THE EVOLUTION AND IMPLEMENTATION OF ELECTRONIC PROTOTYPING SYSTEMS

by
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ABSTRACT

In traditional product development processes, system level design integration and design verification are often conducted with the use of physical prototypes. Unfortunately, construction of physical prototypes for large, complex products can be very costly and contribute significantly to product development cycle time. In an environment of intense global competition, it is increasingly necessary for manufacturers to reduce their product development times and related costs. As a result of this competitive pressure and recent improvements in computer aided design tools, there is now a trend to replace the use of physical prototypes with increasingly complex, analytical prototypes.

This thesis examines the evolution toward the use of increasingly comprehensive analytical prototypes in the design of complex products. The basis for this evolution is a comparison of the activities which have occurred within the aircraft and automotive industries at The Boeing Company and the Ford Motor Company. Specifically, this thesis documents the lessons which can be learned from the successful implementation of a comprehensive analytical prototype on the Boeing 777 aircraft. In addition, based on current functions of prototypes in the automotive development process and future prototyping needs, future steps in the evolution of analytical prototypes are proposed. It is proposed that a future opportunity for the use of analytical prototypes lies in the integration of both product and process data. To achieve this, a new generation of 4-dimensional design systems will be necessary which will be capable of capturing assembly sequence information. This information will enable analytical prototypes to be used to communicate assembly process, detect assembly interferences, and calculate assembly variation.

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Acknowledgments

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1.0 Introduction

Traditional product development processes have relied upon the use of physical prototypes to confirm designs and provide an opportunity to evaluate the design. Unfortunately however, the construction of physical prototypes for large, complex products can be very costly and can contribute significantly to product development cycle time. In this era of intense global competition, substantial competitive advantage can be gained by a company which is able to reduce its development cycle and related costs. Due to the rapid improvements in computer capabilities and innovations in 3 dimensional solid modeling systems, there now exists the possibility of reducing this reliance on physical prototypes.

As evidenced by the development of the Boeing model 777 aircraft, it is now possible to design a complex product entirely on the computer without the need to build a physical prototype. Using three dimensional solid models representing the components of the aircraft, Boeing engineers were able to design and 'build' an electronic prototype with which to confirm the design prior to beginning production. As a result, integration errors such as interferences, gaps, and misalignments could be detected and corrected while still in the design phase, thereby significantly reducing the cost of rework and scrap during production start up. This process was extremely successful and resulted in a reduction in changes, errors and rework by over 50% from previous programs.

Due to this success and the increased availability of the required computer aided tools, many other industries are also adopting similar approaches to development. One of the areas where this is occurring is in the automotive industry at Ford Motor Company. Within Ford and most auto manufacturers, computer-aided design tools have been extensively used for many years. However, the capabilities and use of these tools have not yet been applied to integrate the system level design on the scale which occurred at Boeing during the 777 program. Since this is now being attempted, there is considerable interest in sharing in the learning to be gained from Boeing's implementation and the processes and procedures that were necessary for its success.

1.1 Objective of thesis

The objective of this thesis is to document the evolution toward the use of increasingly comprehensive analytical prototypes in the automotive and aircraft development process. Specifically, this will focus on the revolutionary progress achieved during the 777 program and the successes and problems encountered during this effort. In addition to documenting the historical progress to date, a roadmap illustrating the potential future evolution of analytical prototypes will also be presented. This future evolution is based on the current trends observed at both companies and future needs of the automotive prototyping process.

1.2 Method of study

The information for this thesis was obtained over a six month period as part of an internship with the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology. The LFM program is a joint partnership with between the MIT School of Engineering, the MIT Sloan School of Management and 13 major U.S. manufacturers. Among these sponsoring corporations are the Ford Motor Company and The Boeing Company which provided much of the subject matter for this research. The information sources for this project primarily consisted of interviews with members of the design community of both corporations as well as personal observations obtained through participation in the implementation of an advanced design system. Other sources of information include software product literature, demonstrations and presentations on related topics such as assembly modeling, virtual reality and product data management.

2.0 Company Backgrounds and Comparisons

One of the primary objectives of this project was to share information regarding electronic prototyping activities between the two companies involved in this study. Specifically, this project was designed to share the lessons learned from Boeing's use of the Digital Pre-Assembly (DPA) process on the development of the model 777 aircraft. This information was subsequently used at the Ford motor company to assist in the pilot implementation of a similar system. Much of this information consists of problems and success factors discovered during Boeing's implementation which is contained in the fifth chapter of this thesis. An independent study regarding a different topic was also conducted simultaneously which resulted in a reciprocal transfer of information. Although much of the information transfer for this project was in one direction, many of the general trends which were observed were the result of an assimilation of activities being pursued at both companies.

