Building Core Competencies in Auto Body Panel Stamping Through Computer Simulation

by

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S.B. Materials Science and Engineering
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Submitted to the Department of Materials Science and Engineering
and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Materials Science and Engineering

and

Master of Science in Management

at the
Massachusetts Institute of Technology
May, 1992

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ABSTRACT

Stamping of auto body panels has historically been based on trial-and-error, artistic expertise as opposed to scientific data or analysis. The workforce of experienced die developers is decreasing, and there are few mechanisms in place to transfer or replace their expertise. Also, global competition is pressuring die manufacturing groups to reduce costs and lead-time, raise quality, and work interactively with other product and process functions.

This thesis explores how computer simulation of body panel stamping can be used to

- develop and document company expertise in draw die development
- reduce the cost and lead-time of die prove-out
- predict and verify die performance
- promote simultaneous engineering between product and process groups
- improve die quality by complementing workforce expertise with scientific analysis

Based on observations and interviews at three U.S. auto companies, one European auto company, and several stamping die suppliers, this thesis is a guide to the benefits and implementation options available for simulation programs. Many examples and case studies are included. Technical choices include specifying, building, and verifying the simulation software. For implementation, companies must define who will use the simulation, what hardware and data linkages are necessary, and how results will be used. Defining a long-term strategy and addressing cultural barriers will increase the likelihood of reaping the full rewards of process simulation programs.

By far the largest challenges to success are cultural barriers both within and between auto companies and their die suppliers. Even with the most advanced software, simulation efforts require strong information linkages, management support, and workforce cooperation, communication, and education in order to be successful.

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Acknowledgments

The author gratefully acknowledges the support and resources made available to her through the Leaders for Manufacturing Program.

I would also like to thank:

The dozens of people at my principal internship company for their enthusiasm, determination, and countless hours of conversation about their past experiences, hopes for the future, and innovative ideas. I learned much about the auto industry, auto body panel stamping, people, and life.

My advisors, Tom Eagar and Jim Utterback, for giving me the support and openness to maximize my learning and for challenging me to reach a little bit further.

Tom, Steffie, Eva, Mike, Morgan, Tony, and all the LFM fellows who each in their own way have pushed me to think and learn something over the past two years.

Larry Wilhelm, Joe Billadeau, Norman Wang, Dee MacDonald, John Hinkley, Toni Szylagi, Dick Rupli, Paulette MacDonald, and Glenn Gardner for befriending me, supporting my work, and inspiring me with their determination to reach their individual goals. Good luck.

Representatives from Chrysler Motor Corporation, Ford Motor Company, General Motors, Renault Motors, and die suppliers throughout the metropolitan Detroit and Michigan area for their valuable insight and willingness to be data points.

My entire family for reminding me of where I'm from and what I'm about.

> *Whatever you can do, or dream you can, begin it.*
> *Boldness has genius, power, and magic in it.*
> -Goethe

> *...went through a lot of changes, turned a lot of pages...*
> -R. Hodgson, R.Davies

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I.1 Organizational Learning and Auto Body Panel Stamping

The concept of "organizational learning" has appeared in progressive managerial journals as a cliché of the 1990s. But what does it really mean, and why is it important? Obviously, learning itself is not a new idea; we have all done it in school and throughout life and know that it is a natural process. Webster defines learning as knowledge or skill acquired by instruction or as modification of behavior based on experience.[1] Within the context of organizations, learning can be a much more difficult, though just as crucial, task. Certainly, individuals must learn before an organization can learn, but that alone does not guarantee organizational learning.[2] Knowledge has to be transferred between people and parts of an organization where it can be beneficial.

Effective learning in an organization depends both on how well individuals gain knowledge and how that knowledge is transferred and used. An example helps to demonstrate this relationship. In the auto industry, there are individuals who have spent decades developing and working with dies that will be used to stamp auto body panels. As a result of long-term experience, specialization, and repetition, these die developers build a highly refined intuition for how metal flows in dies. This intuitive, artistic approach has been so strong in the past that there was little need to supplement it with further analysis or a more scientific approach. What happens, though, when those learned artisans leave the company? If there is no mechanism (such as record-keeping or an apprenticeship) in place for transferring their accumulated experience, or learning, to other individuals, then the company effectively loses the individuals' learning. Such is the common predicament of some U.S. auto companies who have lost many die experts due to cost-cutting early retirement offerings and layoffs.

Why is organizational learning so important? In the above example, learning is critical because it could capture expertise that has cost many years and much trial-and-error to build. Learning curves that forecast how cycle time for jobs can be reduced over time are partly based on learning through repetition or iteration. Effective learning also keeps organizations from having to relearn fundamental lessons and allows them to avoid costly mistakes. Beyond these rewards, organizational learning is also the foundation of core competencies. Prahalad and Hamel actually define core competencies as the

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[1] Webster's New Collegiate Dictionary, G&G Merriam Co, 1981, p.649.
[2] Senge, 1990, p.139.

collective learning in an organization.[3] Meyer and Utterback frame core competencies as being either strengthened or diminished by organizational learning.[4] A core competency can be a technology or an integrated stream of technologies in manufacturing, product development, or any other functional area that is integral to a company's success. They are often skill- or expertise-based and are difficult or impossible for competitors to purchase (from outside sources) or copy over the long-term.

In auto companies, die development should be, but has not always been regarded as, a core competency.[5] Car customers demand flawless body panel surfaces and may often be more swayed by a car's appearance than by any performance variables when making a purchase. Die development helps control the quality of those surfaces and how easily they will be achieved in the stamping plant. The cost of taking stamping dies from conception to finished steel can exceed $100 million for a single car platform.[6] A significant portion of this cost is incidental and varies depending on the amount and type of engineering changes made and the difficulty of proving-out the dies in the stamping plant.[7] As a result, poor die developments often result in very costly delays and changes which must be made during die prove-out.

Due to dwindling expertise, U.S. auto companies often pay outside companies or die shops to perform die development for them (in an industry practice coined "outsourcing").[8] If an organization has not effectively learned and nurtured the expertise of die development inside, then it typically turns to outside contractors as opposed to suffering the necessary costs of slowly developing that competency. "Outsourcing" feeds on itself though and is only a short-term, lower-cost solution to core competency deficiencies.[9] "The embedded skills that give rise to the next generation of competitive products cannot be "rented in" by outsourcing... because [outsourcing] typically contributes little to building the people-embodied skills that are needed to sustain product leadership."[10]

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[3] Prahalad, 1990, p. 82.

[4] Meyer and Utterback, January, 1992.

[5] I refer the interested reader to Appendix A for an in-depth discussion of the stamping process, dies, and the auto industry product development process, as well as related terms and concepts.

[6] An estimate given by two US auto companies.

[7] Appendix A-2 discusses the impact of engineering changes and tryout on die costs and lead-time.

[8] For instance, one auto company outsourced die development for 85% of their major dies on a 1992 vehicle. Another US company outsourced as much as 95%.

[9] There are ways in which an outsourcing strategy can be used to help build a core competency, but these are still limited in effectiveness, given the US auto industry die supplier culture. Chapter 1, Section 3 discusses the supplier relationship and how it can be leveraged in an interim to build core competencies.

[10] Prahalad, p. 84.

I.2 Building and Destroying Organizational Learning

Practices such as "outsourcing" cannot replace and can sometimes prevent organizational learning. How then does a company encourage learning? Theories abound as to the answer to this question, and they largely fall into two categories. The first deals with fostering the learning of individuals, usually by creating open, trusting environments and allowing individuals to master their crafts.[11] A major barrier to this step in the die development area is with "outsourcing"; company workers must have the opportunity to develop their skills. Otherwise, die developers are basically expected to develop their intuition over time and use it effectively. Major limitations inhibit the second need of transferring or learning from that knowledge. Historically, the auto industry has been populated with many functional masters. Stable workforces, booming product markets, and minimal competition allowed U.S. auto company workers to take many years to develop specialized, functional expertise. They could then transfer that craftsmanship via multi-year apprenticeships. Also, lead-time and costs were not as constrained in previous years, and efficient information linkages to share expertise and data were not emphasized. As a result, records and other transfer mechanisms were often viewed as superfluous[12]

Some domestic companies from other industries and foreign auto companies have seemingly retained such a stable workforce and the learning environment it can create. Alternatively, they have also developed strong communication links that allow knowledge to be shared and spread in their organizations. U.S. auto companies, however, have had to adapt to other circumstances. Constant reorganizing and restructuring to cut costs and create new infrastructures have moved people in and out of organizations and constantly changed their relationships with other functions. Cost reductions have also eliminated many training and apprenticeship programs that historically facilitated continuous learning. Added to this is the push within auto companies to work with new auto body shapes, innovative geometries, and new materials with which the workforce has had no experience. Though some are now altering their strategy, U.S. auto companies' past decisions have undermined some of their traditional expertise and organizational learning processes and, hence, have hindered their ability to respond to industry evolution. Figure I.1 summarizes the circumstances that I observed have most

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[11] Senge, pp. 139-73.

[12] Even during more stable or highly-profitable times, auto companies representatives state that they did not have record-keeping measures or understand that they are necessary for continuous improvement.

contributed to the breakdown of organizational learning in U.S. auto companies, particularly in die manufacturing organizations.

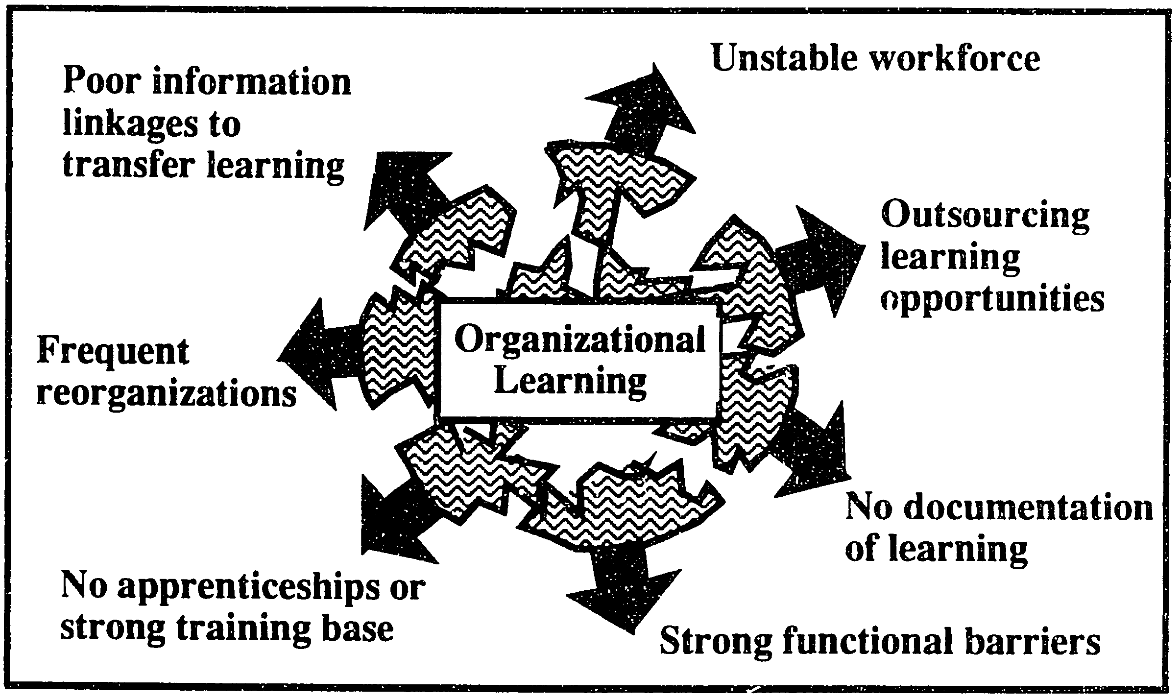

Figure I.1- A combination of many factors can contribute to the breakdown of or inability to achieve organizational learning in U.S. auto companies. In my interviews and observations, I found these seven factors most commonly preventing learning.

Given these circumstances, companies must move to strengthen organizational learning (and thereby reap its benefits) within existing organizations. There is no guarantee that workforce stability or other remnants of the U.S. auto companies' past will return, although some companies are trying to encourage such trends. Nonetheless, all are pursuing new systems that can accommodate industry changes. A more scientific approach to die development could help overcome some consequences of these shifts and facilitate continued organizational learning in the stamping die development area. One method of doing just that is through the computer simulation of stamping, specifically of the draw die operation. Draw die deformation is typically the first step of the stamping process that gives body panels their overall shape, stiffness, and strength. (For further information about draw dies, please refer to Appendix A.1)

I.3 Thesis Purpose and Organization

This thesis presents how finite element analysis (FEA)-based computer simulation of stamping can promote organizational learning (and as a result, reduce lead-time and costs) in the U.S. auto industry. Most major auto companies in the world are pursuing the development of FEA-based analysis for stamping simulation, and many conferences and technical papers have addressed the technical potential and limitations of FEA in modeling body panel stamping accurately.[13] This knowledge base, however, lacks an emphasis in several areas: the actual implementation of simulation systems, the cultural and managerial issues and barriers involved, and the progress that U.S. auto firms (as opposed to European or Asian) have made in the area. I address these issues in depth. The information, observations, and conclusions I present were gathered from over 100 informal interviews with representatives from the Big 3 U.S. auto companies, one European auto company, 2 U.S. piece part suppliers, and 8 Michigan-area die shops.

I understand that those who read this document have a wide variety of backgrounds and purposes. I assume the primary audience to be manufacturing representatives (from the auto industry and otherwise) who are interested in using process simulation packages or related computer-aided-design or -manufacturing (CAD/CAM) analyses. I especially hope to help those who, like myself, have little or no foundation in software technology and have been confused in the past with the variety and options available.

The thesis body is organized into four chapters, with three supporting appendices. Chapter 1 describes how auto companies can maximize the benefits of using simulation and use them to plan a long-term simulation strategy. Section 1.1 and 1.2 describe the implementation of simulation programs at the draw die development and product engineering stages, respectively. Section 1.3 discusses how simulation can be used to improve and leverage die supplier relationships. In Section 1.4, I use prototype tools as an analogy for stressing that in order for simulation (or any other analysis) to be useful, proper information linkages must be set up to disseminate and use generated simulation results.

Chapter 2 focuses on the organizational and cultural barriers that can hinder or even prevent the successful implementation of simulation programs. Section 2.1 describes workforce reactions to new business practices, analytical or computer tools, and

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[13] For those interested in more technical information about sheet metal forming models, I suggest conference proceedings, such as NUMIFORM, Detroit, MI, 1986 and 1989, ICTP3, 1990, and VDI Berichte 1991. (Bibliography gives full citations.)

how management can address them. Section 2.2 continues with issues surrounding the perception of simulation or any computer simulation as miracle tools. Following, I summarize some crucial roles of management in Section 2.3. Section 2.4 picks up from Section 1.2, and I discuss how inter-company functional barriers must be overcome to use simulation across function. Section 2.5 draws from Section 1.3 and is a representation of traditional company-supplier relationships. I have included relevant comments about cultural issues throughout the text, not just in Chapter 2.

Implementation and logistics options and questions are the focus of Chapter 3. The basic technical choices involved in designing simulation algorithms are discussed in Section 3.1. In Section 3.2, I discuss how hardware options and CAD data linkages affect the efficiency of simulation. Section 3.3 presents some issues to consider when deciding whether experts or trained company engineers should run simulations. Finally, Section 3.4 describes the necessity and process of validating and continuously improving the accuracy of simulation codes.

Chapter 4 follows with a short presentation of conclusions and recommendations. My findings are not tailored to particular companies because each organization I observed has different principal problems and barriers to address. As a result, each reader may want to take a different path through the thesis. In particular, Appendix A is an introduction to auto body panel stamping and product/process development. Appendix B reviews (in lay terms) the fundamentals of finite element analysis. Appendix C is a discussion of the advantages of choosing either commercially or internally developed simulation programs.

Chapter 1

Getting the Most from Stamping Simulations

By replacing physical repetitions with predictive analysis and supplementing long-term experience with scientific data, stamping simulation can encourage organizational learning and long-term expertise. I have already introduced the importance of and motivations for organizational learning, but how are learning and expertise realized through simulations? I discovered through interviews with auto companies and their die suppliers that companies are using simulation to reap a wide range of benefits. In this chapter, I present how simulation can provide measurable benefits and how each of them can facilitate organizational learning.

In this chapter (Sections 1.1 and 1.2), I discuss the rewards of using simulation software at the die development stage and at the product engineering stage of auto body development, respectively. The models used and potential rewards of simulation at the two stages differ extensively even though the software may be identical. In Section 1.3, I discuss how simulation can be used in supplier relationships when auto companies "outsource" die development. Section 1.4 addresses the topic of making optimal use of the information that simulations (and other analyses) generate.

Drawing from all the potential benefits discussed below as well as others, simulation software developers need to form a long-term implementation strategy. Many people I interviewed complained about their management's resistance to investing in a long-term technology. From my discussions with some of those managers, I learned that often they were unaware of the extensive, possible benefits of using simulation and that they had no coherent strategy for reaping those benefits over time. This section describes many rewards that can be part of a strategy to implement simulation. Such a strategy will help both management and the die/stamping workforce to understand how and why simulation can be an asset.

1.1: Simulation for Die Development

Draw die developers have the task of designing the surfaces and binding mechanisms of the draw die that will be used to form body panels from metal sheets. Typically, draw die developers start their tasks after Product Engineering has defined most of the geometry and details of the body panels. Using CAD or manual data, developers define the die addenda surfaces, binder rings, draw beads, and other drawing surfaces that will be used to form the panels.[14] Expertise goes into these developments, but their performance is historically not analyzed until soft (prototype) tools are made, or even later when hard tools are manufactured and taken to the stamping plant for tryout. Prototype tools can cost more than $100,000 each depending on the size of the part, and time spent for such iteration adds to the lead-time critical path. Final tryout in the stamping plant may take from several weeks to a year depending on the extent of any formability problems.

Using simulation to analyze formability at the draw die development stage of process development is by far the most common use I observed. There are a number of benefits of using simulation to supplement the expertise of draw die developers that can counter the complexities and limitations of the traditional die analysis procedures mentioned above. Tryout expenses and lead-time can be reduced and budgeted more accurately. Simulation can be used as a training tool for new draw die developers to learn about formability. Furthermore, simulation records form a basis for documentation and a database of draw die and formability expertise. Also, simulation results are the foundation of more advanced computer analyses such as expert systems which in the future will be able to automatically design and optimize draw die developments on the basis of performance data and scientific analyses. The sections below describe these benefits in more detail.

Tryout expense and lead-time savings. Finite element simulation allows the draw die developer to test a development without the expense or time delay of physical tools. Simulation can change a mostly trial-and-error-based methodology to a predictive one. A developer can build up the die development on a CAD file, analyze it with FEA, and change parameters to optimize the die development right on the screen. Figure 1.1 shows the information flow chart that draw die developers can use to analyze die developments. One analysis iteration may take anywhere from two minutes to several hours.[15] This "on-screen tryout" lets the developer run "what-if" scenarios to test how robust his development is to variations in punch force, binder force, friction, and other dynamic variables of stamping. Simulations can be run to see the metal deformation that occurs at different punch increments, from initial binder clamping to a fully closed die. It is also

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[14] If you are not familiar with draw die manufacture, you may want to refer to Appendix A.1 where I discuss draw dies and their development components in detail.

[15] Analysis time depends on many factors including the size or detail of the part being modeled, the type of computer hardware used, whether the analysis is two- or three-dimensional, logistical delays in a particular company, and the efficiency of the particular FEA algorithm. See Chapter 3.

