	2	105	36.8
143A3221-31	JD	12	off	y	2	95	37.8
143A3221-33	JD	12	off	y	2	95	24
143A3221-34	JD	12	off	y	2	95	46.8
143A3241-37	JD	12	off	y	2	105	20.4
143A3241-46	JD	12	off	y	2	105	21.9
143A3261-36	JD	15	off	y	2	120	23.4
146A3204-16	JD	12	off	y	2	100	72
146A3254-17	JD	21	2 cr	y	2	110	28.5
143A3221-21	FD	21	3 cr	y	4	110	48
143A3221-22	FD	18	3 cr	y	4	110	24
144A3522-5	FD	30	6 offs	y	4	130	72
144A3522-7	FD	24	3 cr	y	4	110	6
146A3204-12	FD	18	2 cr/off	y	4	120	16
146A3234-28	FD	18	2 cr/off	y	4	110	17.4
146A3254-16	FD	18	2 cr/1 off	y	4	120	25.3
146A3254-18	FD	33	3 cr/off	y	4	130	64.1
143A3241-34	FD	50	3 cr	y*	5	280	74.1
143A3241-45	FD	44	3 cr	y*	5	260	23
143A3140-16-032	2MJD	15	2 cr	n	6	120	24.2
143A3140-16-032	2MJD	15	2 cr	n	6	120	4
143A3140-16-032	MJD	15	2 cr	n	6	120	20
143A3140-16-045	2MJD	15	2 cr	n	6	120	13.1
143A3140-16-060	2MJD	15	2 cr	n	6	120	25
143A3140-16-060	2MJD	15	2 cr	n	6	120	19
146A3104-31-049	3MJD	15	2 cr	n	6	120	17.6
146A3104-31-058	3MJD	15	2 cr	n	6	120	13
146A3104-31-063	2MJD	15	2 cr	n	6	120	31.1
In-House							
P/N	**Type**	**Size**	**Features**	**Springs**	**Compl.**	**Hrs**	**TTO**
143A3261-30	2JD	12	off	n	1	80.4	17
143A3261-30	JD	12	off	n	1	104.1	18.3

143A3261-31	JD	21	2 cr	n	1	182.7	32.8
144A3521-12	FD	24	2 cr	n	1	186	19.5
144A3521-18	FD	15	2 cr	n	1	130.3	16
146A3234-20	FD	12	2 cr	n	1	129	16
146A3234-24	JD	24	2 cr	n	1	119.7	16
143A3241-39	JD	12	off	y	2	201.3	24
143A3241-41	JD	18	2 cr	y	2	217.2	25.4
143A3241-44	JD	12	off	y	2	157	44
143A3261-39	JD	15	off	y	2	178.3	54.2
144A3521-15	FD	15	2 cr	y	2	138.8	31.7
144A3521-19	3FD	18	2 cr	y	2	264.1	17.6
143A3261-28	FD	21	3 cr	y	4	143.1	14.7
143A3261-29	FD	18	3 cr	y	4	220.7	54.3
144A3521-19	2FD	21	3 off/2 cr	y	4	272	20.9
144A3521-19	FD	15	2 cr/off	y	4	277.3	19.2
143A3140-1-032	MJD	15	2 cr	n	6	182.8	16.3
143A3140-1-032	MJD	15	2 cr	n	6	196.1	33.3
143A3140-1-056	MJD	15	2 cr	n	6	173.2	18.7
144A3521-14-063	MJD	15	2 cr	n	6	128.1	31.1
144A3521-14-063	2MJD	15	2 cr	n	6	77.4	17.5
144A3521-14-063	3MJD	15	4 cr	n	6	82.8	35.1
144A3521-14-071	MJD	15	2 cr	n	6	78	22.4
146A3104-31-045	2MJD	15	2 cr	n	6	210.4	16

Appendix 3 Die Process Steps

Punch and Die Process - In-house Fabrication (conventional machining)