To provide a context for this information and its transferability between industries, a brief comparison of each company and their products is discussed below. Although there are order of magnitude differences in some criteria, there is sufficient similarity between the design challenges which face each company.

The most significant similarity between these companies is in the sheer complexity of their products. Due to this complexity, both automobiles and aircraft design can be considered to be what Eppinger [1] refers to as "Product Development in the Large". As such, development programs consist of several hundred, even thousands of engineers organized in groups that are responsible for segments or subsystems of the products. In this type of environment, integration of the various pieces of the design becomes a significant challenge and communication between different design groups is essential. As shown in Figure 2-1, Boeing's challenge in this area is quite formidable. The quantity of unique parts contained in an aircraft is approximately 130,000 as compared to an automobile which, although still quite complex, only contains approximately 13,000. Equally daunting is the number of design team members required to produce the new aircraft design. At its peak, the 777 program combined the efforts of approximately 3,000 designers and engineers. In comparison, an automobile program may involve several hundred. Although there is approximately an order of magnitude difference in the complexity of the design, both design efforts are large enough to necessitate a similar approaches. As soon as a design team reaches a size where it is not possible for all members to attend system level design reviews, similar organizational structures and procedures are required. Therefore, any techniques which are successful in the larger, more complex design of an aircraft should also be applicable to a smaller endeavor.

Figure 2-1: Comparison of Product and Process

Type of Attribute	Boeing	Ford
Number of Unique Parts	130,000	13,000
Total Number of Parts	3 MM	15,000
Annual Production Volume	Tens	200,000- 500,000
Number of Customers	Tens	Millions
Number of Active New Programs	1	2-3
Number of Derivative Programs	3-4	5-10
Platform Lifetime	15 - 20 yrs	6 - 8 yrs
Development Cycle Time	4 yrs	3.5 years
Size of Design Team	Thousands	Hundreds

One of the more interesting aspects of this comparison is the duration of the product development cycle. Despite the difference in complexity, the product development cycle is approximately the same for each product. One reason for this is attributable to the enormous difference in production volumes. Although an aircraft may be more complex, annual production volumes may be only 50 per year. In the automobile industry where production volumes may be several hundred thousand per year, production preparation comprises a much greater portion of the design process.

This difference in production volume is much more significant than the differences in product complexity because a different emphasis must be placed on manufacturability in the design process. Although manufacturability is also a concern in the aircraft industry, the customized nature of the product results in a design system which heavily favors engineering integration rather than engineering and manufacturing integration. Therefore, when applying the lessons learned from Boeing's implementation, great care should be taken so as to not neglect the importance of manufacturing input.

Other differences which may affect the ease of implementation is the product lifetime and frequency of new product introductions. The former of these presents a greater challenge to Boeing, and the latter presents a greater challenge to Ford. As indicated in Figure 2-1, the product lifetime for a new aircraft program can be on the order of 15 years or more. In such an environment, issues of legacy data become a significant problem. Due to the nature of Boeing's products, designs are modified for nearly every aircraft which enter production. As a result, the design systems which were used to originally design the aircraft must be maintained for the lifetime of the product. In addition, for regulatory purposes and to facilitate any servicing of aircraft in the field, accurate records of design information must also be maintained. This problem is readily apparent in the older aircraft programs which still have much of their designs recorded on traditional, mylar three-view drawings. Thus, even though technology may have advanced significantly since Boeing's decision to adopt their system, the high switching costs may prevent Boeing from moving to a new system. Therefore, system features and implementation guidelines should be the focus of any knowledge gained from Boeing, rather than specific technical attributes such as the software or hardware used.

Although product lifetimes are much shorter in the automobile industry, implementation of a new design system is complicated by the number of new product development programs. At any given time at Ford, several new product development programs may be active and at different phases of their development. Since a standard system is now used for all programs, any transition to a new design system will require multiple systems to be maintained for a period of time. Some engineering functions and downstream parts of the process, which may interface with several programs at once will have to develop means of dealing with this duality without missing a step. Due to the complexity of the current system and the need to meet commitments, one CAD/CAM manager at Ford appropriately referred to the problem as " attempting to re-shoe a horse in the middle of a race". In contrast, the Boeing 777 implementation, although it was a drastic change, could be somewhat isolated from the rest of the organization. In fact, during the development phase of the new aircraft, a semi-autonomous 777 division was created which had full authority to develop new processes and systems solely for use on the new program.