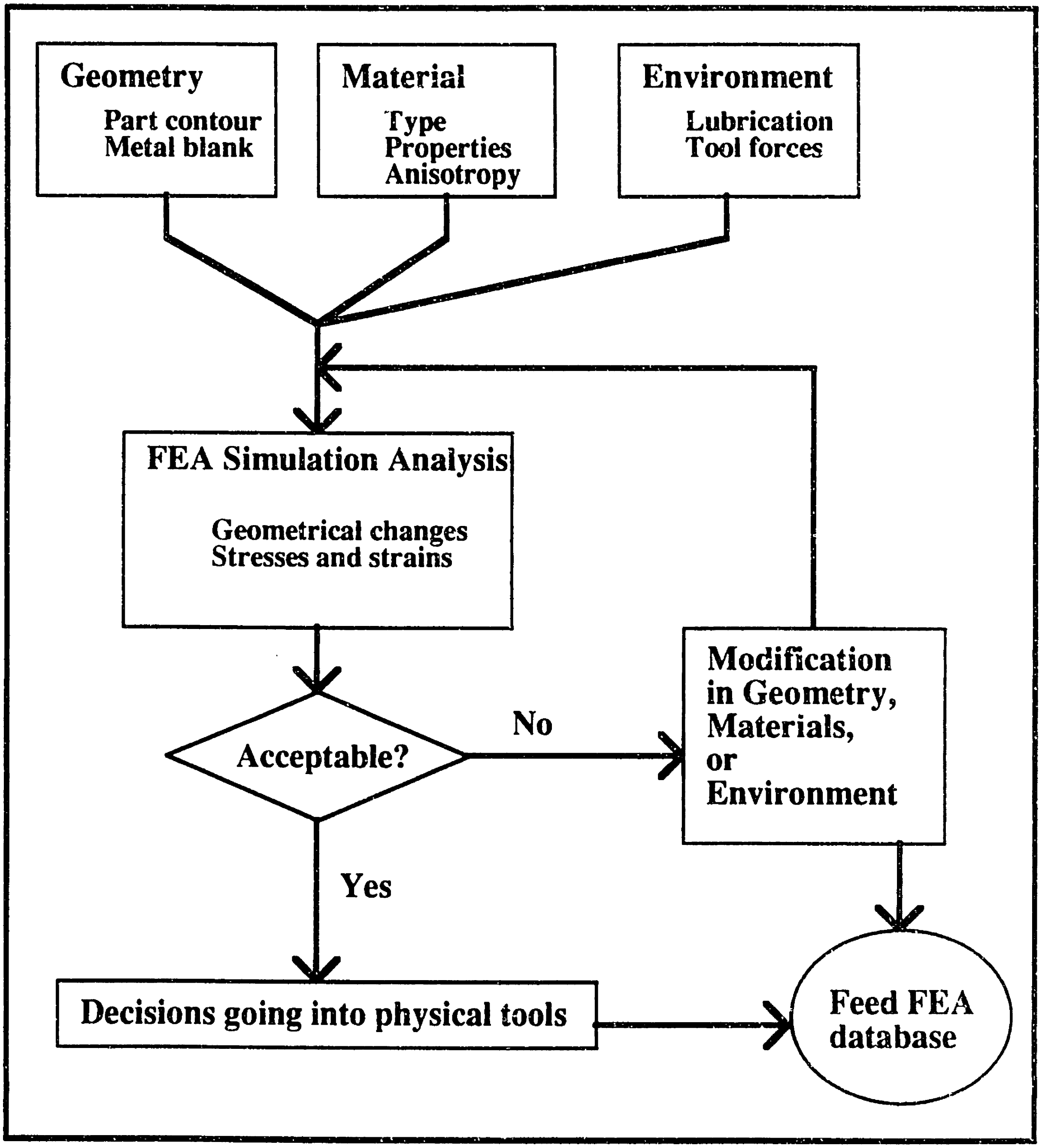

Figure 1.1- This flow chart shows the information input and output of finite element simulation programs. Draw die developers can use the analysis to determine whether their developments will produce panels of acceptable quality before testing them with physical tools. Information generated from analyses could feed a database of formability experience for use in building die development expertise.

possible to animate simulation results so that developers can see where in the stamping process surface defects occur and solve the problems systematically. Figure 1.2 shows some representative simulations of a metal blank drawn into a quarter panel.[16]

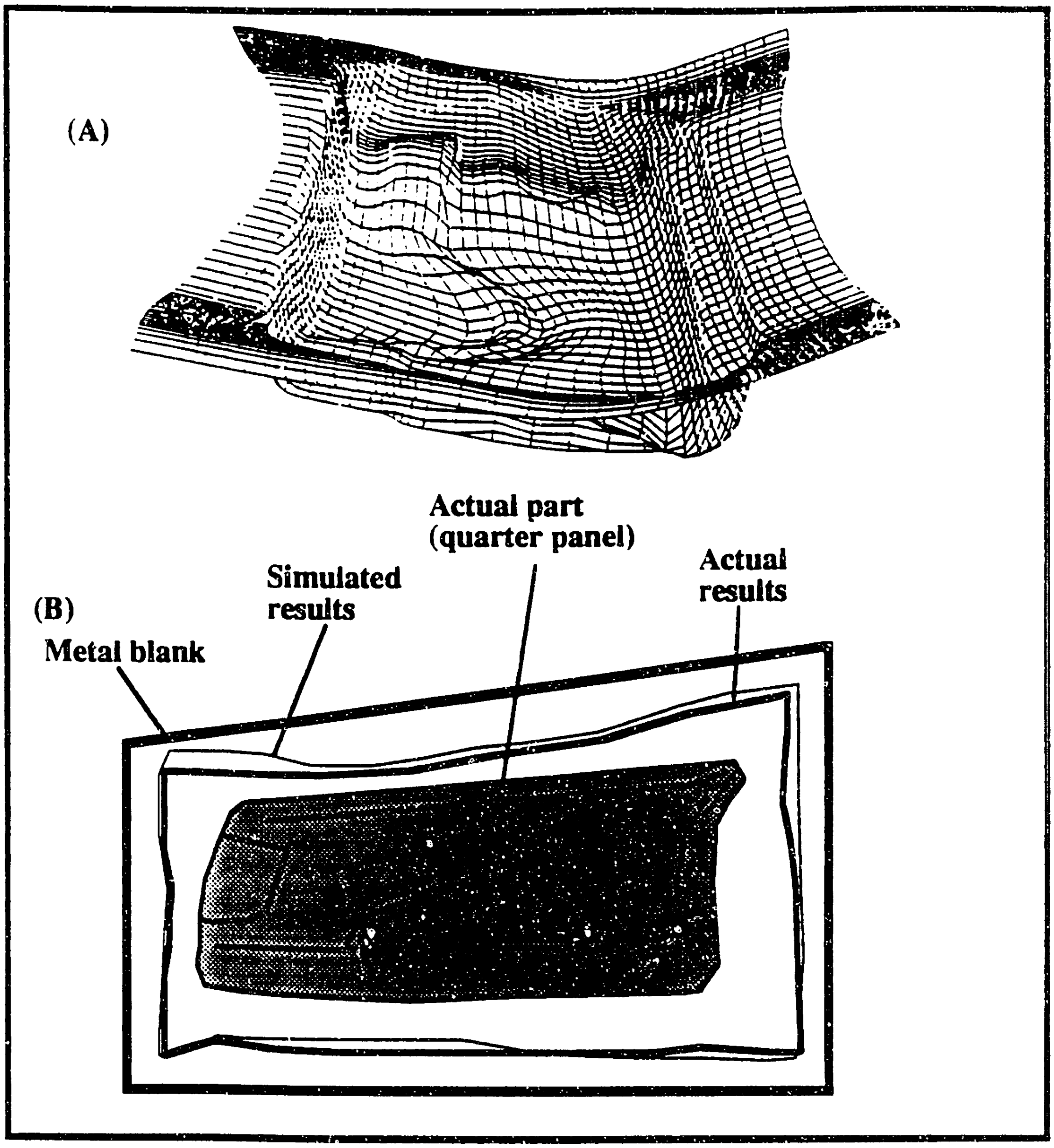

Figure 1.2- These figures show two of many types of possible simulation output. The three-dimensional figure (A) would be accompanied by color graphics indicating metal thickness, stress, or displacement. Such results help developers focus on problem forming areas such as wrinkles or splits. The two-dimensional results (B) show the simulated metal blank draw-in during stamping. This type of information helps developers minimize scrap material produced during stamping. Experimental results superimposed on the actual results help indicate simulation accuracy.

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[16] Grober and Gruber, 1991, p.598.

"Given a fully operational CAD/CAM system, no models or soft tooling should be required; most proving will have already been accomplished via detailed computer model testing. Any prototypes that might be made would be used more as design verification devices, rather than as first stabs at models requiring refinements."[17] Finite element analysis is able to predict a number of formability problems such as metal wrinkling and splitting due to uneven metal flow in the die. Programs currently available, however, are not able to diagnose all the forming problems that appear during final die tryout. The accuracy and detail level of simulations cannot catch such phenomena as the formation of "low spots".[18] Hence, soft tools may still be necessary in the die prove-out process. Program developers and die development managers were split in opinion as to the potential of FEA simulations eventually replacing soft tools. Most view simulation as an opportunity to analyze several development options; then, soft tools can be used to verify the most promising or robust development. All agreed, however, that it is important to use prototype or soft tools to help verify simulation accuracy and gain credibility for the computer simulation among cynics in the organization.[19]

Proactive tryout scheduling. Due to the difficulty of predicting all potential forming problems using FEA or any other analysis, there will be problems that FEA cannot detect. There will also be stubborn phenomena such as wrinkling that a developer cannot remove through what-if scenarios and a series of FEA simulations. In such cases, changing many different variables in simulations still leaves a die that has unsolved formability problems. Hence, some final die tryout will always be necessary to refine dies until acceptable panels can be produced. However, by diagnosing expected difficulties, FEA allows developers to alert a stamping plant to anticipate extra tryout time and thereby avoid costly delays. For example, in the case of a hood outer panel, a developer tried five different iterations of binder design to remove wrinkles that simulation showed as likely to form near the hood edges. Though his attempts failed to rectify the problem, the developer contacted the stamping plant who would be receiving the die and relayed the potential problem. The stamping plant was able to schedule extra tryout time (which was needed), request extra tryout funding quickly, and avoid costly overtime and logistical delays.

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[17] "Toward World Class Manufacture of Automotive Bodies," 1988, Appendix C, p.3.

[18] An industry term for shallow dents that may be less than a millimeter out of tolerance, yet they are very visible as defects when high gloss paints is applied to the sheet metal.

[19] Chapter 2 discusses cultural issues such as gaining credibility for simulation programs and replacing physical tools with computer tools.

Training tool. Based on my industry observations, I think the opportunity to use FEA simulation as a training tool is one of the best benefits. Ideally, all developers would have direct experience with die tryout and a developed intuition with regard to metal formability. However, I discovered they may actually have little or no experience with dies, much less tryout or stamping plant experience. Hence, their expertise is gained slowly and through much trial-and-error. Many auto companies no longer have apprenticeship or training procedures in place and are looking for low-cost training mechanisms that require the least manpower. With simulation, developers can start to learn how certain variables and combinations of variables affect body panel quality. Since the output of FEA simulation shows numerical values of expected stress and strain, developers can also learn to correlate the results they observe and their intuition with engineering phenomena.

One piece-part supplier I interviewed is using simulation programs successfully to train new stamping department staff (die developers, designers, or maker and stamping line operators). Before these people start working with dies directly, they spend time simulating very simple but practical part geometries and understanding how dies affect their formability. They are also introduced to such deformation concepts as stress, strain, plastic flow, and springback and how they occur systematically during stamping. When the workers go to the shop floor, they can then correlate the stamping conditions they observe with basic engineering intuition. Such scientific training has not been part of historical training programs, and as a result, many people are intimidated by engineering data and scientific analyses such as simulation. Workers trained with simulation can learn to integrate their experience with physical tools and scientific analyses from the beginning, instead of developing dispositions opposed to computer analyses. Such experience is also likely to train better die developers (or die designers or die makers) who can rely not so much on "rules of thumb" but on experimentally-proven scientific principles and data.

Record-keeping and documentation. As I mentioned in the Introduction, in the past draw die developers and other stamping personnel have not concentrated on record-keeping. With the current industry changes, however, record-keeping and documentation as mechanisms for building expertise have become necessary for long-term success. One of the weaknesses I observed in my research is lack of record-keeping in (and general lack of communication between) the die development and final die tryout stages. Without the data to correlate die development and tryout results, developers do not learn how their developments fared in tryout. What changes were necessary in tryout that might have avoided or anticipated? Without this information, developers are likely to continue to make the same mistakes and fail to refine their intuition and die development skills

By virtue of being a computer analysis, finite element analysis simulation is ideal for record-keeping. Each simulation trial, whether a success or failure, can be saved as a computer file and referenced in the future. Computer files have advantages over other record-keeping means (such as drawings or photographs of dies); they do not degrade over time, are not prone to loss, and have quantitative as well as qualitative data readily available. They do require that operators be trained to access and manipulate computer files, but such training is also necessary to perform FEA simulations. As a developer works with different examples of similar parts (for example, a series of fenders for different car models over five years), he can add information from simulations about how to develop robust dies to a centralized database.[20] Referencing such a database, a developer can design dies for future parts quickly, even those with which he has limited experience.

Moving toward expert systems. A database is required to develop expert systems that can automatically generate the surfaces and features of draw die developments. Information about similarities between parts and correlated data (between simulations and actual performance) would aid the development of an automated design system for die development. Much near-term research will likely focus on developing such expert systems and knowledge-based CAD systems for die development.[21] These systems are programmed to automatically generate optimal binder surfaces, die addenda, and other draw die features. Most expert systems use historical cause-and-effect trends between features and draw die performance and on engineering analysis such as FEA to make design decisions. As computer analysis programs become more popular, many companies are also trying to maximize their design functions with the use of integrated CAD/CAM/CAE (computer-aided design, manufacturing, and engineering) systems.[22]

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[20] Ideally, this database of information would contain, in addition to FEA simulation results, data from soft and hard tool tryout as well as the stamping production line. What formability problems can a developer anticipate for a certain part type? What refinement is usually required at soft and hard tool tryout, and how can the developer avoid it? How robustly have dies of such parts performed in the stamping production environment? Armed with such information, a developer can make the best attempt at developing a robust draw die, even with minimal personal experience.

[21] Bull and Morrison, 1991.

[22] For more information about CAD/CAM linkages, please see Chapter 3, Section 3.

Using finite element simulations at the draw die development stage of auto product development is the most common implementation point for U.S. auto companies and the one on which all three are focusing currently. The potential benefits cited above of using simulation to supplement long-term expertise with predictive, scientific analysis can encourage organizational learning along many paths, as well as generating cost and lead-time savings. Each company I studied is pursuing simulation for a different combination of the above benefits, but I think none of them realizes the potential for them all. Planning a strategy for simulation that includes a plan for incorporating these benefits, as well as others, will help to convince management to invest in and support simulation development. A strategy will also help any involved workers to understand how simulation will complement or change their traditional business procedures.[23]

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[23] Chapter 2 explains a variety of cultural barriers to simulation implementation, including the lack of workforce understanding of the role of simulation and how they can be a part of simulation capability development or usage.

1.2: Simulation for Product Design and Engineering

The rewards to be reaped by using simulation at the die development stage, as shown in the previous section, are substantial. The potential for increasing organizational learning is even higher when simulation is implemented at the product design and engineering stage.[24] The principle advantage of using stamping simulation during product design and engineering is time. In the same way that using die simulation and analysis at the draw die development stage occurs before tryout and is therefore predictive about formability, simulation as part of product design and engineering can occur even earlier and be much more effective in making parts manufacturable. As opposed to making dies robust to produce a well-defined part, simulation during product design and engineering occurs before part specifications are solidified, and engineers can address formability problems and stamping robustness by altering part surfaces and features. With this flexibility, the odds of solving formability problems is substantially higher than when only die variables can be changed.

In this chapter I discuss how simulation can be used to develop simultaneous engineering between manufacturing and product design groups and the benefits that can result. Interviews with auto company representatives uncovered a number of benefits from using simulation at the product design and engineering stage of development. Unfortunately, only one of the U.S. auto companies is focused on this stage of implementation, but the rewards go beyond those achievable by using simulation strictly for draw die development (see section 1.1) and can result in longer-term learning and cost reductions. As a result of earlier interaction between product and manufacturing groups through simulation and considering manufacturability earlier in product development , engineering change cost and frequency can be reduced. For longer-term improvement in manufacturability, simulation results can be used to develop general, quantitative design guidelines that product groups can use to make tradeoffs between formability and product design. Simulation is also useful for analyzing the feasibility of using new part materials and manufacturing processes before resources are committed to un-investigated ideas with which the company has little or no experience. The sections below describe these gains more fully.

Facilitating simultaneous engineering. All three U.S. auto companies are expanding efforts and changing their business structures to facilitate simultaneous or

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[24] Appendix A.2 explains how information flows through different stages in the overall auto product development process.

concurrent engineering. Such organizations bring together Product Design and Engineering, Manufacturing, and other functions to work interactively. The goal is to bring a car to market through cross-functional team effort, as opposed to the traditional series of functional hand-offs.[25] However, "manufacturability must not dominate design decisions; rather it must be carefully balanced with design quality issues...."[26] Reaching this delicate balance in decision-making can be difficult, and there are often many cultural barriers to such groups working together. If, however, they can be lowered, then tools such as FEA simulation can be an element of a company's simultaneous engineering strategy.

Finite element simulation can be used to evaluate the feasibility of manufacturing an auto part. Simulations can be run with very little part geometry information to determine potential formability problems. By running designed experiments (or "what-if" scenarios) with various options in part geometry or material types, a product engineer can optimize a part design within styling, engineering, materials, and manufacturing constraints.[27] Such parametric studies show the user how interdependent operations interact at different values. Simulation also generates quantitative and visual data that can help unfamiliar personnel understand and learn how design affects stamping better than just verbal communication or descriptions.

These analyses could be run by a manufacturing support group, or the software could be directly accessible from the product engineer's CAD workstation. Many auto industry software developers stress the need to train engineers to use and interpret FEA analyses themselves.[28] To provide motivation for product engineers, several U.S. auto industry representatives also mentioned the importance of educating product engineers about the real costs of stamping hard-to-form panels. Panels with poor formability do not just create more frustration for stamping groups. Extra dies or excessive die tryout may be required, or it may be impossible to make robust dies for the parts. Manufacturing groups desire dies that are as robust as possible, meaning they are insensitive to changes in operating conditions and are able to make high quality parts over a wide range of variables, such as press tonnage. One U.S. auto company is furthering their simultaneous

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[25] For readers interested in simultaneous engineering efforts in the auto industry, I recommend Womack et al, 1990 and Clark and Fujimoto, 1991.

[26] Clark and Fujimoto, 1991, p.240.

[27] For example, all stamping and die manufacturing personnel I spoke with said that part areas with small radii and deep draws, such as on an inner door panel, create the most difficult forming conditions. A product engineer could run stamping simulations with several different radii or depths of draw to determine which is most likely to be stamped without wrinkling over the largest variation in punch force (press tonnage) and other operating variables.

[28] Anderheggen, 1991, p.233.

engineering via simulation effort by having die engineers access product data much earlier than before and perform computer feasibility analyses from menu-driven software. Regardless of whether manufacturing or product engineering personnel run analyses, representatives emphasize the importance of making manufacturability part of the product engineering group's goals and making the first analysis as early in the product development timeline as possible.[29]

Another possible implementation point for stamping simulations within product engineering is with the structures analysis group, or whatever organization is responsible for determining the structural integrity of a vehicle design and whether it conforms with impact safety standards. These groups typically use some type of finite element analysis simulations for crash test analysis.[30] Coordinated efforts to integrate simulations could be beneficial for both groups. For example, one U.S. auto company die development group is trying to provide simulation data about the expected metal strain caused in outer panels during stamping for use in more accurate crash-worthiness analysis. In exchange for that information, the die development group has access to product data earlier and is able to participate in material and part design decisions indirectly to minimize potential formability problems.

Regardless of the stage of implementation, simulation can be used to isolate formability problems earlier than they are found using physical tool verification or even simulation at the draw die development stage. The effect of this simultaneous engineering can be compressed development time (and hence, less overall auto lead-time). Product and die engineers could effectively overlap their tasks, share information, and reduce the number of late engineering changes made to increase formability.

Reducing engineering change cost. Engineering changes are necessary for refining the quality of an auto, but they can be a very expensive component of auto product development.[31] At one U.S. auto company, engineering changes represented from 8% to over 30% of the total investment in dies and tooling for four different car

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[29] Some respondents touted the potential of using simulation as far back in product development as the styling/conceptual stage where the first clay models of the vehicle are manipulated and approved. It is important to implement the simulation at a point where there is enough product data to justify analysis expense. For instance, if outer panel forming problems are targeted for analysis, then the styling stage is a logical analysis point. Inner panels (a major source of formability problems), however, are not defined until further into product design and engineering. From interviews, most representatives said the greatest formability problems occurred in inner panels and in the details of outer panels, geometries that are not defined until after initial Styling reviews.

[30] Miles, 1991, p.1.

[31] In Appendix A.2 I describe in detail the role of engineering changes in product development.

platforms.[32] The total cost attributable to engineering cost is often hard to track, and the cost of rebuilding a die is only one component.[33] The later that engineering changes are implemented, the more likely it is that die construction has begun and expensive metal rework will be required. Sometimes, extremely late draw die changes may require the construction of entirely new dies, or possibly the addition of an expensive reinforcement or change in material.

Simulation cannot eliminate manufacturing (or process)-driven engineering changes, but it could reduce their cost and frequency. For example, one U.S. auto company was unable to predict metal forming problems for an outer door panel. During later physical tool verification, there was a recurring problem with insufficient metal stretching in the draw die. To solve the problem, the appropriate engineering change would have required a very expensive draw die modification. Instead, a heavier, more expensive metal was used for the doors, and an additional reinforcement was added underneath the panel to strengthen the door. Simulation may have predicted the insufficient level of strain expected, and before physical tools were purchased, draw die developers and product engineers could have worked together to make the necessary design changes.