1) Order material to excess length to allow for band saw cuts (.25" +.25"/segments)
2) Heat treat bar stock(plus anneal if flame cuts)
3) Rough mill all 6 sides
4) Grind 3 sides square
5) Rough mill profile using wheel cutter and/or end mill (leave .007" excess for grinding)
6) Finish grind profile
7) Saw cut segments and ID
8) Mill segments to length
9) Mill and/or grind segments to joggle configuration (each segment individually)
10) Grind ends and joggle transition length
11) Drill and tap for bolts
12) Assemble with bolts

Punch and Die Process - New Tech Fabrication (Wire EDM)

1) Order material to excess length to allow for band saw cuts (.25" + .25"/segment)
2) Heat treat bar stock
3) Rough mill all 6 sides
4) Grind 3 sides square
5) Saw cut segments and ID
6) Mill segments to length
7) Wire EDM segments (All segments done at one time)
8) Grind ends and joggle transition length
9) Drill and tap for bolts
10) Assemble with bolts

.10 inch joggle					.25 inch joggle			
Distance	Joggle Ratio				Distance			
Along Part (in)	15 to 1	6 to 1	10 to 1		Along Part (in)	15 to 1	6 to 1	10 to 1
-0.0021209	-0.00200	-0.00578	-0.00368		6.23E-03	-0.01500	0.00001	0.00053
0.2507	-0.00013	-0.00346	-0.00194		0.25953	-0.00976	0.00119	0.00129
0.50419	0.00051	-0.00207	-0.00160		0.51274	-0.00543	0.00140	0.00154
0.75714	0.00056	-0.00192	-0.00116		0.76605	-0.00239	0.00210	0.00140
1.0106	0.00031	-0.00125	-0.00102		1.0194	-0.00036	0.00211	0.00115
1.2637	-0.00004	-0.00141	-0.00058		1.2728	0.00118	0.00261	0.00111
1.5172	0.00000	-0.00094	-0.00043		1.5263	0.00211	0.00212	0.00127
1.7703	0.00025	-0.00090	-0.00009		1.7799	0.00215	0.00222	0.00122
2.0238	0.00059	-0.00023	0.00005		2.0337	0.00198	0.00203	0.00108
2.2769	0.00064	-0.00049	0.00049		2.2875	0.00162	0.00253	0.00104
2.5306	0.00058	-0.00023	0.00064		2.5414	0.00156	0.00224	0.00060
2.7838	0.00004	-0.00050	0.00058		2.7954	0.00089	0.00194	0.00026
3.0375	-0.00012	0.00007	0.00052		3.0495	-0.00027	0.00115	-0.00008
3.2909	-0.00037	0.00012	0.00047		3.3038	-0.00214	0.00116	-0.00022
3.5447	-0.00063	0.00058	0.00011		3.5582	-0.00310	0.00037	-0.00026
3.7983	-0.00098	0.00011	0.00015		3.8126	-0.00387	-0.00002	-0.00010
4.0523	-0.00143	0.00017	0.00030		4.0667	-0.00513	-0.00071	-0.00004
4.306	-0.00228	-0.00051	0.00024		4.3206	-0.01090	0.00010	0.00003
4.5603	-0.00175	-0.00046	-0.00002		4.5745	-0.01946	0.00002	0.00129
4.8141	-0.00062	-0.00040	0.00042		4.8285	-0.02832	0.00313	0.00206
5.0683	0.00161	0.00079	0.00255		5.0824	-0.03669	0.00704	-0.00738
5.3217	-0.00182	0.00571	0.00677		5.3362	-0.04515	-0.00635	-0.02502
5.5755	-0.01418	0.01176	0.00095		5.5899	-0.05372	-0.04235	-0.04276
5.8288	-0.02693	-0.00795	-0.01951		5.8433	-0.06258	-0.07884	-0.05970
6.0822	-0.03948	-0.04773	-0.04235		6.0965	-0.07135	-0.10914	-0.07655
6.3349	-0.05351	-0.07529	-0.06270		6.3494	-0.08031	-0.14064	-0.09309
6.5877	-0.06735	-0.07834	-0.07499		6.6022	-0.08938	-0.17785	-0.10964
6.8407	-0.07504	-0.07695	-0.07415		6.8548	-0.09914	-0.19795	-0.12640
7.0936	-0.07340	-0.07473	-0.07232		7.107	-0.11021	-0.19645	-0.14495
7.346	-0.07057	-0.07273	-0.07048		7.359	-0.12337	-0.19495	-0.16391
7.5983	-0.06833	-0.07134	-0.06904		7.611	-0.13733	-0.19796	-0.17106
7.8506	-0.06758	-0.07078	-0.06850		7.8633	-0.14650	-0.19746	-0.16801
8.1032	-0.06733	-0.07053	-0.06885		8.1157	-0.14656	-0.19766	-0.16676
8.3557	-0.06788	-0.07100	-0.06960		8.3678	-0.14263	-0.19827	-0.16722
8.6085	-0.06832	-0.07106	-0.07016		8.6197	-0.13859	-0.19877	-0.16797
8.8613	-0.06887	-0.07153	-0.07001		8.8717	-0.13736	-0.19857	-0.16882
9.1144	-0.06911	-0.07159	-0.07007		9.1239	-0.13732	-0.19957	-0.16927
9.3673	-0.06926	-0.07216	-0.07012		9.3763	-0.13799	-0.19977	-0.16882
9.6204	-0.06931	-0.07222	-0.07018		9.6288	-0.13875	-0.20046	-0.16837
9.8734	-0.06956	-0.07259	-0.07013		9.8814	-0.13912	-0.20066	-0.16782
10.127	-0.06952	-0.07254	-0.07049		10.134	-0.13888	-0.20146	-0.16747
10.38	-0.06967	-0.07280	-0.07074		10.387	-0.13815	-0.20156	-0.16691
10.633	-0.06982	-0.07286	-0.07100		10.64	-0.13711	-0.20235	-0.16636
10.886	-0.07026	-0.07343	-0.07125		10.893	-0.13607	-0.20235	-0.16540
11.139	-0.07041	-0.07359	-0.07151		11.146	-0.13484	-0.20295	-0.16505
11.392	-0.07066	-0.07416	-0.07166		11.399	-0.13360	-0.20214	-0.16440
11.645	-0.07012	-0.07401	-0.07162		11.652	-0.13177	-0.20154	-0.16334
11.898	-0.06967	-0.07448	-0.07187		11.905	-0.12983	-0.19994	-0.16129