Provided that the differences discussed above are accounted for, valuable lessons can be learned from the common design challenges faced by both companies. Even though there may be order of magnitude differences in the attributes stated above, there are sufficient similarities between the two companies in this study to warrant this sharing of information.

3.0 Types of Prototypes and Their Functions

Prior to any discussion of future trends in electronic prototyping systems, it is first necessary to establish a definition of the types of prototypes and the functions that they serve in the design process. The objective of this chapter therefore is to establish a baseline framework on which to build a foundation for the evolution of prototyping systems.

3.1 Definition of a Prototype

Much of the work in the field of prototypes can be found in the literature by Ulrich and Eppinger [2] and Wheelright and Clark [3]. As defined by Ulrich and Eppinger in their text Product Design and Development, a prototype is "an approximation of the product along one or more dimensions of interest". Although this definition may be considered somewhat broad, it expresses the true diversity both in form and scope that a prototype may entail. Such a definition does not restrict a prototype to be a physical entity nor does it require that it incorporate all functionality of the final product. This liberal definition encompasses the entire range of prototypes including an initial concept sketch, a non-functional clay model, as well as a fully functional pilot production unit. Due to the wide scope of this definition, frameworks will be presented in the next two sections which can be used to classify the types of prototypes and the purposes that they serve in the development process.

3.2 Types of prototypes

To elaborate on the types of prototypes, a classification framework presented by Ulrich and Eppinger will be used. According to [2], prototypes can be classified along two dimensions: the degree to which it is either physical or analytical, and the degree to which it is either focused or comprehensive.

Physical vs. Analytical

Physical prototypes are corporeal, tangible representations of some or all of the product features. Typically, such prototypes are constructed for demonstration purposes, to test the functionality of a feature, or to assess the durability and reliability of the product. Examples of physical prototypes include non-functional models to review aesthetics, structural models to be used in destructive life testing, or fully-functional hardware for experimentation. Alternatively, analytical prototypes are much more ephemeral representations of the product and/or its behavior. Analytical prototypes usually reside on a computer, and typically consist of mathematical representations of geometry or equations describing the behavior of the product. Whereas a physical prototype can yield direct measurements to determine quantities of interest, an analytical prototype uses measured data to calculate *derived* quantities of interest. Examples of analytic prototypes include computer simulations, three-dimensional computer-rendered images, or systems of equations in a spreadsheet.

Focused vs. Comprehensive

The continuum from focused to comprehensive seeks to classify the number of product features which are being modeled by the prototype. Focused prototypes are usually constructed to develop a greater understanding of a particular aspect of the product. An extremely focused prototype, for example, might be constructed to understand the stresses on an individual part or mechanism. Such prototypes are generally created early in the design process to develop the technology for particular components or subsystems independently from the entire product. Comprehensive prototypes, on the other hand, are typically created later in the design cycle to assess the overall integration of product elements. Comprehensive prototypes are typically full-size, fully-functional versions of the product which can be used for customer feedback, or for system-wide qualification tests such as for crash safety. Because of their complexity, comprehensive prototypes are typically the most expensive and time-consuming to construct.

To illustrate how these dimensions can be used to classify prototypes, a perceptual map is shown in Figure 3-1. The horizontal axis of this diagram represents the degree to which the prototype is focused or comprehensive and the vertical axis represents the degree to which the prototype is physical or analytical. For illustrative purposes, several examples which would be typical in the automotive industry have been placed on these dimensions. Although their placement on the matrix are approximate, the positions of each type of prototype relative to one another is relevant.