If simulation analysis is used at the product design or engineering stage to predict forming problems, then product engineers can initiate proper engineering changes sooner, when they are less expensive and disruptive to product or die development. One U.S. auto representative estimated that 90% of manufacturing-driven engineering changes (ones that affect part formability) could be eliminated through use of simulation for product design and engineering, which at that company would save approximately $3 million.

Creating Design Guidelines. One U.S. auto company is using simulation programs to create design guidelines that correlate certain part geometries with potential forming problems. Figure 1.3 shows a channel similar to one that would be found in an auto rail component.[34] By running a series of designed experiments with different values for the channel angles and widths and materials, a company can develop a set of quantitative guidelines that product engineers can use to consider manufacturing tradeoffs as they designs parts.

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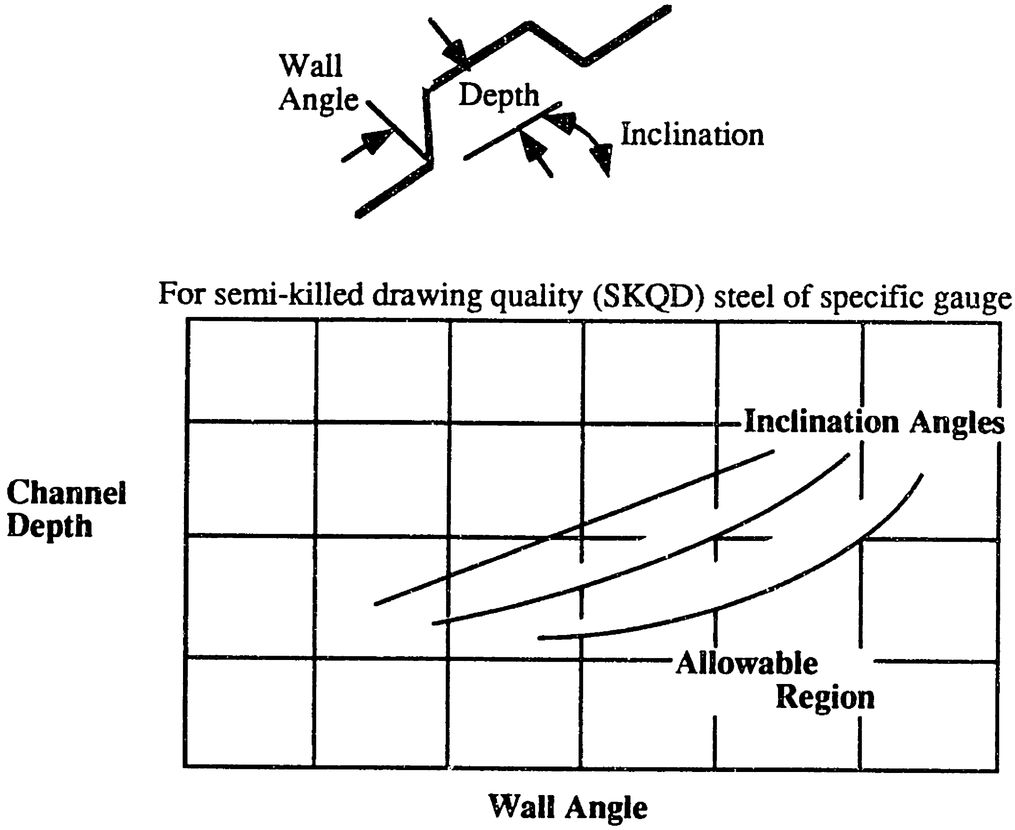
[32] Roodvoets, 1991, p. 49; see also, Clark and Fujimoto, 1991, p.187.

[33] In his 1991 thesis, Roodvoets also discusses how the real costs of engineering changes are much higher than what is reported and usually do not include such elements as transaction costs and duplicate engineering and design effort which can be significant.

[34] Dr. Norman Wang, Chrysler Corporation, Detroit, Michigan.



Sample **design guidelines** for long channels, such as are found in automobile rails, are shown in the graph. This information correlates three design parameters (wall angle, forming inclination angle, and channel depth) for a given material (which will have an associated cost.) Outside the allowable region, combinations of variables are likely to cause formability problems. Simulation programs can generate this type of data quickly for many variables and values.

Figure 1.3- Simulation programs can be used to generate generic design guidelines that can help product engineers consider manufacturability as a product design tradeoff. The example above is an example of a recurring geometry in auto body design whose design guidelines will be applicable over many car models.

Manufacturing groups in all three U.S. auto companies have representatives who provide suggestions (in various formats) to product designers and engineers about how to make parts that will be easier or cheaper for the company to manufacture. Many product engineers complain that formability advice from manufacturing groups is often difficult to follow because it is too limiting, is only qualitative, or differs with every car model.[35] Design guidelines from simulation can take into account many different variables and can be general enough as to be applicable over a wide range of parts and part styling. With these rules, product engineers can innovate and use combinations of geometries or materials that are less likely to cause formability problems. One U.S. auto company representative said he found product engineers very receptive to simulation-generated guidelines especially because they were transferable from car model to model.

Experimenting with new materials and processes. As the pressure mounts for automobiles to be more fuel-efficient, lower total auto weight becomes a more crucial measure of good auto engineering. Many car companies are experimenting with plastics, composites, and new sheet metal grades and gauges to achieve auto bodies that are both light, inexpensive, and easy to manufacture. Most auto bodies have historically been made of sheet steel, and as a result, die engineers have little experience or expertise with the forming behavior of other materials.

A simulation program can be used to evaluate the formability of any sheet material as long as certain engineering characteristics are known.[36] Much like the design guidelines mentioned above, simulation programs can run designed experiments that test which of a variety of material types or gauges can be used to make a certain part most robustly (or with the least probability of encountering forming problems). Due to a lack of experience, this is knowledge that the established workforce cannot provide.

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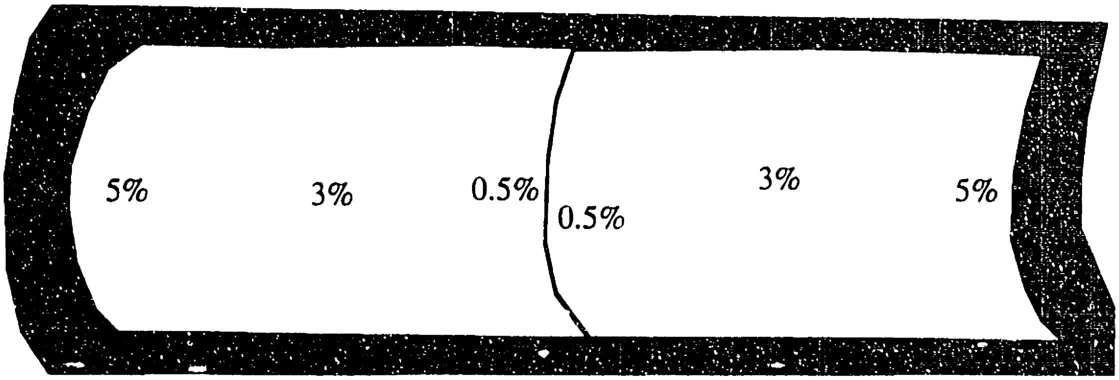
[35] In Chapter 2, Section 4, I discuss more of how a negative relationship between functional groups (here, manufacturing and product engineering) hinders such simultaneous engineering efforts as using stamping simulation.

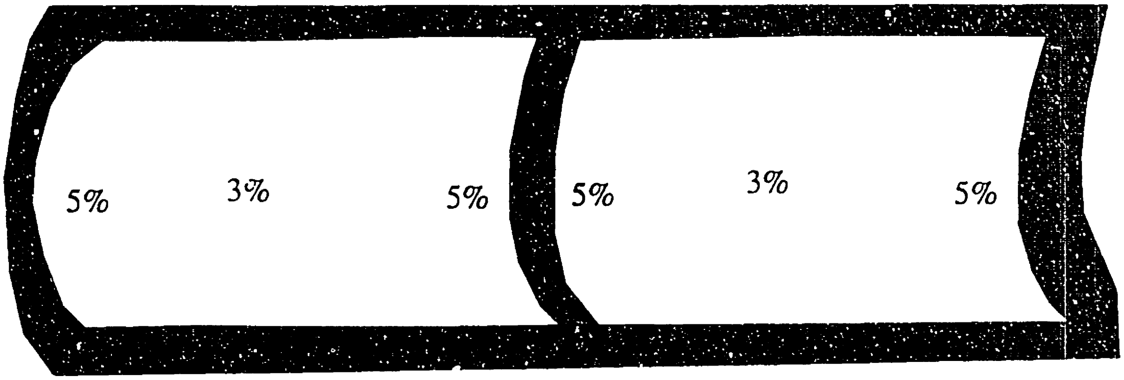
[36] The information required depends on the material models used within the particular simulation program. They usually include effective thickness, strength and modulus parameters, and material anisotropy coefficients.

In addition to new materials, companies are trying to use innovative die configurations for forming body panels with fewer dies, less maintenance, and less engineered-in scrap material. Similar to experimenting with new materials, simulation can predict formability problems inherent in stamping configurations that a company has never tried before. As a simple example, several auto companies have tried stamping out nested or connected parts from a single metal blank . Figure 1.4 shows a schematic drawing of two doors (front and rear) which were produced connected and from a single die set, as opposed to two in the traditional process. Die developers found during soft tool tryout that the die development shown (A) caused insufficient metal stretch in the center of the panel to give the doors the required stiffness. Discouraged by the prospect of paying and waiting for multiple soft tool trials, the company gave up and returned to the traditional stamping process (which was more expensive). Later, another company proved that the connected configuration was feasible, but only if the die development were modified with an additional binder surface (development B). A simulation program could have tested a number of different die developments at minimal cost and may have kept die developers from returning to the old process.

Development A:



Development B:



☐ **-Door die surfaces** ■ **-Die binder surfaces**

Drawings A and B are two schematic die developments for forming a joined front-and-back-door body panel as opposed to the traditionally separate doors. Forming two panels together can save scrap material costs and requires fewer dies for stamping.

Simulation is able to predict the strain levels achievable in each die. Results would show that development A forms doors of inadequate strain in the center of the panels to meet safety and structural specifications. Due to the extra section of binder, development B allows greater stretching and control of metal flow in the draw die.

Figure 1.4- This figure shows how simulation can be used to evaluate new drawing configurations with which auto companies have no experience. (The strain values shown in the figure are for illustration purposes only.)

1.3: Improving the Supplier Relationship

As was mentioned in the Introduction, "outsourcing" is a business practice that many managers in U.S. auto companies know is inherently counterproductive to developing core competencies in die development. Because of cash problems, insufficient internal expertise, and a short-term focus, however, they each continue (to varying degrees) to pay outside vendors to develop dies for large body panels. It is indeed unrealistic to expect companies to be able to develop internal die development expertise immediately if there is a lack of experienced individuals in the organization. By effectively learning from the expertise of outside suppliers, however, auto companies could contribute to their own knowledge base.

Supplier relationships are not inherently negative or unproductive. However, in the U.S. auto industry, supplier relationships often exhibit arms-length communication and interaction where the two parties behave as adversaries.[37] Information exchange is limited to dollars and specifications, and as a result, little learning happens across company barriers. There is also little reciprocal commitment and risk taken on by the auto companies and suppliers. At two U.S. auto companies, representatives complained about the use of outside suppliers for die development. Because suppliers leverage their die expertise in development contracts, they may charge high rates and take longer to finish development work than is necessary. The supplier's accumulated expertise becomes his competitive edge. Suppliers may also view engineering changes as profit-making opportunities and benefit from U.S. auto companies' lack of discipline or cooperation. At one U.S. auto company, there were no records of die developments done by outside firms. In several cases, if I wanted to see a physical model of the development or a sample part, I would have to go to the supplier, and some suppliers did not keep any records at all. If U.S. companies make a policy of getting data from soft and hard die tryout at outside suppliers, they can add information to a die database from which new draw die developers can learn as they build expertise. Observing die tryout sessions and other development efforts can also allow auto company personnel to learn from suppliers.

Simulation could provide mutual benefits to the outside supplier and the auto company. Even with their high expertise level, die suppliers rely heavily on trial tools to verify die performance. If die suppliers were to sit down with auto company die personnel and run simulations on prospective die development, the cost and time of development could be reduced to the benefit of both parties. Furthermore, both

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[37] Clark and Fujimoto, 1991, p.138.

individuals would be able to expand their die intuition. The goal of supplier partnerships should not just be to pay-for-service but to internalize as much as possible the partner's skills.[38] With skill-building as a goal, outsourcing could feasibly contribute to core competency building for a limited time period.

Two U.S. auto companies are actively trying to define the business agreement under which die suppliers can use their proprietary software for stamping simulations. Neither wants to sell the technology to suppliers; instead, they want to create a partnership whereby the supplier can use the simulation for development jobs only from the source company. Both companies stressed the need to answer several strategic questions: Who will pay for the simulation service?, Who will be held responsible for the ultimate performance of the die?, Will auto company personnel run the analyses, or Will we train supplier personnel?, How do we motivate the suppliers to supplement their long-term experience with such a tool?, and Will the suppliers have to change developments they feel are adequate but that the simulation indicates could create surface defects or low quality?. In effect, these questions largely revolve around who retains control and responsibility for the die development in such a partnership. They also inherently favor longer-term, more trusting and interactive supplier relationships. Because this type of relationship is different from the traditional business deal between auto companies and suppliers, these questions are proving difficult to answer. At least one company warned against letting the novelty of these questions bar the eventual implementation of such a system. Leasing or selling software to suppliers is perhaps easier to accomplish than working interactively, but the rewards to the company with regard to learning and reduced lead-time and costs are likely to be much less.

I interviewed managers from eight die suppliers, some that specialize in die development and others that offer it as a service in a large line of die manufacturing services. None of them have internal FEA simulation capabilities; some have heard of the technology while others have not. One supplier is using geometric simulation CAD tools which have limited accuracy and rely much more heavily on operator interpretation and experience.[39] In general, die suppliers think the costs of developing or purchasing such computer software (especially FEA tools) is beyond their investment capability. Nonetheless, supplier representatives are unanimously intrigued by the notion of computer simulation and are interested in experimenting with it if their customer auto companies provide the software.

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[38] Prahalad, 1990, p.85.

[39] See Appendix B.3 for a brief discussion of how geometric and FEA simulations differ.

With regard to actively using simulation as a part of draw die development, suppliers express a number of concerns. Three suppliers focus on the additional cost of such a service, and at least one said he would be unwilling to use it if his firm was charged directly for it. By far, the greatest supplier reservation is the accuracy of such a computer simulation. Several suppliers are also wary of the time commitment that would be required to interact with auto company die personnel. One supplier manager stated bluntly that his workforce would likely not be interested in tools that helped reduce die development lead-time because it would detract from the flexibility and overtime to which they were accustomed. Another observation I made was that suppliers who avidly use CAD systems as opposed to manual drawings for translating body panel data are visibly less anxious about using a computer analysis tool.

One auto company also noted previous negative experiences with trying to encourage the suppliers to use the simulation without thoroughly educating them about the theory and verified accuracy level of the software.[40] Workers from two different suppliers had both been exposed to an auto company's simulation programs, and both developed the impression that the simulation operators were "inexperienced technical types" and unfamiliar with the software's real capability. As a result of those experiences, they have an inherent distrust of the software in general. Auto companies who try to create supplier partnerships around simulation usage may have to confront and diffuse this distrust.

While these are selected supplier comments, they voice concerns that should help die departments when they are trying to formulate strategy for utilizing simulation programs in their supplier relationships. From these and other reactions, I propose that suppliers are enthusiastic about experimenting with FEA simulation, but have reservations for a variety of reasons. The auto company will have to address all these barriers if simulation is to become a regular part of business.

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[40] Chapter 2 discusses the barriers which prevent skilled die personnel from trusting or using a computer tool that relies heavily on scientific theory.

1.4: Using Information

In the above sections, I describe some benefits of using FEA stamping simulation in different examples. Many of the benefits are quite large, but it is important to realize that simulation on its own will not solve U.S. auto stamping's learning problems or break down barriers to effective simultaneous engineering and problem-solving. The product of using simulation is simply information. The benefits that occur depend on how that information is used.

Many representatives I interviewed talked about the potential of simulation replacing the need for soft or prototype tools. There is a danger, however, in expecting simulation to provide automatically more effective or useful information than soft tools. Like simulation, soft tool tryout periods are sources of information. Their success in testing die developments depends on whether they are used optimally.

From my personal observations as well as interviews, I learned that many soft tool or prototype tool tryouts are not used fully. Soft tool developments may be made with inaccurate or old part information. Also, the tryouts may be made with very unrealistic stamping conditions, such as slow press speeds or excessive lubrication. In many cases, soft tools are not used to evaluate stamping feasibility but only to generate prototype body panels which are used on pre-production vehicles. Dies which produce prototype parts easily may perform miserably under actual stamping conditions. Furthermore, soft tool tryouts that are focused on testing stamping feasibility may only certify the production of body panels under optimal operating variables. I observed few instances of tryout periods being used to verify the robustness (or determine the "makeability' range or possible operating window) of a die in realistic stamping conditions. In general, I learned that three ill fates may befall soft tool tryouts: either insufficient information is generated via soft tools (even though they are sunk, or already incurred, costs), or tryouts are performed too hurriedly or inaccurately, or that results are not dispersed to parties who can use it.

The failure of prototype tools to generate useful information is not an inherent failure in the method but rather a failure to use the method correctly or optimally. The same failure possibility exists with simulation and may be even worse given that simulations can potentially generate large volumes of data. If the uses or needs for that data are not well defined, then simulation efforts may be wasted. Furthermore, once information is generated, there must be efficient *information linkages* for transferring that information to parties that can learn from it.

Returning to the prototype analogy above, I found many individuals in various auto company departments who want much more information from tryout periods and are in a position to increase their expertise as a result. For example, several draw die developers are interested in being present for both soft and hard tryouts so they learn what elements of development cause frequent problems and might be avoided. Simulation developers need detailed data about how dies fare in tryout for use in verifying and improving their algorithms. Information about how die developments correlate with robustness during actual production could help draw die developers to improve. This information is necessary to facilitate learning regardless of whether die development is "outsourced" or completed by internal personnel. Figure 1.5 shows a potential network of information linkages for die tryout data.

It is a challenge to management as well as simulation supervisors or developers to find innovative ways to use simulation capabilities. Who are the individuals or functions in the company that could benefit from data generated by simulations? Not only must someone identify those groups but also create procedures whereby the simulation data is made available to them. I frequently found company representatives in die departments who were oblivious to the availability of die simulation services.

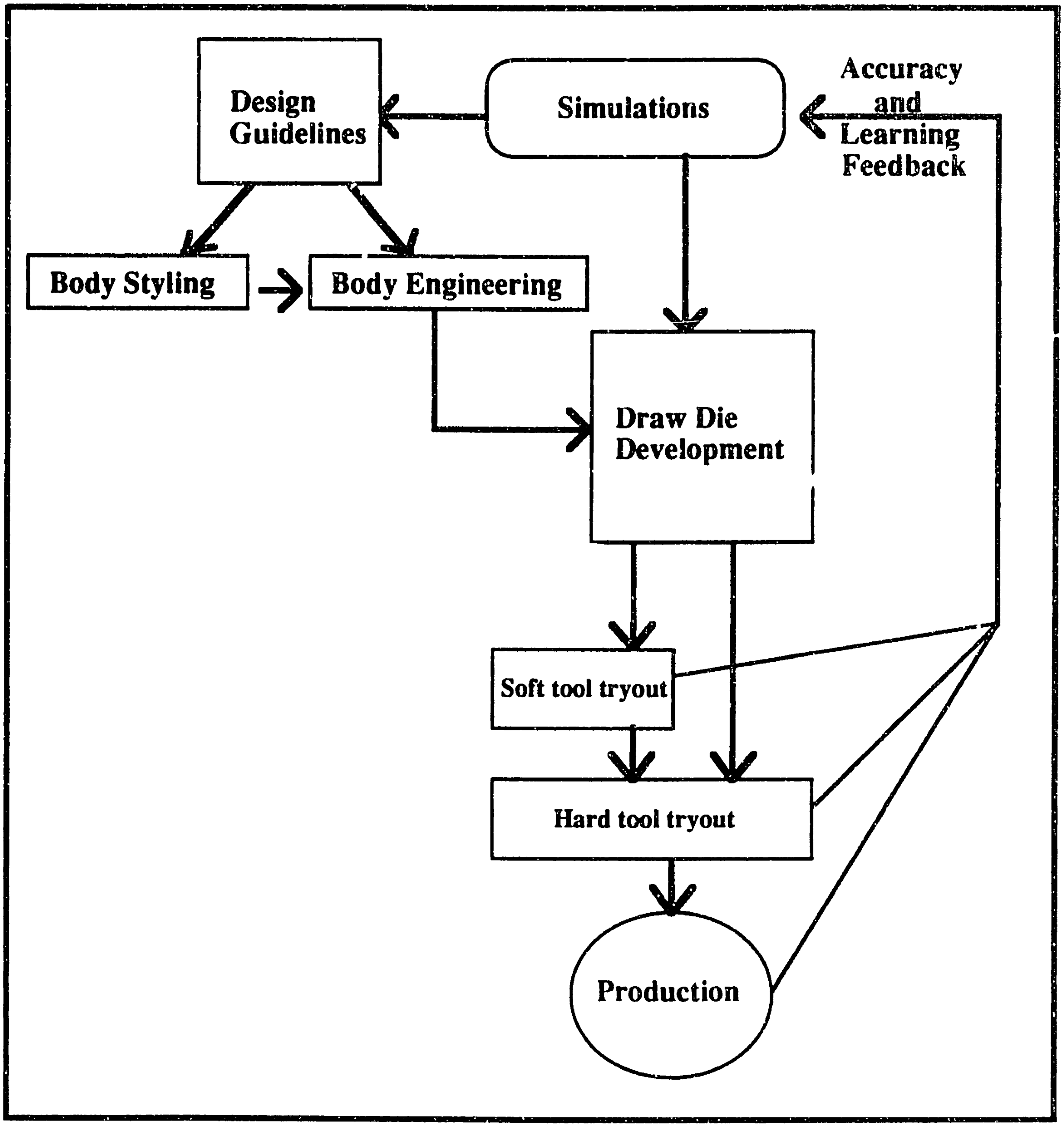

Figure 1.5- In order to use information from any type of analysis effectively, a company must define a strategy for translating and learning from the generated information. The above model shows a network of communication for sharing data from die tryout periods. Note how information is used to enhance simulation programs and thereby contribute to learning in both product and process development groups.