.25 inch joggle		10 to 1 ratio		
Distance	Hat Right Side	Hat Left Side		
Along Part (in)	Deflection (in)	Deflection (in)		
0.5	0	-0.001		
1.5	0	0		
2.5	-0.001	0		
3.5	-0.001	0.001		
4.5	-0.003	-0.005		
5.5	-0.034	-0.031		
6.5	-0.113	-0.112		
7.5	-0.199	-0.198		
8.5	-0.188	-0.187		
9.5	-0.185	-0.182		
10.5	-0.183	-0.181		
11.5	-0.182	-0.18		
12.5	-0.183	-0.18		
13.5	-0.184	-0.181		
14.5	-0.184	-0.181		
Other equilibrium deflection measurements (average between 9.5 and 13.5 in along part)				
Joggle Ratio	CMM Data (in)	Die Joggle (in)	Springback	% with .01
6	0.035	0.048	37%	9%
6	0.044	0.058	32%	9%
6	0.12	0.15	25%	17%
6	0.122	0.154	26%	18%
6	0.35	0.43	23%	20%
10	0.02	0.03	50%	0%
10	0.022	0.034	55%	9%
10	0.022	0.033	50%	5%
10	0.126	0.17	35%	27%
10	0.128	0.166	30%	22%
10	0.283	0.39	38%	34%
10	0.36	0.48	33%	31%
15	0.08	0.114	43%	30%
15	0.122	0.164	34%	26%
15	0.123	0.164	33%	25%
15	0.125	0.173	38%	30%
15	0.253	0.345	36%	32%
15	0.3	0.425	42%	38%