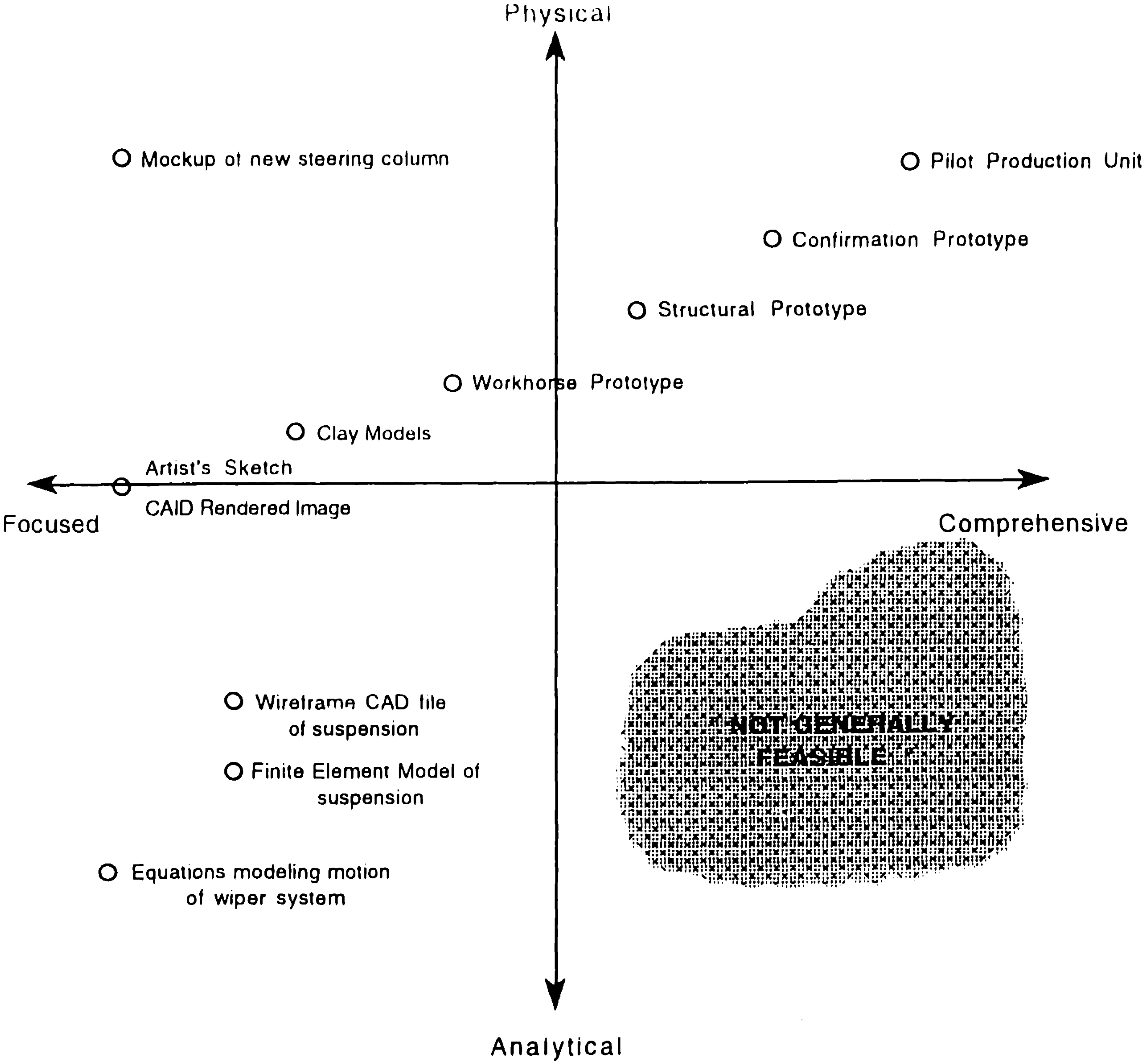


Figure 3-1: Perceptual Map of Prototypes

As shown in the diagram, there is a wide variety of prototypes that are constructed in the development process. After placing examples of prototypes on the matrix, it becomes apparent that there is not only a distinction between analytical and physical, but that there is also a 'degree' to which a prototype may be more physical (or analytical) than another. In addition, although time is not a dimension being displayed in this diagram, it becomes apparent that there is a definite progression of prototypes towards physical comprehensive later in the design process.

For example, a new development program may begin with a focused, analytical prototype in the form of an artist's sketch or a CAID (Computer-aided Industrial Design) rendered image. Such a prototype would be regarded as analytical in that the medium used is paper or computer, and would be considered focused in that it only considers the aesthetics of the design. Later in the process, this concept is made more tangible in the form of a physical clay model that can be used to further evaluate aesthetics or ergonomics. Further into the design cycle, workhorse prototypes are created which use a similar car platform as a backbone to install and test components. Since actual materials are used for these components, the model can be regarded as 'more physical' than clay, and since functionality is being evaluated it may be regarded as being more comprehensive as well. Still later in the design, structural prototypes and confirmation prototypes are created to certify critical structural elements of the design and evaluate the integration and performance of components. Each of these prototypes incorporate progressively more of the functionality of the design as well as production intent materials. Finally, pilot production units are produced which can truly be regarded as physical, comprehensive prototypes. In such prototypes, all materials are produced using production intent materials and processes, and thereby accurately represent the manifestation of the product as the customer would encounter it.