Technology managers (or other designated individuals) must be responsible for introducing the technology to relevant parties and creating a structure whereby they can benefit from the results. For example, product engineers may not know that simulation manufacturability guidelines can be generated and made available to them. Simulation developers must be close enough to the actual draw die development function (and also perhaps, product engineering and the stamping plant) to understand and plan how simulation can be used most effectively. If users are consulted ahead of time about their needs and preferences, they are also more likely to take advantage of the technology and develop an interest in helping to define usage policies.[41]

Figure 1.6 shows a closed loop of information and feedback flow that extracts and spreads learning from analyses like simulation or prototypes. These types of operating structures cannot be left to fate and should be approached creatively to keep simulation from having the same fate as prototype tools.

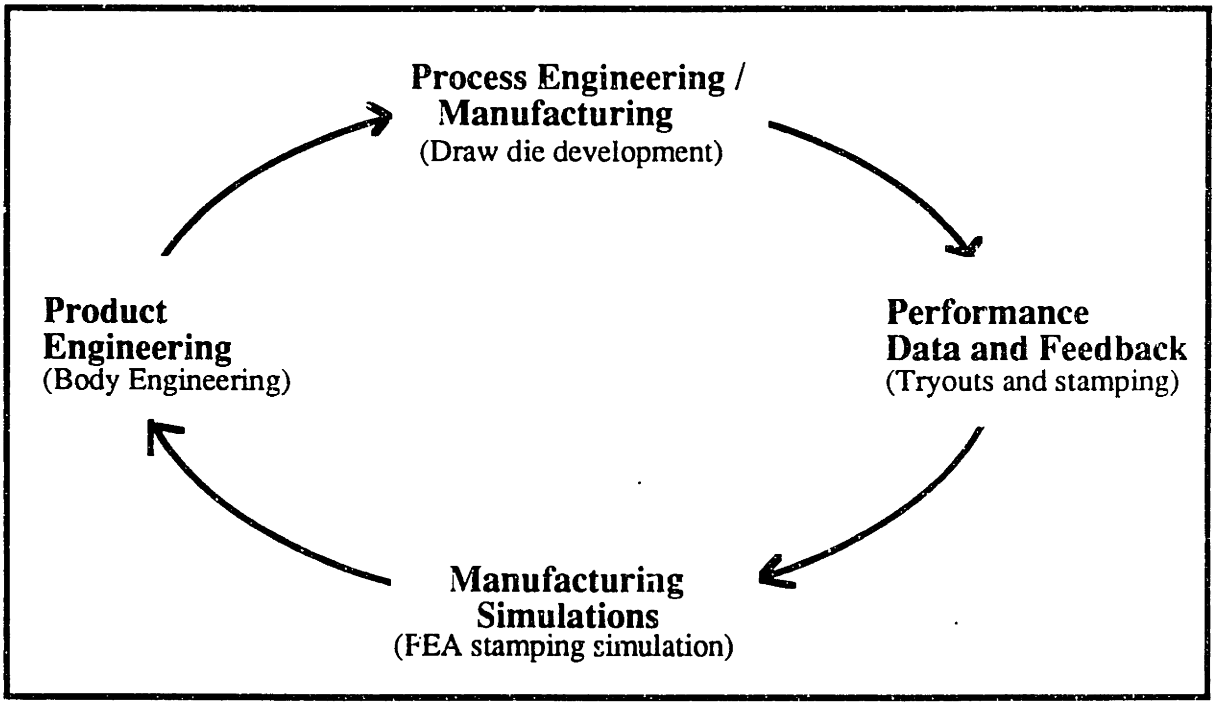

Figure 1.6- The closed loop of information feedback is a model of how to continuously learn from analyses and experience in any manufacturing environment. For auto body panel stamping, feedback and data from tryout periods and production supports scientific analyses such as simulation. Manufacturability information obtained from simulation help product engineering to design better parts which in turn support the draw die development and manufacturing functions.

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[41] Roberts and Frohman, p.99.

Bridging Cultural and Organizational Barriers

There are many technological questions surrounding stamping simulation, and many people are devoted to developing accurate, user-friendly, and inexpensive-to-run algorithms. Even with the most effective software and implementation, however, the success of stamping simulations will undoubtedly be influenced by the environment and culture in which it is implemented. A culture within a company has many of the same traits as a societal culture. As a result of their experiences, people who work together develop and sustain a set of assumptions which guides their attitudes, activities, feelings, goals, and behaviors. VanMaanen defines culture as the set of norms or regular behaviors observable when people interact and respond to their environment.[42] Schein gives a more specific definition of culture:

> A pattern of basic assumptions--invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration--that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems.[43]

Because the use of simulation or any other new technology or tool changes the business practices of a department or a person, it will challenge or be counter to an established culture. Because of the emotional foundation and generational growth of organizational cultures, they tend to be very strong, and members of a culture will resist actions that threaten to change or weaken their culture because it is the credo by which they define, function in, and find security in their surroundings.

The powerful tenets of a culture create what I term "cultural barriers" to change. When I interviewed representatives from all three U.S. auto companies and a European auto firm,[44] all of them cited cultural issues as the biggest barrier to successful implementation. Cultural barriers can be of many types and are defined by a variety of factors. Company policy and personality seem to determine some of them, but overall, there are many cultural difficulties that seem inherent in U.S. auto company

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[42] VanMaanen, 1979.

[43] Schein, 1985, p.9.

[44] All people who were able to view and judge the effectiveness of using FEA in regular operations.

organizations. Perhaps some of these difficulties are inherent in human beings, and that is what makes them so commonplace and yet so hard to overcome.

In this chapter, I discuss a number of reactions that people have to using simulation or new technologies as a result of the culture or organization in which they are used to working. I have chosen to address these cultural barriers in particular because they are the ones which I observed preventing successful implementation of simulation most often or most effectively. Section 2.1 discusses several reactions people may have to simulation because it changes the artistic, trial-and-error, traditional approach to stamping that auto companies have taken for decades. In section 2.2, I describe the perception of FEA simulation as a miracle tool and how that false impression aggravates successful use of the technology. The role of management in defining, understanding, funding, and encouraging simulation development is detailed in section 2.3. Section 2.4 describes traditional cross-functional barriers of auto companies, and section 2.5 illustrates the cultural barriers that may inhibit use of simulation between auto companies and their die suppliers. There are certainly other barriers that can be destructive beyond the ones I emphasize in this chapter.

It is important to note that the cultural barriers to simulation usage that I encountered in U.S. auto companies are basically the same problems any company faces with any new technology or business implementation. I have read numerous organizational studies from the past two decades that isolate cultural barriers to change, and they report similar results. People have to feel it is safe and acceptable to change their activities before they will, and management must foster such a safe environment in order to facilitate change.[45] Creating a new environment may require redefining a culture. The pervasiveness of cultural problems is not due to lack of identification of or attention to barriers but to the difficulty of making change within a given cultural context or else trying to manipulate a long-standing culture to accommodate change. Management theorists have offered many suggestions and guidelines to bridging cultural and organizational barriers by both these routes, but the challenges faced by each company are still fierce and unique. In this chapter, I offer suggestions for facing and overcoming the particular barriers to using stamping simulation in U.S. auto companies.

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[45] In particular, E.H. Schein treats how cultural barriers hinder the implementation of new technologies in Organizational Culture and Leadership, particularly p.36-9.

2.1: Change Causes Stress

Regardless of the industry, company, or technology, implementing a new technology will cause changes in business-as-usual procedures and operations. Implementing stamping simulation creates many such changes and may uncover several cultural barriers. In the sections below, I discuss three changes that simulation use causes: from an artistic to a scientific basis for die analysis, from a repetitive, trial-and-error problem-solving method to a predictive one, and from physical tools to computer tools. The loss of a person's identification or power caused by any of these changes will likely cause him to resist the technology. From the beginning, management must understand that people do not resist the technology itself as much as they do the cultural change the technology dictates. Then, their goal becomes to integrate the technology into the accepted culture or push the culture to evolve into something more appropriate to the technology.[46]

From an artistic approach to a scientific one. In an environment that has traditionally used experience and intuition as engineering tools, many workers reject the notion of using computer tools to analyze or supplement their intuition. These individuals may be draw die developers, die designers, stamping plant personnel, product engineers or manufacturing supervisors or management, and their reasoning for questioning the simulation capability varies greatly. Many individuals claim they simply mistrust the engineering theory inherent in the simulations. As one stamping plant die-tryout supervisor proclaimed, "There are just some things a computer can't do."

"Stamping is perceived as an art because the variables that control it are numerous and may not be easily recognized or understood."[47] Die makers may joke about it, but some will also admit seriously that their developed instinct is that draw dies work according to "black magic." Others have commented that refining dies until they produce flawless panel surfaces is "really an art form." Without formal engineering education, some do not understand that the phenomena observable during metal stamping can be described mathematically or modeled. Some individuals also admitted feeling insecure about their education level. Others may understand how stress and strain occur in a die, but they may still fail to believe that engineering principles can be applied in a predictive manner.

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[46] Schein, 1985, p.37.

[47] "Managing the Stamping Process," October, 1991, p.1.

The main feedback I received about overcoming this disbelief and intimidation is through education. At one piece-part supplier that has invested in FEA simulation capability, the company is paying for all draw die developers to take courses in basic stress/strain theory, forming limit diagrams[48], and fracture theory. This education can help developers correlate the phenomena they view with engineering principles; it could also make the simulation theory less intimidating. It is also important to be honest about the complexity of simulation theories; physicists and mechanics specialists can spend their careers trying to understand material models for simulation programs. If education is provided, people are also more likely to approach simulation optimistically as a result of feeling an important part of the technological update It is not as important for people to know the ins-and-outs of an algorithm as it is for them to trust it and use it effectively.[49]

From the security of iteration to predictive analysis. Traditionally, draw die developers have been able to test out their developments physically through the use of plaster tools, soft dies, and extensive hard die tryout periods. Even though they are confident of their expertise, these individuals find security in iteration. Simulation is also an iterative analysis, but without the verification of testing each die development physically, the method is also predictive. When asked how they would feel about using simulation programs, some individuals are concerned that management feels their expertise must be inadequate or need verification. These insecurities and questions must be addressed openly by management if prospective users are to understand the role of simulation in traditional business practices.

Simulation provides an opportunity to record die development iterations for use on future parts. The verification procedures used to validate simulation programs also require extensive record-keeping with regard to soft and hard die tryouts. Record-keeping, however, implies accountability. Individuals may not be comfortable with having their lack of expertise retained for all of posterity and viewed by their peers. This reaction applies to both internal company die developers as well as supplier personnel who may be involved with simulations. Simulation represents a large cultural shift from the security of iteration and lack of record-keeping. To encourage their participation and

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[48] Forming limit diagrams are graphs that plot two components of strain that a material experiences and how likely it is that a material will fail when exposed to those conditions. One is shown in Figure 3.5.

[49] The level of applied education that a draw die developer might need with regard to operating simulation programs or interpreting results varies depending on how involved he will be in the actual operation of the simulations.. Chapter 3, particularly Section 4, discusses issues around choosing program operators and interpreters.

support, users (as well as affected parties, such as tryout personnel) must not feel threatened by the implementation of simulations. It might be easy for personnel to jump to the conclusion that simulation is just another method for managers to check up on them.

A new way of doing business. Regardless of whether a new tool is particularly scientific or radically new, changes in "the way we do business" will cause stress in any company or environment. Several draw die developers express the desire to be involved in defining the organizational structure for using simulation. As opposed to having new systems imposed upon them, potential simulation users could offer suggestions and practical advice as to how the technology transfer could be implemented. Some important questions to ask involve use, transfer, and documentation of simulation results. Who will interpret FEA simulation results and when? Is the designated simulation program user-friendly? If not, how might it be made so? If simulation users feel important in the success of the technology and consulted as valuable participants, successful technology transfer and implementation are greatly increased.[50]

There were also two individuals who said that computer simulations would be unacceptable in their departments, because visualizing three-dimensional dies on computer screens is too difficult. Many people I interviewed are worried about not being able to understand computer results or extrapolate results from a small monitor to changes on full-size dies. Some feel they could learn to visualize results, and others insist they are incapable of doing so. There are commercial education courses available for teaching such skills, as well as some options in monitor size and results processing that companies can select to aid interpretation. There are also options of using two-dimensional as opposed to three-dimensional simulations, though there are tradeoffs in effectiveness and completeness.[51] Despite these options, inability to visualize results is a valid concern of users and simulation developers. As CAD tools become more prevalent in auto manufacturing, auto representatives believe repetition and conditioning will make more people capable of visualizing physical objects on computer screens. In the meantime, the ability to continuously compare simulation results with soft tool trials or stamping experiments is the only other method suggested to help people visualize results. As a result, using computer screens as a change from two-dimensional drawings or physical tools will likely cause some unavoidable resistance and may be impossible for some workers .

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[50] Roberts and Frohman, p.99.

[51] See Figure 3.4 for further information about differences between two- and three-dimensional simulations.

2.2: Simulation: The Miracle Tool?

In my interviews with company representatives as well as die suppliers, I found many individuals who perceived FEA stamping simulation as a miracle tool. Most of them have little understanding of the analysis theory. Hence, many of their reactions are based on false assumptions and yet can effectively hinder the implementation of the technology. In this section, I discuss how a miracle tool perception discourages people from adapting to and accepting simulation in their work environment because they fear simulation may replace their jobs or their expertise.

Miracle tools mean loss of jobs. Several individuals expressed concern about a successful simulation program eliminating the need for die expertise and, possibly, all human input. At least two die makers envisioned computer simulations as perfect expert systems that automatically generate complete die developments and designs. Similar misconceptions were common. The accuracy and usefulness of any type of simulation is limited by the expertise of user. By virtue of being an approximation, simulation results are never perfectly accurate, and users (individuals or teams) must have some intuition about draw die behavior as well as knowledge about possible simulation quirks. Users also need a general sense as to whether simulation results are feasible given the input variables. Education about the role of die expertise and intuition in simulation use is a responsibility of management.

Use of simulation has the potential to eliminate all soft tools and tryouts. As I mentioned in Chapter 1, I encountered much debate as to whether simulation should be used to eliminate the use of verification tools, whether they be die models or soft tools. There are some companies who manufacture separate soft tools to make prototype vehicle parts. For purposes of verifying draw die performance, the potential of eliminating soft tools for at least simple parts (that vary less from model to model) is significant. Especially if a miracle tool perception is widespread, however, personnel may not understand that simulation accuracy must be validated by actual experimental data and comparison with soft and hard tool trials. Education and exposure to comparisons between soft tool tryouts and simulation predictions may increase the confidence and excitement of users who are skeptical of simulation accuracy.

2.3: The Crucial Role of Management

Most of the potential cultural barriers mentioned so far have involved draw die developers, die makers, supplier personnel, and stamping plant employees. As with the transfer of any technology, guidance and buy-in by appropriate managers is necessary. In this section, I discuss several pitfalls I observed whereby managers can hinder successful simulation implementation. Management must take the role of guiding, understanding, encouraging, and funding simulation development and implementation.

Financing simulation development. Though there are many benefits to stamping simulation, most of them are unfortunately difficult to quantify. Many variables determine the length and cost of tryout periods, and reliable comparisons between results-using-simulation and results-not-using-simulation are difficult to make and would be questionable. One U.S. company has successfully estimated the cost savings attainable through simulation [52] and has tried to forecast savings over the next few years in order to garner further management support. Management must be able to evaluate investments such as simulation development thoughtfully even when accurate pay-back data are not available.

Furthermore, simulation (and other CAE) investments represent a long-term commitment to expertise which will not likely pay for itself in five years and, as a result, may be a radical change in the type of investments U.S. auto companies have favored in the past. Traditional cost accounting methods which are company policy may inherently obscure the degree of cost recovery for long-term technology investments.[53] In order to reap the advantages of such strategic investments, management must restructure its evaluation standards and focus on long-term core competencies and viability.

Understanding and managing simulation development . For many reasons, a manager's attitude toward simulation can hinder technology development. I found development efforts that had been stifled due to either a manager's short-term investment focus or a "prove-it-to-me" attitude. The benefits of simulation are long-term expertise and learning, and management must evaluate the cost of such technologies in light of the

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[52] Their estimate is tryout cost savings of up to 30% in the next three years as a result of using simulation to assist draw die development for large body panels.

[53] "Toward World Class Manufacture of Automotive Bodies," 1988, Appendix C, p.1.

full benefits. The "prove-it-to-me" attitude involves a situation in which a manager has supported simulation development for a couple of years or is completely new to the concept. Before he wants it used to test actual parts, however, the manager wants to see it simulate with utmost accuracy. Since simulation accuracy is achieved only through continuous verification and refinement, this managerial attitude may cause a simulation effort (or any other CAE or similar learning tool) to be deserted way before its full potential is realized or even known.

Managers also need to understand the time required to develop simulation so they do not oversell the company on a technology that will not be ready when promised. Repetitive delays and extensions in the introduction of new technologies are likely to raise suspicion and aggravate the organizational conflicts already inevitable. I encountered two managers who had overestimated simulation capabilities because they did not understand them and had not gone to the simulation developers in the company to get a realistic assessment. When the guaranteed results did not materialize, upper management viewed the development plan as questionable and refused to allocate further funds to the project.

Another crucial need I found for many simulation development efforts is a simulation project manager. In many cases, academic researchers or simulation programmers are put in charge of forming simulation strategies for the company who do not have enough knowledge of or credibility within the company to manage the development effort effectively. These mechanics and programming specialists would be better left to concentrate on their areas of expertise and the simulation capability itself. An experienced auto company manager needs to plan and execute a company's strategy for using simulation, "sell" the simulation capabilities to other areas of the company, educate and arrange for training for simulation users, and define the implementation strategy to be used in various areas of the company. In two auto companies I studied, I believe the lack of a central simulation manager is the reason implementation has been limited or become stagnant.

Estimating and preparing for the real costs of simulation. Simulation capability can be either purchased from a software firm or developed internally by company programmers.[54] In either case, the costs of software, necessary hardware, training, and associated activities may be higher than expected. Development efforts may suffer because management fails to anticipate all the associated costs before they are incurred or

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[54] In Appendix C, I discuss the pros and cons of using either commercially- or internally-developed simulation software.

in time for budgeting. For example, I found several scenarios in which management had approved adequate money for programming but had failed to allocate time or money for training, supercomputer time in order to run analyses, or increases in manpower needed for training and simulation use.

Management may also make funding mistakes as a result of setting a short time horizon for simulation development without researching the realistic time required to develop an effective program. In at least one case I researched, a developed simulation program was ready for implementation but never implemented because funds were depleted. Especially with the tight cash flow considerations of auto companies now, lower and middle managers will have to convince upper management of the viability of new technologies in order to get approval for manpower increases. One company I studied went successfully to upper management directly, and two others are trying to strategically use and rotate available manpower until they can present quantitative proof of simulation benefits.[55]

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[55] A related problem I observed at one auto company was an organization whose manager was unwilling to "lend" or share his skilled human resources to the simulation development effort. Though the lower level managers and personnel were anxious to work together and combine their talents, their respective managers refused to "give up" some of their "territory" for a cause they both viewed as vital for the company. This is a classic example of mangers' territorial skirmishes effectively hindering company advancement.