Whereas the prototypes previously described represent major milestones in the development process, there are also many other prototypes that are created in support of these events. For example, highly focused physical prototypes are often created to test a newly developed component such as a new headlamp system or steering column. Typically, these prototypes are constructed by an advanced engineering function or supplier which specializes in the design of the particular subsystem. The intent of such a prototype is to learn about the behavior of very specific aspects of the design and to evaluate the suitability of the new concept. Typically, this activity is completed independently from the major development program to create and develop proven, 'off the shelf' concepts to be incorporated on future vehicle development programs.

In addition to these 'ad-hoc' physical prototypes, additional analytical prototypes are also instrumental to the design process. Examples of such prototypes are shown in the lower left quadrant of Figure 3-1. An example of a highly focused analytical prototype could be a spreadsheet containing the equations governing the motion of the suspension system or wiper system. Such a prototype would be created prior to a physical model and possibly used to optimize the geometry prior to more detailed design. Other examples of analytical prototypes that may be more common are computer-aided design (CAD) models or finite element models used to describe the geometry and mechanical behavior of the suspension components.

As shown in Figure 3-1, the lower right quadrant of the perceptual map does not contain any examples of prototypes. According to Ulrich and Eppinger, the comprehensive-analytical quadrant of the perceptual map is considered to be 'Not Generally Feasible'. Although there are many challenges associated with producing a comprehensive analytical prototype, there is a growing trend toward the use of more complex analytical prototypes. The main focus of this thesis will focus on the growing capability in this area as well as the challenges associated with implementing a design process based on comprehensive analytical prototypes.

3.2 Functions of a Prototype

In their book, Revolutionizing Product Development, Wheelwright and Clark [2] present a generalized framework for describing the functions of a prototype. They classify the functions under four primary purposes: Learning and Feedback, Communication and Information Sharing, Outside Evaluation, and Monitoring of the Development Schedule.

Learning and Feedback

The learning function applies to the ability of a prototype to further the understanding of the design team as to the suitability of a design. All prototypes serve this purpose to some extent, however this role is typically the dominant function of early, focused prototypes which are produced to evaluate the functionality of a particular subsystem or component. All prototypes are essentially created with this purpose, however, with later, comprehensive prototypes, the learning is typically in the areas of integration or communication, which are discussed below. Prototypes serve the learning function in that they answer the question, "will it work?" or "does it satisfactorily meet the purpose intended?".

Communication and Information Sharing

The communication and information sharing role of a prototype is crucial to the integration of the various subsystems of a product. In this role, the prototype is the vehicle by which different groups within the design team can identify conflicts and communicate system-level issues and concerns. This is particularly important for large, complex products such as aircraft and automobiles where the design team can consist of hundreds or even thousands of designers and engineers. In this setting, individuals are assigned the responsibility for only a small segment of the design and often find it difficult to obtain information about other parts of the product. The process of constructing a prototype, however, requires that this information, in the form of current designs, be brought together in a single location. During assembly of the prototype, interferences and manufacturability issues which may be easily overlooked in the design stage, can be readily identified and corrected.

Outside Evaluation

Another purpose of a prototype is to communicate the design concept or level of completion of the design to individuals who are not directly involved with the core design team. For example, a prototype may be shown to senior management or members of the financial community to stimulate interest and obtain funding for future development. In addition, early prototypes may be shown to potential customers and suppliers to solicit their perceptions and suggestions so that they may be incorporated in the final design. In this role, a prototype represents a concentrated version of all of the information developed for a project so that it can be easily evaluated. This allows customers and others who may not have the time or technical expertise to follow the design team to obtain a 'sneak preview' of the design while it is still evolving.

Pacing and Monitoring of the Development Schedule

A very important function of a prototype is its role as a milestone in the development process. Due to the large amount of information contained within a prototype, many details of the design must be completed before the prototype can be constructed. As a result, prototype build points represent the culmination of the best and most current designs. Subsequent testing of the prototype results in the identification of improvements which will be addressed and incorporated in the next prototype build cycle. In this way, the development process becomes divided into distinct design phases, with each prototype build marking the completion of a phase. In the traditional design process, utilizing physical prototypes, long lead times are often required which places the prototype build process on the critical path. Therefore, managing the number, frequency and duration of prototype cycles is often used as a convenient way to manage the overall development effort.

4.0 Design Processes at Boeing and Ford

In the previous chapter, frameworks were presented which classified the general types and uses of prototypes in the development process. The purpose of this chapter is to briefly describe the design processes used by each of the companies in this study. Specifically, this discussion will focus on the role that prototypes have served in the development process in the past and how the types and uses of prototypes have evolved to the present day. Although the computer-aided tools which are used at each company are discussed, due to the rapidly changing technology in this area, the goal of this chapter is not to suggest specific software tools or compare technical attributes of the systems. The primary purpose of this information is to give the unfamiliar reader a basic understanding of the types of design processes used at each company and establish a vocabulary and context with which to apply the lessons to be learned in the next chapter.

4.1 The Boeing Design System

The design system which was used during the development of the Boeing 777 aircraft represented an unprecedented improvement in design integration for Boeing. In fact, it is these dramatic changes and their resulting benefits that motivated this study and transfer of knowledge. To illustrate the revolutionary changes which were accomplished and the changing role of prototypes in the process, the design processes which were used *prior* to the 777 program as well as *during* the 777 program will be discussed in the sections which follow.

The design process prior to the 777 program

In order to gain an appreciation for the progress which was achieved during the 777 development, it is first necessary to understand the type of design process which was used prior to the 777 program. On previous new airplane programs, the design environment at Boeing could be characterized by a very traditional, functionally-oriented process. This functional orientation was not only apparent between the engineering and manufacturing functions, but also within the engineering function itself. Organizationally, engineering program management was divided into functional groups such as Structures, Electrical, Hydraulics, Lofting, Aerodynamics, etc. These groups were typically not co-located with one another and communication between these very interdependent subsystems was limited. With the lack of daily multi-functional involvement, communication between the various functions was typically conducted through the slow, tedious exchange of coordination memos and specifications.

This lack of adequate communication was further strained by the type of design systems which were used. Although computer aided design tools had been adopted in some areas, the use of these tools was not universal throughout the program. As a result, the principal medium for information exchange and master designs was still officially 2-dimensional, 3-view drawings. These drawings were not only difficult and time consuming to create, but in a design as complex as an aircraft they are also difficult to interpret. As a veteran engineer at Boeing humorously recalled in an interview, "In those days, [previous airplane programs] our design integration often consisted of holding our mylar drawings and those of adjacent systems against the nearest window to see if any lines crossed .... I'm still amazed that everything came together in the end". Although this may have been an extreme example, it illustrates the difficulties associated with detecting interferences in designs that are this complex.

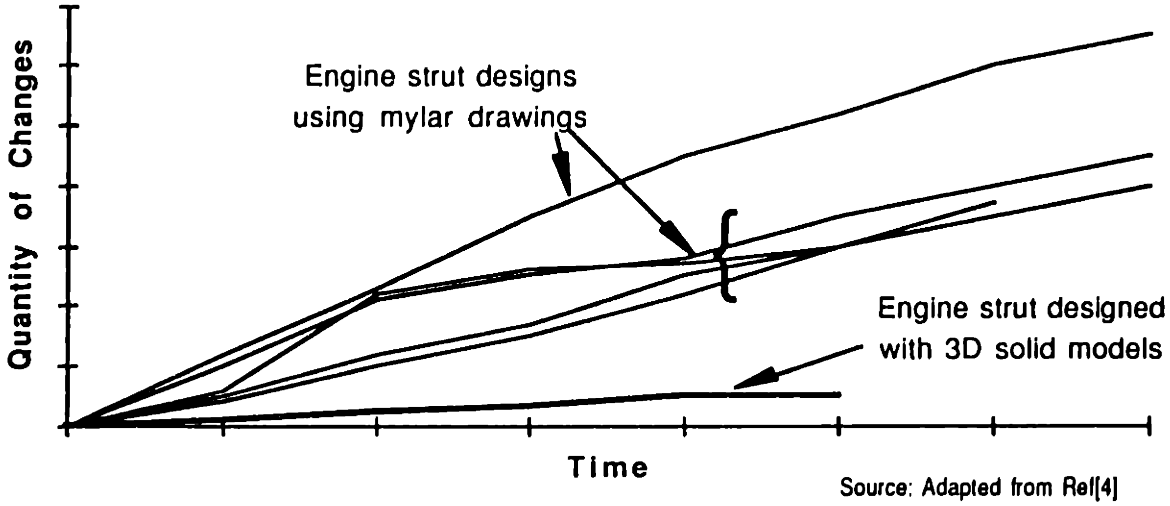
Due to the lack of multifunctional involvement within engineering, and the difficulties in detecting integration errors through traditional drawings, the principal vehicle to perform this system level integration was via a physical prototype. By creating and assembling physical representations of their designs, engineers were able to identify interferences with neighboring subsystems and correct any problems prior to production. This was particularly important for the design of subsystems such as electrical or hydraulic systems which interface with nearly every area of the aircraft. For these systems, the components were often designed directly on the physical prototype. Parts such as hydraulic tubing were routed to fit the prototype and became the only documentation of the geometry for the part. In addition, manufacturing personnel depended heavily upon the physical prototype. By participating in the prototype build process as well, manufacturing engineers took advantage of the opportunity to determine tooling requirements and verify assembly sequence.