2.4: Inter-company Barriers

Simultaneous engineering has the potential to reduce both lead-time and development cost and to increase learning by overlapping product and process engineering tasks. Such teamwork is necessary for all the simulation strategies mentioned in Chapter 1, but it is difficult to achieve. Historically, functional groups in U.S. auto companies such as product engineering and manufacturing have worked with different constraints and objectives. These differences have also generated cultural barriers and an "over-the-wall" philosophy about exchanging information. Many auto company representatives blame a lack of mutual respect or understanding of each other's constraints for the negativity and lack of cooperation and communication between functional groups. Indeed, simply co-locating these groups and scheduling joint meetings will not create teamwork or simultaneous engineering.[56]

Cross-functional barriers to communication and effective interaction are certainly not new organizational problems. In the 1960s Lawrence and Lorsch studied several plastics and food companies and isolated the barriers to functional units working close together based on their goal and activity differentiation.[57] Their findings and recommendations for facilitating cross-functional interaction are essentially those reported by Clark and Fujimoto thirty years later in their 1990 study of the global auto industry:[58] Downstream organizations will always have conflicts with and be at the mercy of upstream organizations, and mutual respect and joint responsibilities between functions are necessary before they can work together effectively. Schein also reports a number of studies of organizational conflict and functional competition with similar findings. As he comments, "The chief stumbling block remains not so much being unable to think of ways for reducing intergroup conflict as being *unable to implement some of the most effective ways*."[59] Hence, the inter-company barriers I observed are not new and can be just as effective in barring the use of multi-functional technologies today as they were in the past.

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[56] In fact, as Clark and Fujimoto (1991) found in their extensive study of the auto industry, overlapping groups' tasks without making requisite changes in their communication, organizational, and management structures may actually "reduce product quality, incur unintended schedule delays, and lower morale" as opposed to improving performance.
[57] Lawrence and Lorsch, 1967, p.54-83.
[58] Clark and Fujimoto, 1991.
[59] Schein, 1980, p.176.

Inter-company friction has developed in many areas of auto companies, and functional groups are constantly fingerpointing and faulting one another. Product engineering and manufacturing groups are always arguing about responsibility for engineering changes. Figure 2.1 shows some typical interactions and conflicts between the two organizations. Similar barriers exist between simulation developers (or other "R&D" groups) and manufacturing personnel. Due to discrepancies between their levels of education or engineering knowledge and their practical experience, the two groups mistrust each other's capabilities. There is seldom a sense of interdependency between the two. Stamping plant personnel may also have a adversarial relationship with draw die developers or other Manufacturing groups.

Characteristics...	...of isolated functions	...of cooperative functions
Mutual regard	Mistrust, enemies	Respect, partners, teammates
Level of interaction	Minimal, guarded	Frequent, collaborative, strategic
Responsibilities	Functional, traditional	Joint, interdependent
Incentive base	Function's performance, individual tasks	Company performance, customer satisfaction, final product quality, linked, team performance
Type of communication	Over-the-wall, defensive	Face-to-face, systemic, cooperative
Information exchange	As late as possible, only when necessary	As early as possible, frequent, honest, thorough

Figure 2.1- Auto company cross-functional efforts between traditionally isolated functions can hindered by historically negative, isolated, and competitive patterns of communication and interactions. This table shows characteristics of those isolated functions and of the more cooperative functions that are necessary to sustain teamwork.

Negative relationships between functions develop for different reasons, but in many cases two groups may view one another as enemies despite their coexistence in a single company. The isolated nature of functional groups combined with their task interdependence tends to create competition between the groups. As a result of different goals and attitudes, a function may view their upstream and downstream organizations as enemies who hinder the function's progress.[60] In extreme cases, the competition may create an "I win-You lose" scenario where battles between the organization are destructive to overall company performance.

To generate true teamwork between functions, management must be *creative* in finding joint responsibilities and goals with which to unify the groups' efforts. For example, product engineering and manufacturing groups should be focused on the final customer, not their micro-functional tasks. Incentive systems should reflect peoples' abilities to meet *joint* goals. Trying to meet different budgets and financial goals can further alienate functional groups.[61]There must be a mutual commitment to each other's success, not simply a willingness to sit next to each other and answer questions. Management may need to provide education about the importance and various constraints of other functional groups, or perhaps basic training in the skills of other functions . Focusing on common enemies such as unnecessarily late engineering changes and low manufacturability parts can help keep functions from destructive competition against one another. Also, as was suggested in section 2.2, getting as many users and different functions as possible involved in the definition of joint work structures and goals should also help their ownership of cross-functional activities and new technologies.[62] *There are no "quick fixes" for long-standing cultural problems, but unless management addresses them, the effectiveness of any simultaneous engineering efforts will be minimal.*

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[60] Ibid., p.172.

[61] For example, in one US auto company, draw die developers and "die managers" who had the option of using simulation, or doing more manufacturability analysis, had to pay for simulations out of their operating budgets. Charges for die tryout and soft tools, however, were charged to the stamping plant directly. Because the two groups were not made financially accountable to one another, there was less incentive to work together and save costs for the company as a whole.

[62] Roberts and Frohman, p.99.

2.4: Managing Supplier Relations

Negative relationships similar to the inter-company conflicts discussed above often exist between auto companies and their die suppliers, including die development shops. From my observations, such relationships are typically arms-length with little reciprocal commitment or trust between parties. Auto companies have long debated about the advantages of using long-term, dedicated suppliers as opposed to open-bidding supplier selection procedures. Through the latter, auto companies may do business with the least expensive supplier, but they may suffer from reduced quality and poor learning opportunities. Furthermore, such practices leave the suppliers vulnerable and do not foster the long-term personal relationships that enable the teamwork needed to use simulation effectively across companies. It is not surprising that suppliers are certainly intrigued by opportunities to use simulation interactively, yet they are very suspicious and defensive about associated contract terms, costs, and accountability.[63]

Simple models help to explain die supplier relationships and how they respond to new technologies. Figure 2.2 shows a humorous but accurate portrayal of the predicament auto companies may find while trying to use new technologies with suppliers. Because they are working across large cultural barriers and at arms length, there is little direct communication. The supplier is unprepared to receive the technology due to lack of involvement and education. Furthermore, there is no mutual goal. In Figure 2.3, a much more cooperative situation is represented. The auto company and supplier are working together, using the same hockey pucks (technologies, tools, languages, etc.) to make the same goal (profit via lower costs, higher quality, and continuous learning.) They are committed to the same goal, and if the supplier loses then the company loses also. In Figure 2.3, the auto company recognizes and uses the supplier's strategic positioning in meeting targets that the auto company itself cannot reach. These diagrams demonstrate the characteristics of supplier relationships that managers must leverage in order to use simulation profitably.

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[63] Chapter 1, Section 3, contains more information about US auto companies' relationships with die suppliers and their attitudes toward using simulations.

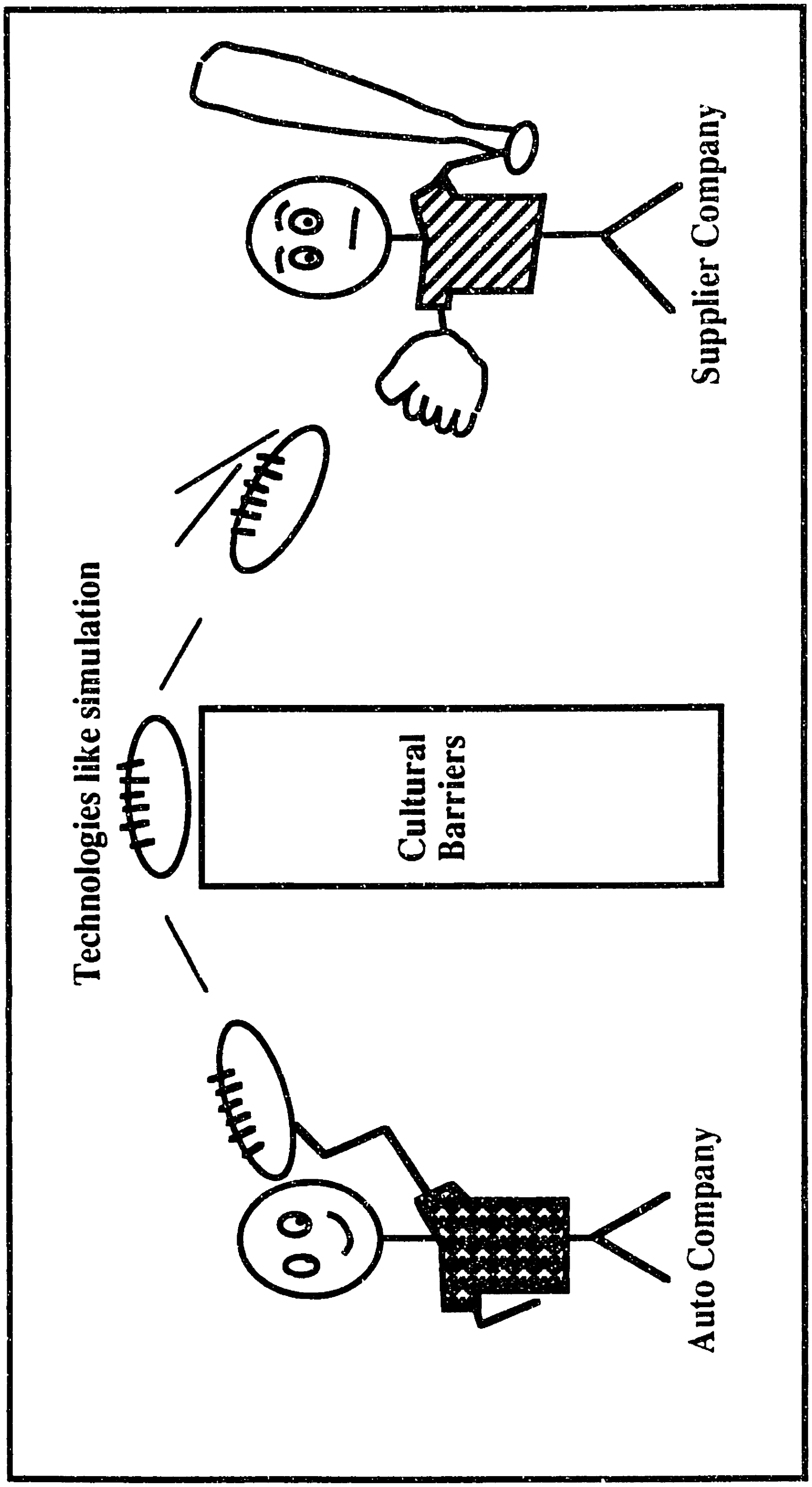

Figure 2.2- Traditional auto company-die supplier relationships have been distant and not coordinated for mutual goals. The sports analogy above shows how lack of communication and commitment and cultural differences can keep auto companies and suppliers from using technologies such as simulation interactively.

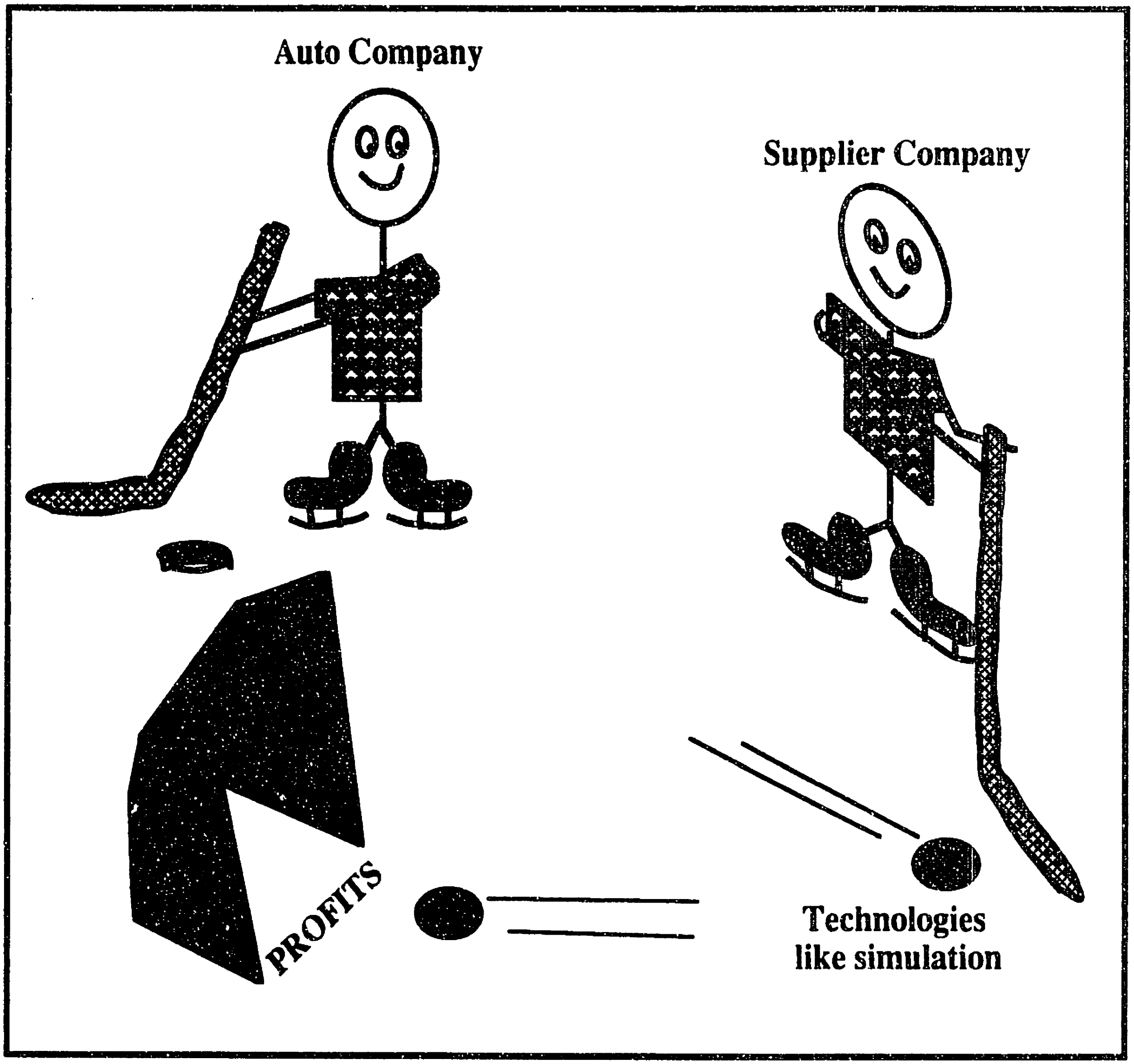

Figure 2.3- Auto-companies with more cooperative die supplier relationships may possess the mutual commitment to goals and profits necessary to effectively use technologies such as simulation for both companies' benefit.

Chapter 3

Stamping Simulations: Building an Effective Simulation Model

After planning for the benefits of simulation discussed in Chapter 1 and anticipating and accommodating the cultural difficulties presented in Chapter 2, managers of simulation development must define a technical and implementation strategy for simulation. In this chapter, I focus on the simulation itself and how companies make the choices necessary to define a simulation strategy. Each company essentially has to answer the question: How are we going to model stamping? Some of the possible choices are technical, such as the modeling techniques in section 3.1. Most are organizational and logistical, such as who will run the simulations and on what type of equipment. In section 3.2, I discuss how computer hardware and CAD linkages are used to support stamping simulations and how they effect the time required for analyses. Section 3.3 describes the tradeoffs involved in deciding who will run simulations: draw die developers or product engineers or simulation specialists. The importance of validating the accuracy and capability of simulation programs once they are developed is the subject of section 3.4. The mixture of subjects in this chapter is not an exhaustive list of issues that must be considered in forming a simulation strategy and carrying it out, but I address the topics that I discovered were most crucial in determining successful implementation.[64]

Managers in charge of developing FEA programs cite a number of "most critical characteristics" of a program used to model stamping. Some focus on cost, model simplicity, speed, and ease of results interpretation. Others emphasize consistency over detailed accuracy or ease of use. Certainly the most important factors depend on a particular company or operating environment and the users' needs. Cost, speed, accuracy, and ease-of-use (both simulation operation and interpretation) were the critical characteristics cited most often. It is indeed important for FEA development groups to define their goals and expectations in each of these areas ahead of time so that progress on building codes will not be hindered by bad surprises. Hence, in the sections below, the effect of various choices on these factors is mentioned where applicable, and some anticipated future developments are also noted. Note that in many cases, the four desired factors conflict directly. For example, accuracy usually requires lengthy analyses and is

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[64] Appendix C addresses another strategic issues of whether companies should develop simulation codes internally or purchase commercially-available simulation programs.

costly, and ease-of-use requires both speed and accuracy. In general, simulation developers must make tradeoffs between two extreme types of programs:

1.) A very quick, global analysis strategy that is relatively inexpensive, applicable to many different parts, and requires a great deal of skill for both running simulations and interpreting results.

2.) A very rigorous, accurate, and specific simulation strategy that is expensive and requires less skill for simulation or interpretation.

Obviously, the challenge is to design a simulation strategy that includes the best of both these scenarios. Simulation programs at both these extremes exist, but much current research focuses on bringing together efficient, accurate simulations that require little skill and training to interpret and use results effectively.[65]

3.1 Building an Algorithm: Technical Choices

This section introduces several of the options available for building an effective simulation program from a technical perspective. A metal blank is likely to go through several different dies during stamping, as is explained in Appendix A.1. The simulations which are the focus of this thesis model draw die action (see Figures A.1 and A.2 for clarification). Though any of the dies in a typical line could be readily simulated,[66] the performance of draw dies remains the most artistic and difficult to predict and control. (Readers unfamiliar with finite element analysis (FEA) should refer first to Appendix B.)

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[65] The proceedings from the 1991 VDI simulation conference (see Bibliography) demonstrate the variety and depth of this research worldwide.

[66] Though draw dies are the immediate modeling concern of the US auto companies, some groups and foreign auto companies are looking at modeling form and trim dies or even the entire line of dies. This enables die developers to study how phenomena such as metal springback and part tolerances are affected by each stage of the stamping process.

Once the draw die is targeted for simulation, the particular parts or phenomena that a company chooses to model depend on their particular stamping problems. A company's modeling philosophy may be to use a general model for many parts and phenomena or a specialized model for particular problems. Certain material theories and elements[67], however, are better designed for certain problems. Figures 3.1-3.4 detail some of the modeling options available for FEA simulation and the particular phenomena for which they are best suited. Further technical details are beyond the scope of this thesis, but there are many FEA texts which discuss them thoroughly (see Appendix B.2).

Though metal behavior in a die is very complex and hard to define, it can basically be described as some combination of **drawing and stretching** or as **bending**. The chart below shows these two basic deforming mechanisms and the phenomena they are often used to model.

Controlling action in die	**Material behaviors**	**Common phenomena modeled**
Drawing/ Stretching	Mostly plastic flow and strain	Stress/strain levels Thinning Necking Splitting
Bending	Combination of elastic and plastic flow	Wrinkling Buckling Springback

Figure 3.1[68]**-** Simulation developers make technical choices about what material behaviors they wish to model.

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[67] In finite element analysis (FEA), elements are the geometric divisions imposed on the part for the analysis. The program calculates how each small area, or element, will react during stamping and then sums those responses to get a global simulation.

[68] For more information about metal forming science and theories, see Hosford and Caddell, 1983.

In a simulation model, metal characteristics and behavior are approximated by many formulas and theories: constitutive equations, yield conditions,effective stress-effective strain relationships, plasticity equations, and material property values.

These choices are made in anticipation of certain metal activity in the die. The example below presents two general flow models and how they may be used to model the phenomena in Figure 3.1. Simulation developers must decide when to make similar trade-offs.

Many simulation developers are investigating hybrid models or combination algorithms that model different metal behaviors selectively.

Metal flow model	**Can be used accurately to model...**	**Comments and assumptions**
Rigid-Plastic Behavior **(RP)**	Strain > 5 %	•Ignores elastic effects such as bending •Simulation faster and less expensive than EP
Elastic-Plastic Behavior **(EP)**	Stress and strain at various levels Bending	•Slower than RP •More rigorous than RP •Required to model springback and elastic effects

Figure 3.2- Simulation developers must choose from and coordinate a number of material theories to accurately model metal activity in draw dies.

Friction and interfacial contact conditions between sheet metal and dies remain the most difficult phenomena to model in body panel stamping, according to every simulation developer I interviewed. Both conditions are highly non-linear and change constantly throughout the stamping process.

Friction between metal blanks and dies play a strong role in determining metal behavior. High friction may cause buckling. Too low friction (such as caused by excessive lubricant) is likely to produce a more even strain distribution but may also encourage excessive thinning or splitting.

Modeling friction is almost always done using a constant coefficient of friction (a value that is a function of the two metal surfaces, any lubricants, the force in the die, and the shape of the die.) Because the friction coefficient actually varies continuously, any chosen constant is an approximation.

Much research has focused on choosing the optimal friction coefficient or a better modeling strategy. Some new techniques include a changing coefficient, different coefficients on either side of the blank or at different locations on the blank, and the definition of friction and contact as a separate liquid or material layer between the die and blank.

Figure 3.3[69]- Friction and contact between the die and the metal blank during stamping are difficult to model accurately, but they are critical characteristics that determine the success of drawing panels.

By choosing certain models, element types,[70] and approaches, a code developer determines to a great extent the accuracy and interpretation difficulty of running simulations with that particular code. If, for example, material flow models are approximated or cannot model some expected phenomena, then the accuracy of a solution is much more dependent upon the interpretation skill of the operator to find and further analyze potential problems. Sheet metal forming FEA researchers at Ohio State University found as an informal observation that the accuracy of FEA solutions depends as much on operator interpretation skill as it does on the details of the FEA model.[71]

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[69] Jackson, 1989, is a good reference for modeling friction and lubrication in sheet metal forming.

[70] There are different element types (such as solid, shell, and membrane of varying shapes and sizes) which are better suited to model either bending or plane strain phenomena. Using the appropriate type and number of elements will optimize simulation speed and, as a result, lower costs.

[71] Lee, Wagoner, and Nakamachi, 1991, p.590.

Auto companies are choosing to model stamping either two- or three-dimensionally for a number of different reasons. Some are using both in a strategic sense, where, for instance, two-dimensional simulations are run for all parts and three-dimensional ones are only run for further or more detailed information. Some use either for strictly outer or inner body panels.

This graph details some of the advantages and disadvantages of the two approaches.

Part data and analysis in...	**Advantages**	**Disadvantages**
Two dimensions (2D)	• Usually faster to run and set-up FEA model • Requires less part data • Can do focused analysis only on problem areas • Usually easier to interpret results	• Cannot show global effects, only localized, for detailed parts • Greater opportunity for inaccuracy • Cannot model entire part in one iteration
Three dimensions (3D)	• Models global and localized effects and shows relationship • Can be used for any part types • Can be run as verification of best 2D iteration	• More expensive and lengthy than 2D • Likely requires more operator skill and training • Simulation development takes longer and numerical problems are more likely

Figure 3.4- When formulating a simulation strategy, developers must decide whether to perform two- or three-dimensional analyses, or both. The above advantages and disadvantages explain the tradeoffs involved in the decision.

Demanding more accurate solutions usually requires having an algorithm perform more iterations of a solution. This will increase computation time, as will choosing to do a very detailed simulation involving a large number of elements.[72] An advantage of FEA modeling is that simulations can be made with very limited geometry or with highly

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[72] As a generalization, computation time increases with the number of elements: linearly for explicit programs and exponentially to the power 2 for implicit programs.

detailed CAD files. As a result, the operator can simplify geometries to speed computation or enhance them to see more detailed results. Computation time is also influenced by the efficiency of the mathematical scheme used to compute solutions. Much future research is expected to improve parallel processing capabilities and vector computation in FEA algorithms that allow them to use computer time more effectively.

Some examples illustrate how modeling choices are made. (Refer to Figures 3.1-3.4 for more details.)

All three U.S. auto companies are concerned about problems with wrinkling on major outer body panels where customers demand a flawless appearance. To effectively model wrinkles, an FEA model must be able to incorporate bending phenomena and areas where metal-die contact is not continuous.

Quality concerns are different for a small piece part supplier that specializes in making dies for (and stamping) oil pans and other parts that involve deep draws. In such deep draws, metal splitting is a common problem, and dies must be developed to allow even metal flow into cavities. Models that predict splitting accurately include detailed failure formulas for the materials in question. For inner panels such as oil pans, wrinkling is not as negative because they are hidden from the customer's view.

Many auto companies are also concerned about failure and controlling metal springback[73] , especially with regard to forming the many bumps, ridges, and different radii of inner panels.[74] Because the modeling phenomena are more complicated for inner panels than for outer panels, at least two auto companies are trying to master outer panel simulation before tackling inner panels. They are developing a different algorithm for each panel type. I found two auto companies using two-dimensional simulations to model problem areas of inner panels because the computation time is much less than it would be for full three-dimensional analysis of inner panels.

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[73] Metal or panel springback is the result of the release of residual stresses in the metal. As panels are flanged or punched, these stresses are released and cause the metal to warp out of the shape made in the draw die, often rendering the part dimensions beyond acceptable specification limits. Berry, 1988, p.61 is a good non-technical discussion of springback modeling.

[74] An example of an inner panel that frequently has forming problems is the door inner which houses all the necessary window and locking mechanisms and reinforces the outer door.

3.2 Hardware, CAD Linkages, and Time Requirements for Simulation

Simulation time or speed (or efficiency) is a critical characteristic defined by managers for choosing a strategy. Therefore, it is important to realize that the overall time required for simulation is much more than the actual run-time for the FEA algorithm:

T(Total) = T(CAD data translation) + T(pre-processing/meshing) + T(defining simulation variables) + T(queuing at any stage) + T(simulation run) + T(post-processing) + T(results interpretation)+ T(iterations)

where T(X) = the non-over-lapping time required to do X.

In fact, the actual run-time is usually the shortest of all these factors. The choice of hardware may effect a number of these times, and hardware decisions should be based on optimizing the overall time, not just an individual component. *Given the rapidity of computer memory and computation speed improvements, however, time reduction for simulations in the future will become much less dependent on technology and more dependent upon operator skills.*

When implementing simulation programs, user groups must decide what computer hardware they will use, and there are certainly many options available. Hardware is used to "pre-process" part data before running simulations, to actually run the FEA simulation, and finally to "post-process" the results, and different hardware are better suited for each use. Also, there must be some sort of data transfer mechanism for obtaining part information for simulations. Most, but not all, part data, comes directly from the product engineering organization or has been entered into a CAD system via some sort of digitization or scanning process. This section briefly describes the hardware options available for those CAD linkages and simulation needs.

Hardware for Pre- and Post-Processing of Simulation Data

Pre-processing programs for FEA are used to refine part data and apply selected element meshes to the part for simulation. These functions usually require little memory though depending on the efficiency of the meshing program, they may take a while. Most simulation users perform all pre-processing on computer workstations or personal computers. Some workstations have the advantage of being directly connected to a CAD network, but personal computers may offer adequate memory and speed at a much lower cost. Many research groups are working on quick automatic mesh generation software, as well as automatic mesh refinement routines that change the mesh size during simulations if needed to enhance the detail level or change the duration of the analysis.

Post-processing needs are similar to those for pre-processing with regard to the memory required. Post-processing algorithms typically display numerical simulation results in easy-to-read graphs, tables, and physical representations of the simulated stamped part. One U.S. auto company uses a free-standing workstation for this work and animates FEA results in order to increase user-understanding of simulated phenomena. Another U.S. auto company processes results on CAD workstations and is unable to animate or show solid representations of the results. They cited the lack of animation capability and solid imaging as a major barrier to acceptance of FEA results. Wireframe representations of stamped parts are too obscure for many users, particularly those inexperienced with computer tools, to understand. A possible disadvantage of using animated results, however, is that they may perpetuate the image of FEA simulation as a miracle tool with absolute accuracy.[75] The message here is to plan for complete user and future needs before making hardware decisions. They are part of the overall simulation strategy.

Simulation Hardware

FEA algorithms may be designed to run more efficiently on certain types of hardware. A software company made a study of processing times for different problems using their ABAQUS. software on various hardware.[76] Their findings show that the duration of FEA simulations can vary immensely as a function of hardware, not just the type of computer (PC, workstation, supercomputer, etc.), but also the particular structure of a brand or model. New FEA algorithms are being designed to take advantage of any parallel processing opportunities of hardware and reduce computation time. There is also work in progress on interactive, real-time simulation graphics that allow the user to stop an analysis midway if results appear unfavorable, thereby eliminating some wasted time.

Some FEA models are so large that they must be run on a supercomputer because of the memory they require. Trends in development are moving toward algorithms that can also be run on super-minicomputers and some minicomputers. In particular, two-

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[75] See Chapter 2, Section 2, for more information on the miracle tool perception.

[76] Hibbitt, Karlsson, and Sorensen, "ABAQUS timing run", Hibbitt, Karlsson, and Sorensen, Inc., Pawtucket, R.I..

dimensional analyses are ideal for running on smaller computers since they are typically smaller models, and at least one U.S. auto company favors them (and is willing to work with the less complete results) in order to reap the time and cost savings. They then use the company supercomputer only for three-dimensional analyses they find necessary after interpretation of two-dimensional results. In general, computer technology is certainly making faster strides than the needs for simulation are growing. As a result of enhanced software and more efficient FEA numerical schemes, users in the next ten years will likely be able to run full, three-dimensional, detailed simulations on ordinary workstations quick enough to provide interactive analysis (perhaps less than thirty minutes for one complete iteration including run-time and pre-and post-processing; see equation above.).[77]

Obviously, however, auto company managers must make simulation hardware decisions in the meantime. Of course, FEA algorithms will run faster on supercomputers, but there is a significant cost and processing time tradeoff that should be considered. For example, one U.S. auto company uses a supercomputer to run simulations. Though the processing time is short, they have had problems with over-capacity demand within the company for the supercomputer's time . As a result, draw die developers may wait a week for results on a four-hour simulation because of time spent in a supercomputer queue. In this case, they would have received results faster with a smaller computer (also less expensive) of which they had sole usage or at least better control of scheduling. This is an example of a failure to utilize the equation for entire simulation time cited above. Supercomputers provide high processing capacity but also require a significant initial investment. Managers must reconcile possible future expansion of simulation needs with immediate and future costs.

Part Data Translation

All three U.S. auto companies cited slow data transfer from product engineering groups as a major source of delay in making stamping simulations. In some circumstances, this is a problem with inferior data transfer mechanisms that cause data loss or distortion, and these problems should be addressed technologically. Of course the optimal solution is to have simulation users directly connected to CAD sources, but this may necessitate conforming to undesirable hardware constraints.

The more prevalent cause for slow data transfer is when product engineering groups withhold part information from manufacturing groups. This dilemma is cultural

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[77] Estimate based on auto company representative comments. All believed that such quick analyses would be possible, and opinions about the time horizon varied from five to ten years.

and a symptom of the traditional cultural barrier between product engineering and manufacturing groups.[78] Chapter 2, Section 4 discusses this problem in detail and offers possible remedies. One mutual benefit to leverage is that if CAD data is sent electronically to manufacturing groups, then it will be easier to update and spread engineering change information and rerun simulations than it is with manual data hand-offs. Data transfer delays can be the largest factor in the overall time equation (above) and must be addressed when defining the strategic structure for simulation use. Otherwise, companies will not be able to control and optimize overall simulation efficiency.

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[78] In their automobile industry study, "Product Development Performance", Clark and Fujimoto give a very anecdotal description of typical interactions between Product Engineering and Manufacturing and the conflicts they create (p.122-7).

3.3 Organization: Who Will Run the Simulations?

As a component of simulation strategy, auto companies must not only define where simulation will be used within the company (see Chapter 1) but also what individuals will run the simulations. This section does not offer a "right" answer to this question but proposes some issues to consider when making it.

Should simulation developers (largely highly-educated mechanics and programming specialists with minimal die experience) function as an expertise center to run simulations for all users? Location of the expert center will have an effect on how simulation is integrated into traditional engineering tasks, and co-location would help to reduce functional cultural barriers. However, do the experts know (or can they learn without direct experience) enough to make intelligent changes in die development? For instance, do they know to try to eliminate buckling problems in a part before addressing nearby fracture or splits because one is likely causing the other. If not, under what structure can the draw die developers and simulation experts sit down together to analyze and iterate developments?

One auto company is optimizing this "expert" approach by assigning simulation experts to work in various areas of the company. The experts interact with product and manufacturing engineers directly, develop intuition from the engineers' expertise, and run simulations for them. So far, implementation has been relatively trouble-free, but it has only been tried in two areas. The largest problem they have encountered is that as the experts become more knowledgeable about dies, the engineers are off-loading their design work to the simulation experts who effectively have no time left to run simulations. This likely increases the cultural acceptance of the experts in the functional groups, but it may also leave no time for simulations. Management needs to work with such manpower constraints and define a middle ground between completely overlapped responsibilities and separately defined tasks.

Should either draw die developers or Product engineers be trained to use their own simulation programs? Certainly (as mentioned in Chapter 2, Sections 1 and 2) individuals may be more likely to accept and learn to use simulations effectively if they are trained to operate and interpret them. The training costs would likely be high and incurred over a long period. Simulation experts would have a major role in transferring their knowledge to the new users. Management will likely confront problems as users balk against having their personal workloads increased or modified, particularly if they do not understand the benefits of simulation. This difficulty will be even larger if users have not already worked with computer or CAD stations. A European auto company reduced the shock to draw die developers (who already used CAD) by first introducing very simple simulation programs and CAE (computer-aided-engineering) tools (such as the geometric programs described in Appendix B.3.) Die developers were able to use elementary computer tools and see the simulation results verified. Later, they were much more willing to undergo further training to run more complex and lengthy FEA simulations. Another strategic decision is when to hand off FEA simulation programs to non-experts and begin training. During simulation capability development, programmers constantly alter and optimize the codes, but this will likely continue long after the programs are ready for everyday use. Once engineers are trained and empowered to use simulation, retraining will be necessary as the algorithm is changed and optimized.

It is important to define the user when developing an FEA algorithm because expected user skill in operation and interpretation must be incorporated into the simulation design. Representatives from all three U.S. auto companies emphasized the need for further work on friendlier user interfaces and more algorithms that worked like "black boxes" (highly automatic) and were less sensitive to operator inexperience. They were in favor of such simple programs in particular for use by auto stylists or product engineers who are less familiar with die behavior. Conveniently, it might also be easier to make such early manufacturability analysis tools into "black boxes" because they are typically less rigorous and detailed than simulations used by draw die developers.

With regard to guiding simulation development, many managers keep repeating, "Keep it simple!". As computer capabilities improve and cost less, it will be more feasible for Product or Manufacturing engineers to have simulation capabilities on their individual CAD stations. Many U.S. auto company divisions are requiring their new Manufacturing engineers to have more formal education; most engineers with degrees are familiar with FEA and could be more easily trained to run complex analyses. With the uncertainty of this change, however, it seems likely that user friendliness and simple user interfaces will have a large bearing on how effectively engineers use simulations. Even most Master engineers will prefer a less frustrating and more fool-proof analysis tool.

3.4 Code Validation and Accuracy

FEA is a numerical approximation of a real engineering problem, and by definition, simulations cannot model or predict phenomena exactly. For purposes of simulation, I define accuracy as the ability to represent numerically what actually happens in a die. Accuracy and detail are not the same, but they are both components of validation. Due to the complexity of sheet metal drawing, accurate numerical techniques are difficult to develop. There will always be some error, and thus it is important to validate the ability of an FEA algorithm to simulate different types of drawing conditions. Validation also includes defining the detail level that an algorithm is able to simulate accurately. Code validation efforts also help users and observers to understand the actual capabilities of an FEA code so that they are neither under- nor overestimated.

To validate programs, simulation results must be compared to experimental data and real stamping experience. Of course, the ideal validation experiment would be simulating and physically testing identical developments. One U.S. auto company has acquired the funding to run several such experiments, but the cost can be high. Data from soft die and hard die prove-outs is also a good source. If no current parts are available for simulation, then historical tryout data (if it is adequately quantitative) can be used for validation. Several simulation groups I observed are making agreements with their management to run simulations on a set number or type of parts. A common strategy is to start with simple, less complex parts (such as hood or roof outer panels) and work up to more difficult ones (such as inner panels.) Sometimes, though, management's "prove-it-to-me" stance interferes with the progressive validations needed to develop accurate programs.[79] Management may also misjudge the need to validate programs and not provide adequate funding, access to required comparison data, or manpower.

Typically, programmers or engineers compare strain and displacement levels found on actual parts with those simulated. Techniques like circle-grid-analysis are used to obtain strain data that can be compared to simulations.[80] Ultrasound techniques can also measure metal thinning, and engineering data such as forming limit diagrams are also useful for validation. Figure 3.5 shows how circle grid analysis and forming limit diagrams can be used in concert to evaluate formability and simulation accuracy.

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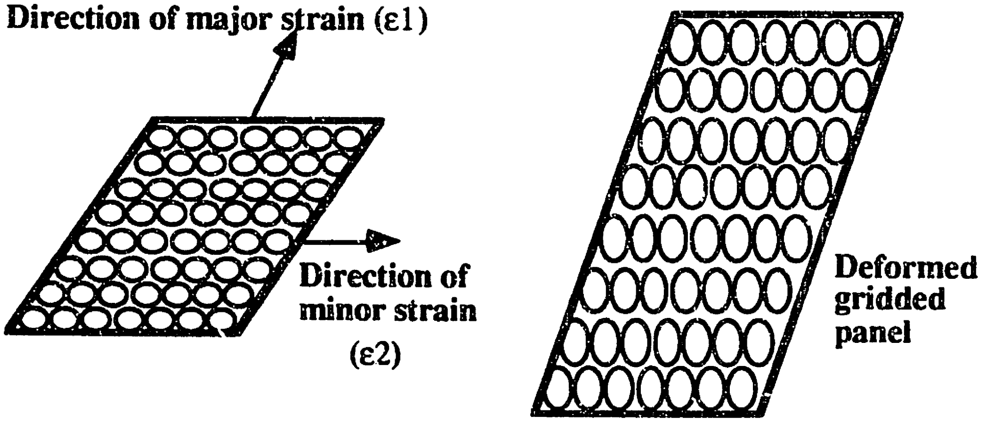
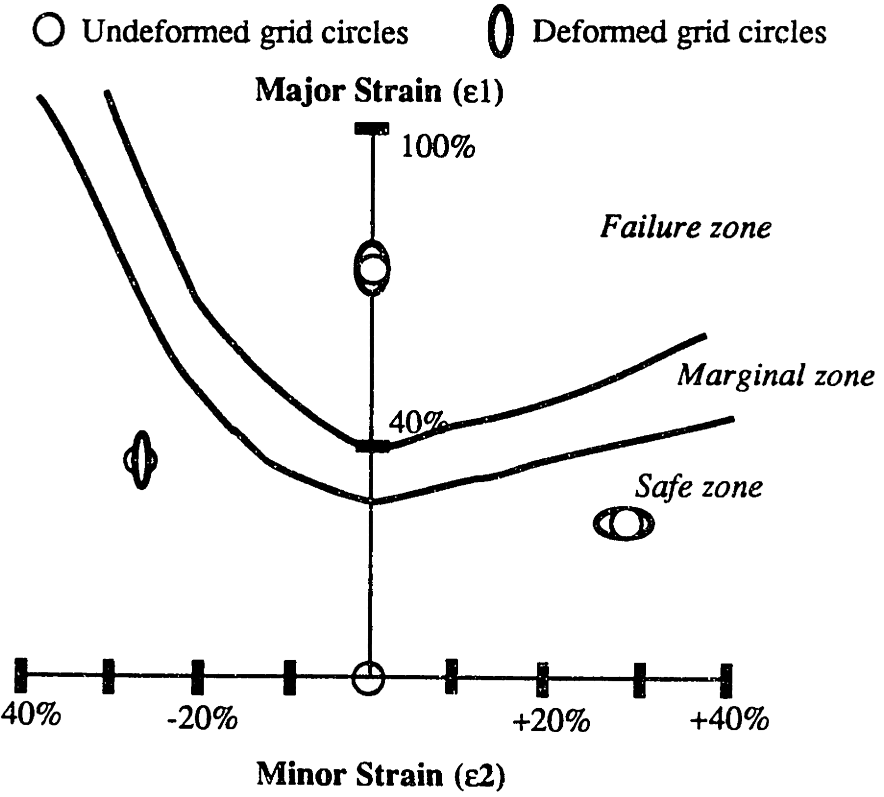
[79] See Chapter 2, Section 3, describes the "prove-it-to-me" syndrome and how it can stifle new technologies.

[80] Circle grid analysis is a technique by which metal sheets printed with small circles are stamped. deformation causes the circles to stretch into ellipses with major and minor axes aligned with the directions of the first and second principal strains. Measuring the elongation gives an approximation of the strain level. The method is common but highly sensitive to operator error. See Figure 3.5.



Circle grid analysis is a technique for measuring the thinning or strain that occurs in sheet metal when it is deformed. Metal sheets are printed with circles which deform along the axes of strain during drawing. These measurements correspond to those shown on a forming limit diagram below.



Forming limit diagrams (FLDs) show the strain conditions under which metal is likely and not likely to fail. The circles shown correspond roughly to the results from **circle grid analyses.** Forming limit diagrams are generated experimentally and are used in many industries. In addition to education, FLDs are used to verify simulation accuracy and help generate Engineering design guidelines from simulation results.