Although many functions relied on the physical prototype, many obvious disadvantages existed with this system. Perhaps the most obvious drawback was the cost of constructing a prototype of this magnitude. An entire organization of engineers and mechanics were required simply to manage the construction of the prototype which may have a total cost in the millions of dollars. Another primary disadvantage was the currency of the design information. Due to the lead time involved with the production and installation of physical items, there was an inherent delay between the level of design which could be observed in the mockup and the most current design. As a result many integration errors remained undetected which resulted in very high rework and scrap costs as the new product entered production. Nevertheless, there was not a better alternative to achieve this integration, and the mockup became the focal point of these earlier design processes.

Impetus to change on the 777 program

This design process and its deficiencies were all to change on the new 777 development program. In a courageous move, Boeing managers decided to remove this reliance on the physical mockup and decided to entirely develop the new aircraft on the computer using a CATIA™[1] solid model design system. The impetus for this decision was based on the potential reductions in cost that were suggested by the results from earlier uses of CATIA at Boeing. One particularly convincing study was the result of a very early use of this system on a 767 engine strut redesign. As shown in Figure 4-1, engineering change data from 5 previous strut designs were compared to the engineering changes associated with an engine strut designed using 3D solid modeling.

Figure 4-1: Engine Strut Design Changes



Source: Adapted from Ref[4]

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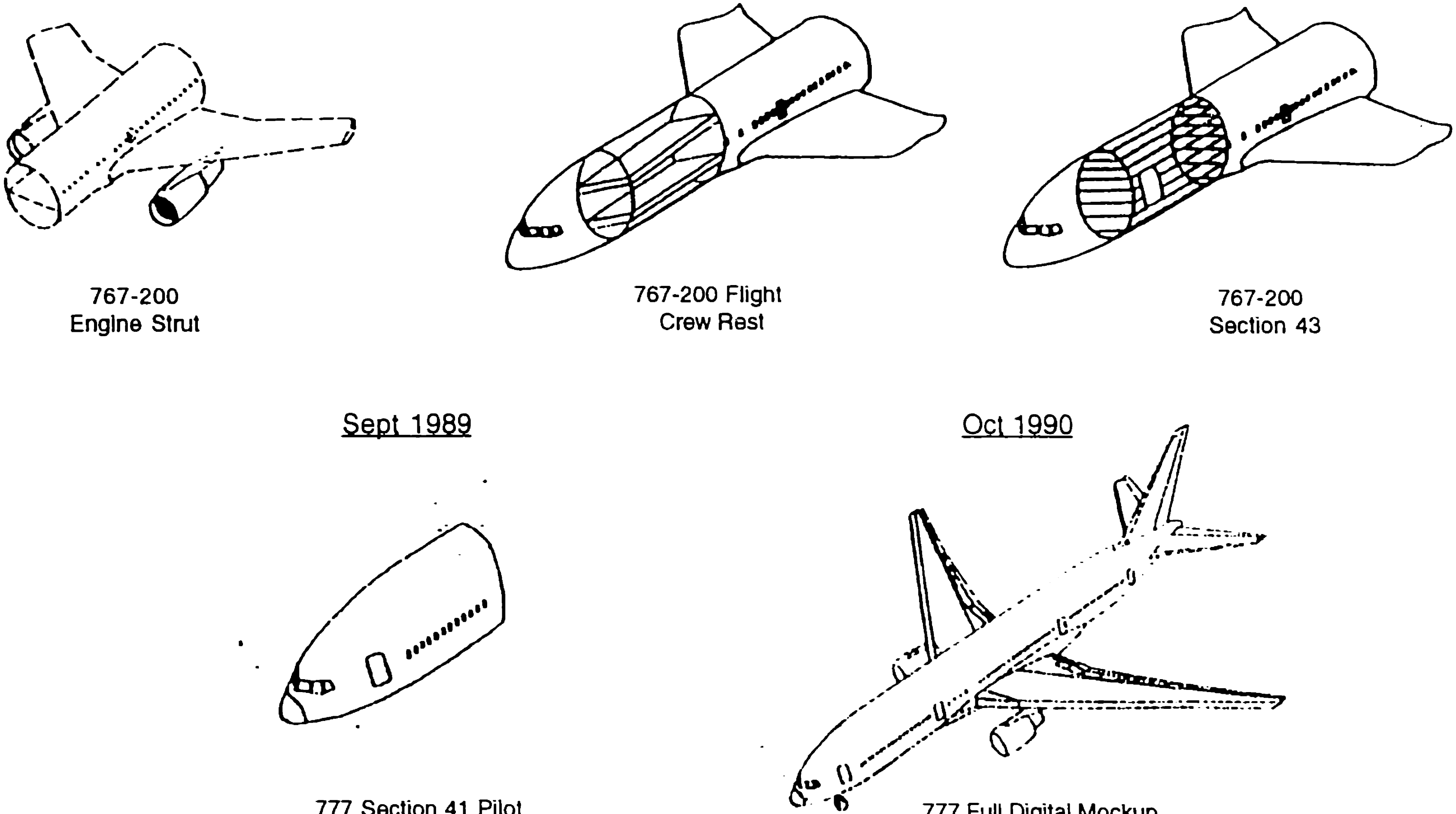
[1] CATIA is commercially available, 3 dimensional solid modeling system from Dassault Systemmes of France.