Figure 3.5- Circle grid analysis and forming limit diagrams are two analysis methods that can be used together to help determine simulation accuracy.

One problem I encountered was the uncertainty of data taken during physical tool prove-outs. For instance, if binder and punch force gauges or monitors are inaccurate, then data obtained with them cannot be usefully compared with simulation data. There are also many sources of error in die manufacture (like die finishing, cutting precision, unexpected or unrecorded engineering changes) that make the dies used in experiments different geometrically from those represented in CAD data used for simulations. Before making validation comparisons, it is important to make the stamping conditions as close as possible to those assumed for simulation. There will of course always be slight discrepancies.

Accuracy should even be regarded as part of simulation strategy. Certainly the enthusiasm of all the companies I studied is contingent upon the simulation being somewhat accurate. However, inaccurate algorithms are not useless, as long as the operators have the skill needed to interpret vague results. There is a danger in using or settling for data of questionable accuracy,[81] though some companies prefer to emphasize their interpretation skill and use less rigorous (and perhaps cheaper and faster) algorithms. Hence, validation is crucial for companies to know what capabilities they have to work with.

Useful information may also be gained from an algorithm that cannot model accurately on a detailed level, as long as the operator knows the accuracy level he can expect and knows how to interpret simulation results accordingly. For instance, two piece-part suppliers I interviewed were using simulation programs that did not capture local formability problems very accurately but were able to isolate problems from a global level. With that knowledge and sufficient interpretation skill, more detailed models can be run to examine local problems.

Without validation, Product engineers, draw die developers, stylists, management, or any other party that can stand to gain from simulation results will resist relying on the technology. Several managers commented, "I think we have a good simulation program in place, but beyond that, I don't think we really know what we have.", and there was a widespread belief that it is hard to leverage a technology unless you verify its potential. Validation is also helpful in dispelling the negative image of simulation as a miracle, 100% accurate tool. In fact, representatives from all three U.S. auto companies cited a need for more validation before further implementation could occur, not only to improve accuracy but also to break down more perception barriers.

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[81] "The push for faster algorithms means that frequently it appears more important to obtain any results in a short period of time than to spend a little more effort (and resources) to obtain reliable results that are truly useful for engineering design." Bathe, 1991, p.201.

It is difficult to make an accurate assessment of the level of accuracy or detail that U.S. auto companies are able to obtain with the simulation development they have made so far. One company I studied was able to verify an accuracy level of within 97% of experimentally determined metal thinning over several entire outer panels, with less accuracy only on sharp ridges or edges of the panel. In general, the accuracy with which companies are able to simulate now varies a great deal depending on the type and complexity of the part being simulated. Because their thinning distributions are more smooth and their geometry is less complex, U.S. auto companies are focusing now on achieving greater accuracy in outer body panel simulations. After reaching that milestone, all plan to tackle modeling inner body panel forming which requires greater detail and modeling accuracy. Simulation developers at all the companies I interviewed are confident of being able to model any body components (including inner and outer body panels, rails, and reinforcements) with "acceptable" accuracy before the year 2000.[82]

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[82] Each company's definition of "acceptable" accuracy is different and in some cases is not yet defined. As was mentioned above, programs of varying accuracy are useful as long as the person interpreting the results knows the accuracy level with which he is working.

Conclusions

Body panel stamping must be a core competency of successful auto companies. My interviews with stamping and manufacturing representatives support an assertion that the ability to control the stamping process correlates with the ability to control many components of manufacturing costs, auto body quality, and eventually the quality of the assembled vehicle body. Customers demand flawless auto body surfaces, and industry safety regulations and competition reinforce the need for manufacturing processes that can produce body panels of consistent and superior properties. Due to their shrinking expertise level and inability to transfer learning with regard to stamping die development, auto companies often find themselves at the mercy of outside die supplier quality standards and costs in order to meet these competitive demands. Because they are often unable to use traditional methods to capture knowledge and facilitate learning, U.S. auto companies must create and emphasize new learning mechanisms in order to develop internal core competencies. Finite-element-analysis-based simulation of body panel drawing is a tool that can help develop the learning structures necessary to build core competencies in stamping. It is certainly not the only, or perhaps even the best, mechanism available for promoting learning, but it is one that is available now and that can be implemented in current auto company organizations for substantial benefits.

Computer simulation of body panel stamping is being developed by the majority of auto companies around the world. There is a wide variety of approaches being taken with regard to algorithm theories, user interfaces, implementation structures, and development strategies. The three largest U.S. auto companies are using simulation (to varying degrees) to analyze draw die developments, while continuously improving their software. At each company, the managerial and cultural barriers vary as a result of individual managers' perspectives and different organizational personalities. Departments with good documentation habits or who are used to scientific analyses in manufacturing development have a decided advantage in simulation implementation. The current challenge for all these companies is to analyze and form a strategy for addressing the specific cultural and implementation problems they face; such problems are the bottleneck preventing further success with simulation technology.

From my observations and many interviews, I conclude that stamping simulation can be a very useful source of manufacturing analysis information and can form the foundation of a scientific, learning structure for body panel manufacturability. The largest barriers to success I observed are

- the lack of a clear, well-defined implementation strategy
- the failure to address inevitable cultural and organizational barriers proactively, especially those between product and process departments
- lack of adequate validation of simulation program accuracy and capabilities
- lack of a "program manager" to coordinate education, implementation, development, and managerial and organizational interfaces for the software development group

Particularly the failure to address cultural barriers appears detrimental to the success of any technology. Education and intensive user involvement are the most common approaches to overcoming workforce mis-perceptions and technology rejection. Also, though few organizations have progressed to the point of encountering it, I anticipate that the lack of information linkages necessary to disperse and learn from simulation results will become a problem and could limit the value of the technology. Preparing for this problem will not only maximize learning from simulation efforts but also from other analysis techniques (such as prototype dies and vehicles).

U.S. auto companies are focused on using simulation at the draw die development stage of process development. There are many benefits of using simulation there, but I conclude that the greatest gains are to be made by using simulation in die supplier relationships, especially as companies continue to "outsource" developments to counter their weak expertise, and as a manufacturability tool in product development. Core competencies in stamping and die development should extend beyond functional lines to be a priority for the total company. Stylists and product engineering groups need to understand and integrate responsibilities and goals for low-cost, high-quality manufacturing into their total auto development process if U.S. auto companies are to meet the demands of global competition.

Unlike U.S. auto companies, many European and Japanese auto companies are combining their simulation development efforts actively through research consortiums and joint ventures. Though there are some similar organizations in the U.S., such as the Engineering Research center for Net Shape Manufacturing at Ohio State University, participation by U.S. auto companies seems limited in both funding, communication, and interaction with researchers. For example, representatives from this research group said there was a lack of real part data made available to them with which to verify their simulation programs as well as a lack of industry feedback as to their particular simulation needs. Foreign companies appear to be approaching simulation development much more aggressively than domestic auto companies and mostly through these collaborative efforts. Similar organizations and long-term investment efforts could be made between U.S. auto companies *if* they are willing to share their learning and downplay proprietary information concerns in order to focus on beating foreign competition.

A cohesive strategy is necessary in order to educate a company about how simulation, or any technology, will fit in and alter existing business practices. Figure 4.1 shows how simulation results can be combined with other company assets and analyses to improve the production of robust draw dies, promote organizational learning, and build core competencies in draw die development and stamping. Scientific analyses combined with incremental learning, verification, and feedback will build internal company competency in draw die development *if* the information linkages necessary to gather and distribute this learning exist. Also, a sense of ownership of the technology and its success will improve the workforce attitudes and their approach to simulation. Formulating such a model helps all functions to understand and form a strategy for how they can contribute to and benefit from new technologies.

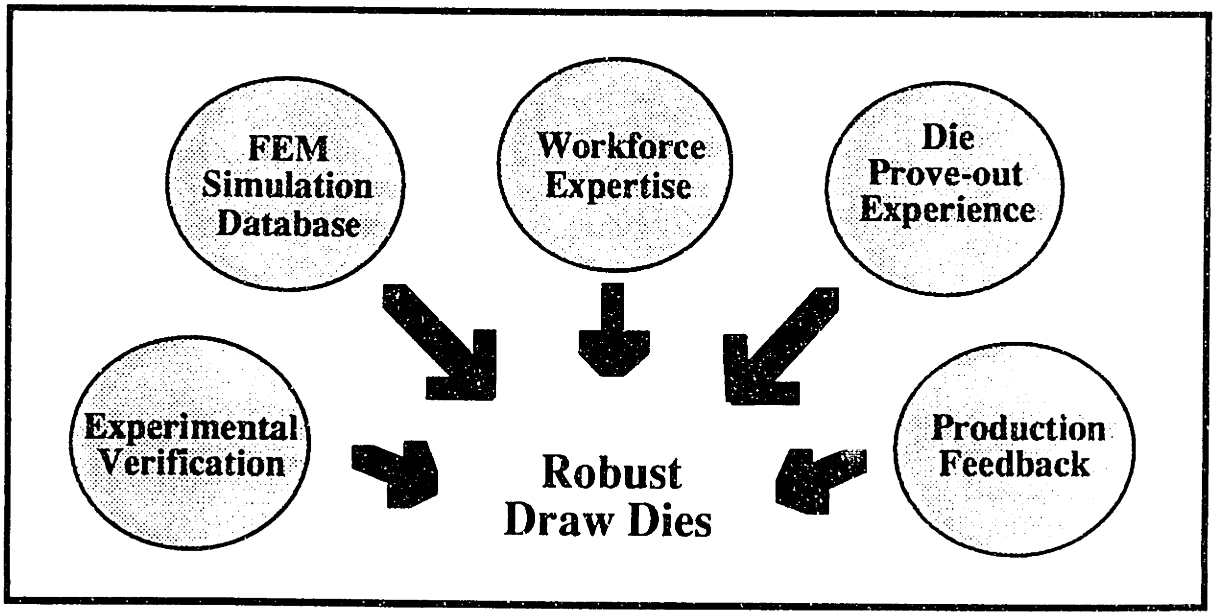

Figure 4.1- By combining scientific analyses with functional expertise experimental data, an auto company can continuously improve its core competencies in areas such as draw die development.

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Appendix A

A.1: Automotive Stamping and Draw Dies

In this section, I explain the basic process used to deform metal sheets into stamped metal car parts, how draw dies are used to deform panels, and what variables determine die performance.

In order to change a metal sheet into the auto body panel or part, a sequence of deformation by several different dies is necessary. Figure A.1 shows a schematic of a typical sequence of dies and the operations they perform. Most but not all parts first go through a draw die which gives a part its initial shape. Then, a series of line dies trim off excess material, punch holds, and add detailed shape. Each die performs a necessary function, and the line of dies must be optimized both individually and as a group in order to produce high quality panels with as few dies as possible. The performance of draw dies, however, remains the most difficult to predict and to perfect.

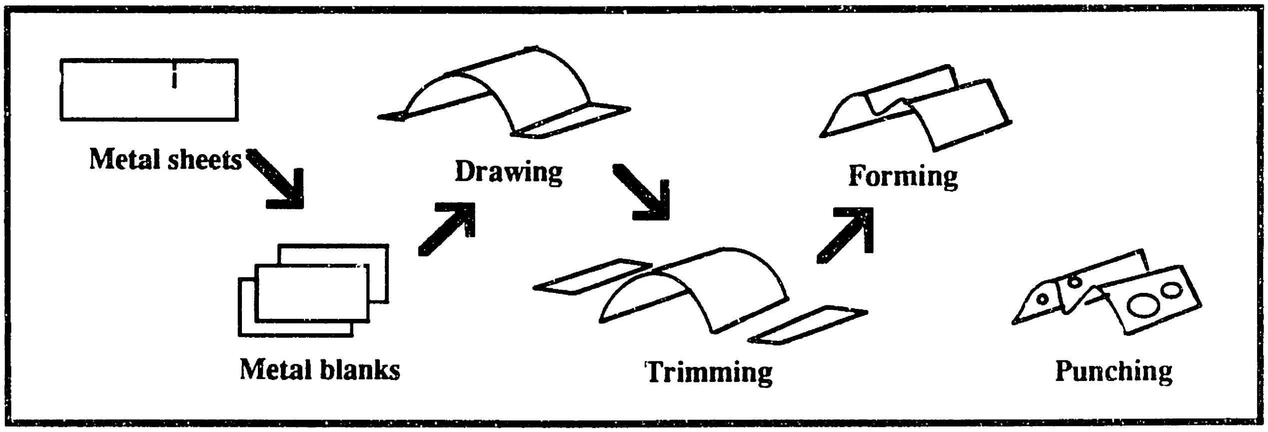

Figure A.1[83]- Body panels are formed by stamping them with a series of different types of dies. This figure shows most typical operations, including a draw die which is the focus of this thesis.

Figure A.2 shows a simple representation of a draw die and its basic features. If a draw die is used to form a panel, then it is a first die in the line. The metal sheet is usually held in the die with a binder ring and, often, some configuration of drawbeads. The force with which the binder clamps down and the restraining of the drawbeads

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[83] Sequeira, 1991, p.39.

control the amount of metal that is drawn into the die. The shape of the binder ring determines how the metal will "wrap" around the punch. As the punch is lowered into the die cavity, metal is drawn into the die cavity as allowed. When further metal flow is restricted, the sheet will stretch over the punch and plastically deform. In the process, the metal sheet (blank) will take on the shape of the die, gain greater strength due to work-hardening, and become more stiff. Though this description and diagram are relatively simple, activity in the draw die is much more complex than implied by this figure.

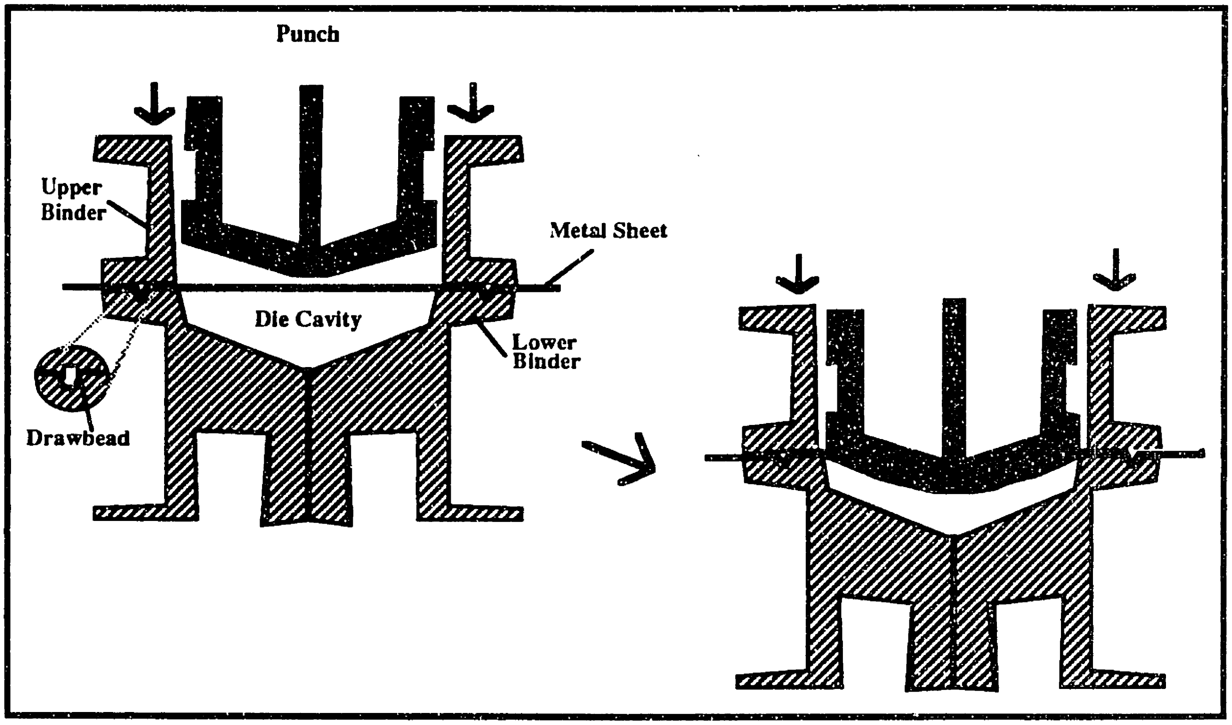

Figure A.2- This figure shows a schematic diagram of a draw die operation. The draw die set (die and punch) in the stamping press deforms the metal sheet held by the binder. Drawbeads may be used to provide extra holding force in the die.

Figure A.3 lists some of the variables that interactively determine metal behavior in a draw die and the quality of the resulting panel. Indeed, it is a very complicated combination of factors that determine whether the panel will achieve the desired increase in strength and stiffness and if its surface finish will be flawless or studded with defects. Compression of metal, uneven flow, overly restricted flow, and other conditions may cause wrinkling, buckling, or splitting in the surface of the metal during drawing. These phenomena are particularly undesirable in the large, expensive outer body panels where perfect appearance is a critical quality characteristic. Some of these variables can be controlled by the "designer" of the draw die (called the developer): specifically, he determines the binder geometry and drawbeads configuration already mentioned. Other forming criteria, such as part shape and metal thickness, have already been determined upstream in the manufacturing or product development process, and still others, like environmental factors are fundamental sources of variation in the stamping process that must be acknowledged in the development of a robust draw die.

Blank:	Dimensions Location in die
Lubrication:	Type Coating thickness and distribution
Stamping press:	Punch guidance and speed Binder force and its variation around ring
Metal:	Thickness Mechanical properties (hardening, anisotropy,etc.) Surface coating
Die:	Alignment in press Surface finish Punch radii and binder ring geometry Drawbeads (number, location, type, and size)
Environment:	Temperature and humidity Dirt or other debris in die cavity

Figure A.3- There are many interacting variables that determine the quality of drawn body panels. Some are controllable by product and process engineers, while others are environmental factors that must be accounted for in order to design robust die developments.

A.2: Information Flow and Dies

This section details how part information flows from product design/engineering through advanced manufacturing to the die construction source. Critical issues in this flow are the role of engineering change notes (ECNs), feasibility analysis, and die try-out periods. This section is based on the basic systems in place at my principal research company, though those systems are changing and improving quickly. Also, I know from my research that systems at the other U.S. car manufacturers are similar in spirit though may be different logistically. These systems should, nonetheless, serve as a good generalization to the U.S. industry.

Feasibility Analyses and Engineering Changes (ECNs)

Due to the advance of simultaneous engineering efforts in the U.S. auto industry, there is increasing early interaction between product engineering/styling and manufacturing groups to analyze the feasibility of producing particular parts (see Figure A.4). At both the advanced feasibility and feasibility stages, manufacturing groups can analyze the feasibility of stamping a particular part successfully. Manufacturing can request concessions or changes in the part's styling or engineering that would make its mass manufacture easier or even possible. For instance, parts (such as quarter panels) requiring deep drawing in corners will likely be easier to form if that corner's radius is as large as possible. With feasibility, vehicle styling (or engineering) groups and stamping personnel can reach a compromise and perhaps avoid expensive engineering change notes (ECNs) later on.

ECNs are documented changes made to parts during product development, and they are necessary to continuously optimize vehicle parts. Such changes may be motivated by styling decisions, engineering problems, or manufacturing difficulties. Usually, ECNs take place after manufacturing has begun engineering dies to form parts, and often, dies or developments must be altered to accommodate an ECN. In fact, the later ECNs are made, the more expensive they are in both time and dollars.[84] Also, if an outside supplier is working on a die, he will likely charge pro-rated fees for any ECNs. Multiple changes can become very costly. Though some expensive changes cannot be avoided or predicted, early identification of necessary ECNs can save much money and lead-time.

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[84] Roodvoets, p.46-50.

Even with the motivation of fewer and more cost-effective ECNs, however, proper feasibility analysis does not always occur. It can be overlooked, insufficiently funded (so that proper analyses, preliminary die mock-ups, or adequate manpower cannot be afforded), or missed because the proper channels of communication in both departments could not be found. Also, feasibility is usually analyzed on a go/no go basis and is based solely on the intuition of experienced stamping experts. This approach makes it difficult to teach any concrete (or qualitative) guidelines to product engineering or styling groups for future reference. It also requires the continued input of a stamping guru (who are usually few in number in a particular company). Furthermore, this type of intuitive evaluation avoids much quantitative, scientific analysis and perpetuates the image of metal stamping (particularly draw dies) as much more an art than a science.

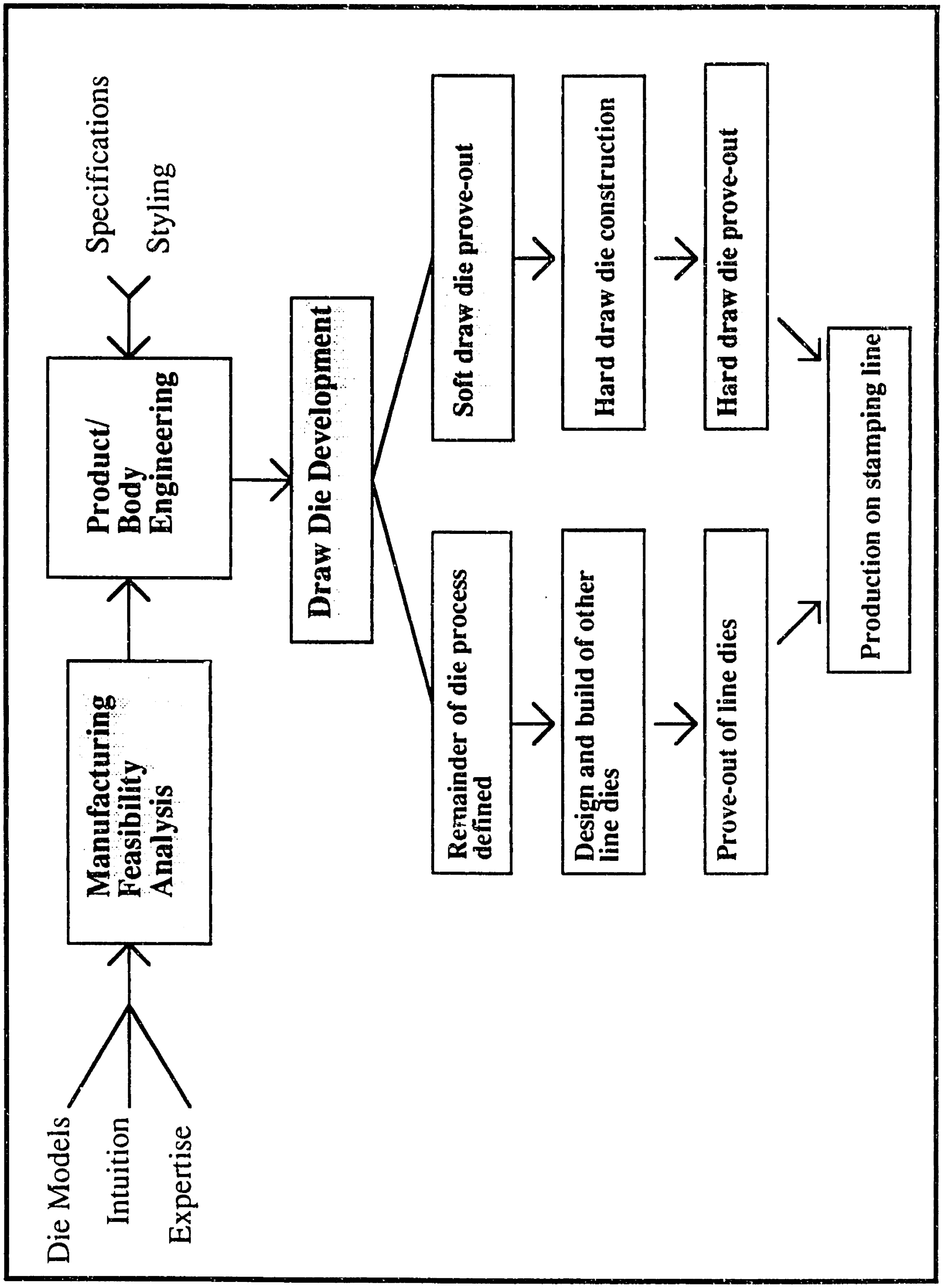

Figure A.4 - This flow chart shows the traditional stages of information flow and die verification procedures used in U.S. auto companies. Though thorough, this stream of procedures can be wasteful and fails to encourage learning within and across functions through teamwork and feedback.

Die Prove-out: Operation Trial-and-Error

Once draw die specifications are released to manufacturing groups, draw die developers begin their work. They take the part information (either on paper or via CAD) and add the addendum (die surfaces over which metal will flow), the binder geometry that will determine how the metal wraps around the punch, and any drawbead configurations that are necessary. Usually drawing only from his experience and few (if any) significant records, the developer presents his best draw die development which a committee must approve (from their collective experience). Then, a process of iterative analysis begins in which the draw die development is "proved-out", or tested, usually in both soft[85] and hard tools.

In soft die prove-out, metal blanks are formed into panels using the soft tool and examined carefully for defects or forming problems. If the panels are acceptable, then the soft tool becomes the development from which a hard tool will be made. If it is not acceptable, than some combination of machining, welding, and tweaking of die surfaces is used to adjust the die. More blanks are tried, and this process continues until the panels are acceptable. Indeed, this trial-and-error verification can be quite costly in terms of lead-time and expense, especially if several different soft tools must be tried for a part. Also, little effort is usually made to record the changes made to the soft die in order to educate the developers and prevent repetitive mistakes in the future. The goal is to tweak the tool until panel quality seems adequate.

With hard tools, a similar iteration takes place. Sometimes because soft tool materials do not behave as similarly to steel (or hard tool materials) as expected, changes are necessary. Other variables such as stamping press setting may also necessitate hard die tweaking. The level of performance required from a hard die prove-out is also higher than that of soft tools because a hard die must stamp panels robustly over the life of the vehicle. The cost of hard die prove-out is higher than that of soft tools because machining takes longer and usually occurs in the designated stamping plant where excess manpower is scarce and expensive. Hard die prove-out also occurs later in the development process where unforeseen delays could directly effect the production launch of the vehicle.

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[85] Soft tools are made of metal alloys that are much "softer" or easier to machine than steel or cast iron, the materials of which "hard" tools or dies are usually made.

Appendix B

In this appendix, I explain the basic theory and application of finite element analysis (FEA) to investigating complex engineering problems. Along with some examples, I present reasons why FEA is viewed as particularly useful in analyzing metal deformation situations.

B.1 What is FEA?

Finite element analysis (FEA) is an engineering analysis tool that has been in use since the early 1960s. Originally, engineers used FEA to model the effects of various wind and vibration forces on airplane structures. In the thirty years since, however, FEA has evolved to encompass applications in many engineering fields. For example, FEA is used to determine the effect of traffic loads on bridges by calculating the expected displacement or strains in the structural material. Perhaps in designing ovenware, one needs to know how a pan's material will respond to heating. FEA is used to predict the resulting temperature gradient in the pan under various heating conditions. Another example is aerodynamic testing of how air flows over a vehicle of various structures at various speeds. In the auto industry, FEA is also used to simulate crash tests and how certain car body designs and materials perform under different impact circumstances. The number of possible applications for FEA is large and quite varied, and new uses continue to appear.[86]

Though the applications may vary widely, all FEA techniques have some basic principles in common. Essentially, FEA is a mathematical simulation of a physical engineering problem. Most realistic engineering problems such as the examples above are much too complex to solve exactly. Even with simplifications, the number of variables involved in describing geometries, material characteristics, forces, and all the issues at bay may generate tens of thousands of equations which must be simultaneously solved. FEA allows the engineer to make some intelligent simplifications and then calculate a solution of controllable accuracy using computer power.[87] Of course the most

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[86] Many texts detail the history of FEA and the variety of past, current, and future applications. Robinson discusses the work of early FEA pioneers, and Brauer is also a good resource for FEA history.

[87] Actually, FEA solutions were originally calculated laboriously by hand, but currently, most FEA algorithms are so complex as to be manageable only by a computer (and usually a large one at that..) See section about hardware in Chapter 3. Though some applications remain simple and can be run on personal computers, most FEA models today require the speed and memory of supercomputers or agile workstations to be effective in an industrial setting.

accurate way to analyze an engineering situation is to run a prototype trial of the situation and simply measure the output. Due to costs, time, safety, and other restrictions, however, engineers usually need to predict how particular systems will perform under expected conditions without, or before, going through physical trials.

B.2 FEA Input and Output: What Goes In and What Comes Out?

To analyze a given situation, an FEA algorithm-user must provide several inputs about the body or structure being analyzed. The computer program must know the details about the body (geometry and materials), the environment in which it is placed, and the constraints under which it acts. Each FEA algorithm is designed to handle a certain range of structures, materials, and circumstances, and a program operator must be sure to fit the engineering problem with an FEA algorithm that can handle it accurately. For example, different programs can model one-, two-, and three-dimensional problems, static or dynamic situations, and linear and non-linear material responses.

Either from a CAD data file or some type of manual or digital input, the geometry of the body in question must be defined in a form the FEA computer program can read. Once put in the computer, the geometry and surfaces are prepared for analysis and "meshed", or divided into small units called elements. Figure B.1 shows a meshed quarter panel, ready for analysis. Operators will often use an area of finer meshing in areas of high detail or rapidly-changing geometry. A finer mesh illuminates more subtle body responses. Defining geometry is the stage at which the most simplifications are usually made in FEA programs. Analyses can be run with extremely detailed meshes if it is crucial for the problem at hand, but the trade-off will be a more complex solution requiring greater computation time and being more prone to error. Hence, it is important to know the level of accuracy required for each problem.

Once the geometry is defined, the structure's material must be described, usually through a series of parameters that the FEA algorithm understands and uses to calculate material responses (such as thickness, tensile strength, and anisotropy ratios). The material parameters can be varied in the area of each element so that the algorithm accurately takes into account any material variations in the structure.

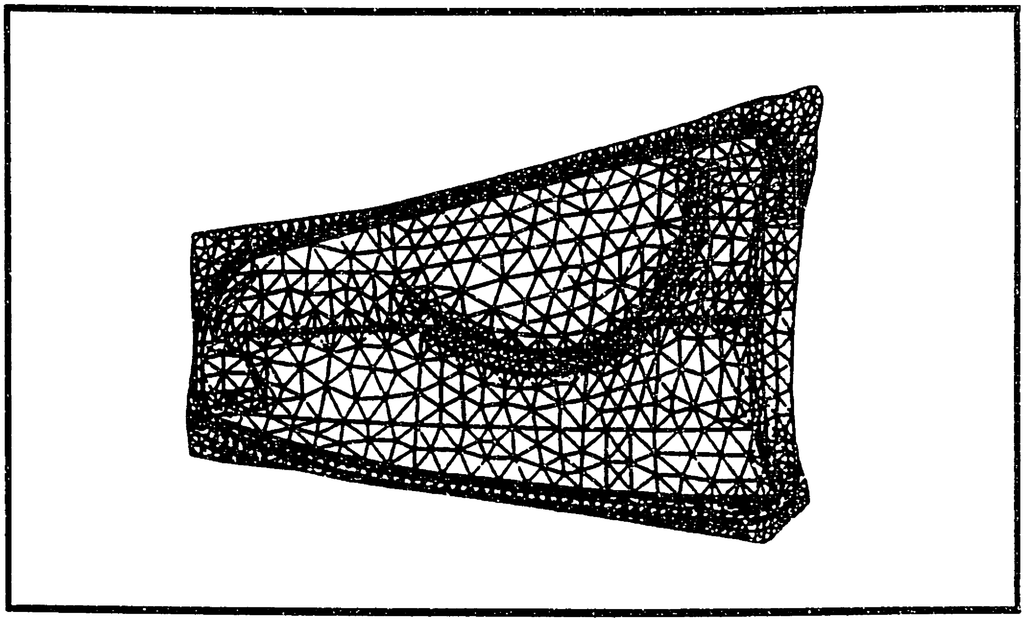

Figure B.1[88]- This quarter panel has been meshed for analysis. Note the finer mesh in areas of detailed geometry or where more detailed results are desired.

With the thing "being acted upon" totally described, the FEA algorithm needs also to know what will be "doing the acting." This stimulus could be an electric or magnetic field, a series of mechanical stresses (in the case of metal stamping), or even a fluid flow potential. A user must input the intensity, distribution over area, and type of stimulus that will act on each element. If the situation being simulated is dynamic and changes over time, then the stimulus's variation over time must also be defined.

The other general category of inputs is constraints. These are usually called boundary conditions, and they are restrictions on the body's response. For example in metal stamping, some boundary conditions are any clamping mechanism used to restrain metal flow into the die and friction between a die and a metal blank.

Once all these variables are entered into the program, the algorithm will calculate how the body in question will respond to the stimulus and constraints. Responses may be several things depending on the type of stimulus. For instance, the heated ovenware pan mentioned above will change temperature. In metal stamping, the metal blank will be deformed, and the program will compute the resulting stresses, strains, and deformations in the panel. Regardless of the output, the program calculates it mathematically, and the general output would be a very lengthy list of numbers showing the output expected at

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[88] El-Mouatassim, et al, 1991, p.659.

each element. Today, most operators use fancy post-processing programs which transform all these numbers into color graphs and graphics of the affected body.

How does an FEA program transform the inputs to the outputs? Within the algorithm is a series of equations which computes how each element and its material will respond to the stimulus and constraints. Because of the number of equations and the requirement that they all be solved simultaneously, the computer iterates through answers until it finds the closest one. This procedure continues across all the elements.

The details of equations and the physical principles used in most FEA programs are beyond the scope of this thesis. There are, however, many general texts dealing with this subject. Bathe and Rao are both relatively theoretical texts which discuss FEA model formulations and the variety of approaches and equations available. Steele and Brauer's text, What Every Engineer Should Know about Finite Element Analysis, both discuss specific formulations but with less complexity and more emphasis on inexperienced-user concerns.

B.3 Why Choose FEA for Stamping Simulations?

FEA is certainly applicable to the analysis of sheet metal stamping simulation (or rather sheet metal drawing), but there are also other types of simulation available. Similar to FEA, there are other numerical techniques such as the finite difference and shell-decomposition methods. Many auto companies are also using geometric simulation programs. Geometric methods vary in complexity, but most are CAD tools which show the physical breakdown of contact between the die and a metal sheet. The operator is left to extrapolate from his experience how the metal will flow and behave because the simulation only shows contact not deformation. Other geometric programs may also use line-length calculations to estimate the amount of strain expected in certain areas of the sheet.

Due to the complexities of auto body panel geometry, non-linear material behavior, and dynamic friction conditions between a die and blank, draw die behavior is impossible to predict exactly. All the above methods, however, may be used for approximate draw die simulations. FEA is widely used because it is flexible enough to handle a wide range of those variables and can compute a detailed yet highly accurate solution.[89] Some other numerical methods cannot handle complex geometries or

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[89] Tseng, p. 13.

accurately model the large displacements and strains characteristic of body panel drawing.

Geometric programs are useful given an operator has sufficient practical experience to interpret the results. They also have the advantage of being easier to operate and requiring much less data preparation and computation time (often a minute or less) than FEA or other numerical methods. Geometric programs, however, cannot calculate the effects of different material properties or subtle changes in die geometry, and so their utility is limited. As a first-cut analysis to uncover possible large-scale drawing problems, geometric programs are ideal. They cannot, however, provide the detailed simulation that FEA can.[90]

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[90] In two of the auto companies I studied, geometric programs are used routinely to analyze every drawing condition, and FEA is used only if the operator, using his experience, anticipates a problem he cannot predict from the geometric, contact analysis alone.

In-House vs. Commercial Software Development: To Buy or Not To Buy. A Comparison of the Options

Auto companies debate internally about whether to concentrate their efforts on developing their own in-house FEA simulation program or to focus on selecting from among the many commercially available programs. Certainly there are many reasons to choose either option, or even both. In this section, I discuss many of the differences and similarities between the two types of development strategies, and Figure C.1 summarizes many of them.

Commerically-Developed Programs	Internally-Developed Programs
• Offers wide application to different types of engineering problems • May provide training or implementation guidance as part of purchase • Can be purchased immediately • Allows for interaction and "debugging" help from other organizations • Includes updates/improvements in algorithms • May come with pre- and post-processing capabilities	• Can be tailored and specific to certain problems • May be cheaper to develop. • May have simpler user interfaces • May require less skill to run simulations or interpret results • More freedom to alter code as needed and quickly • May be faster as a result of being a less bulky algorithm

Figure C.1- There are many tradeoffs to consider when a company is deciding whether to invest in a commercially- or internally-developed simulation program strategy.

Most companies look for advantages in three categories when choosing an approach to developing capabilities in FEA simulation: accuracy, cost, speed, and implementation. Because of the variety of simulation programs presented at national and international conferences,[91] the results of any benchmarks run as part of the festivities are

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[91] Many conferences have focused on or included sections dealing with simulation of sheet metal forming. They are good resources for international progress in the area and for technical papers with some, though not much, applications research. (See Bibliography for VDI, NUMIFORM, and ICTP3.)

good resources for comparing the capabilities of in-house with commercial simulation programs. Conversations with various conference-goers and results from one benchmark in 1990 indicated that there was "no apparent difference in commercial multi-purpose programs and specially written ones with respect to accuracy." They found that computation times were on average higher for commercial programs, but that the main differences between the two broad categories were in implementation advantages.[92] Earlier comparisons of programs showed a greater variation in accuracy overall. but as the scientific community focuses on optimal algorithms, the expected variation in accuracy should continue to diminish.

Advantages of in-house-developed programs. All four auto companies I studied are using in-house-developed simulation programs for stamping. Each has been working on such programs for at least three years; some for many more. In-house programs have the advantage of being tailored to the specific concerns of a company and of being proprietary technologies. As opposed to the general modeling capabilities of commercial programs, in-house development can be focused on solving the most prevalent or expensive stamping problems a company may face as efficiently as possible using the hardware currently available. Also, personnel can easily alter the code if comparisons between simulations and controlled stamping experiments reveal inconsistencies. In-house developers have the freedom to experiment with modeling quirks such as edge-of-technology material models that commercial programs cannot provide. For example, several U.S. companies have targeted the elimination of wrinkling problems in large outer body panels. Code writers, die developers, and die tryout personnel can work hand-in-hand to compare simulations and optimize models. The same investigation is necessary to validate commercial programs, but companies have less power to alter the code itself, often having to wait many months for permission or instructions to make even small alterations. One U.S. auto company has completely rejected commercial programs because in-house efforts give them more control over the codes themselves.

Developing effective in-house efforts, however, also requires a considerable long-term investment in dedicated manpower and a willingness to wait until the code is usable. Many foreign and some U.S. companies are cutting the time required for this R&D by building their in-house efforts from adaptations of publicly-available, U.S., general simulation programs (like DYNA3D). They are also forming consortia and investing money in university and research groups to develop tailored simulation programs.

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[92] Lee et al., 1991, p.590.

Why choose a commercial FEA package? Companies selling commercially available programs have been actively touting their capabilities in sheet metal deformation simulation as the application has received more publicity in recent years.[93] Programs such as ABAQUS, NIKE, ADINA, MARC, and DYNA3D are general purpose programs that can simulate many phenomena using FEA. For example, several of the same programs can be modified to simulate crash tests, aerodynamics, and stamping.

Choosing from among the alternatives. There are several characteristics in which both in-house and commercial programs differ. Their universality tends to make commercial programs bulky, and they tend to be slower than in-house programs with regard to computation time. Also, because of the number of options available to them, operators of commercial programs must be trained extensively in choosing the FEA parameters most suitable to sheet metal forming or whatever application they are using. Fortunately, included in the purchase price, software companies usually provide a service contract that includes on-site training of operators by FEA experts and continual updates about code modifications and new applications. The software companies can also help with benchmarking hardware and determining if the speed and memory they provide is adequate for certain types of simulations using their software. Commercial programs are popular, because they usually include pre- and post-processing programs that assist with data preparation and formatting, thereby eliminating the need for companies to purchase or develop their own.

Even with these efforts, however, some authorities argue that the user-unfriendliness of searching through lengthy, complicated user manuals and manipulating large general purpose programs will make such commercial approaches to simulation obsolete.[94] The training necessary to use such programs is extensive. Also, the prospects of having ready-to-use analysis programs available for each designer's CAD terminal seem slim given the level of user-specialization currently required. Some researchers see the future of process simulation in special-purpose programs designed for easy operation and interpretation, and as a result, future research should focus on algorithm packaging and user interfaces.

Using commercial programs may help overcome cultural barriers if a specific, or similar, program is being used in another part of the company. Two parts of a company may link up to share information gained from simulations as opposed to running

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[93] Miles, February 1991, p.1.

[94] Anderheggen, 1991., p. 231-4.

completely isolated analyses. At least one U.S. auto company also sees the advantage of using commercial programs interactively with die suppliers for stamping simulation because the technology is not proprietary. Furthermore, the suppliers can be trained to operate and interpret the simulations by trained software personnel. One European auto company has a group whose specific assignment is to evaluate commercial or university programs to add to their repertoire of stamping simulation capabilities.

Commercial programs are attractive to some smaller part manufacturers because they do not have the spare manpower or expertise to devote to in-house efforts. Innovative companies such as Forming Technologies Inc.(FTI) of Canada has developed a toolbox of simulation programs that includes FEA and geometric programs designed specifically for its member companies' needs. Organizations like FTI limit their number of customers in order to keep their development efforts focused. This philosophy is a cross between the advantages of traditional in-house and commercial approaches. It is the prediction of some FEA experts that focused commercial and research efforts such as FTI and consortia will continue to enter the market place. User-friendly process simulation is becoming a more commonly accepted and desired approach to quality improvements and cost and lead-time reductions.