As this comparison indicates, there was a significant (approximately 75%) reduction in engineering changes as a result of using this new computer-aided process. Assuming that a similar reduction in change costs could be expected if this were used on an entire aircraft, this represented an enormous opportunity for the 777 program. Likewise however, this decision also represented a enormous risk because the use of such a system had never been used on the scale of an entire aircraft this large.

This risk was not entirely without justification however. Before the decision to use CATIA solid models on this large scale, several pilot applications of the software were conducted to test the scaleability of the system. Some of these early applications are shown in Figure 4-2. As shown in this figure, following the engine strut digital mockup, progressively larger and more comprehensive uses of the system were attempted in order to validate the process and gain confidence in the system. Nevertheless, the use of this system for an entire aircraft required extensive process development and still represented a major leap forward.

Figure 4-2 Chronology of DPA Pilots



June 1987

767-200
Engine Strut

May 1988

767-200 Flight
Crew Rest

May 1989

767-200
Section 43

Sept 1989

777 Section 41 Pilot

Oct 1990

777 Full Digital Mockup

The 777 Design Process

As alluded to above, the new design processes used on the 777 represented many significant opportunities and risks. To ensure that the program was successful, the 777 program management established a comprehensive plan consisting of five bold process-related initiatives:

- **100 % Digital Product Definition (DPD)**
  This initiative referred to the courageous decision to develop the aircraft entirely through the use of three dimensional solid models. Due to the magnitude of the potential savings, the impact on the design process, and the technical uncertainty of managing massive amounts of data, no other initiative on this program represented as much opportunity, challenge, and risk as did this endeavor.
- **Digital Pre-Assembly (DPA)**
  Digital Pre-Assembly is closely related to DPD, but refers to the process of 'assembling' the 3-D solid model parts on the computer. This was the key enabling factor which promoted the early sharing and integration of designs. The purpose of this process is to verify that any interferences, gaps, or misalignments are detected and corrected prior to the design entering production.
- **Design Build Teams (DBTs)**
  Design Build teams represented a significant departure from the traditional, functional-oriented organization of previous programs. This new team structure created a multifunctional, collaborative environment which could bring together the efforts of many functions in the design of a particular zone of the aircraft. Over 250 design build

teams were employed on the 777 development program, each consisting of members from all functions of engineering and manufacturing, as well as customers and suppliers where appropriate.

- **Concurrent Product Definition**

  Due to the new design environment, new techniques for managing the development process were required. Through the Concurrent Product Definition schedule, the timing of hand-offs and release of information between various subsystems of the design was established. This schedule created a series of design phases in the development process after which electronic build points occurred.

- **Hardware Variability Control**

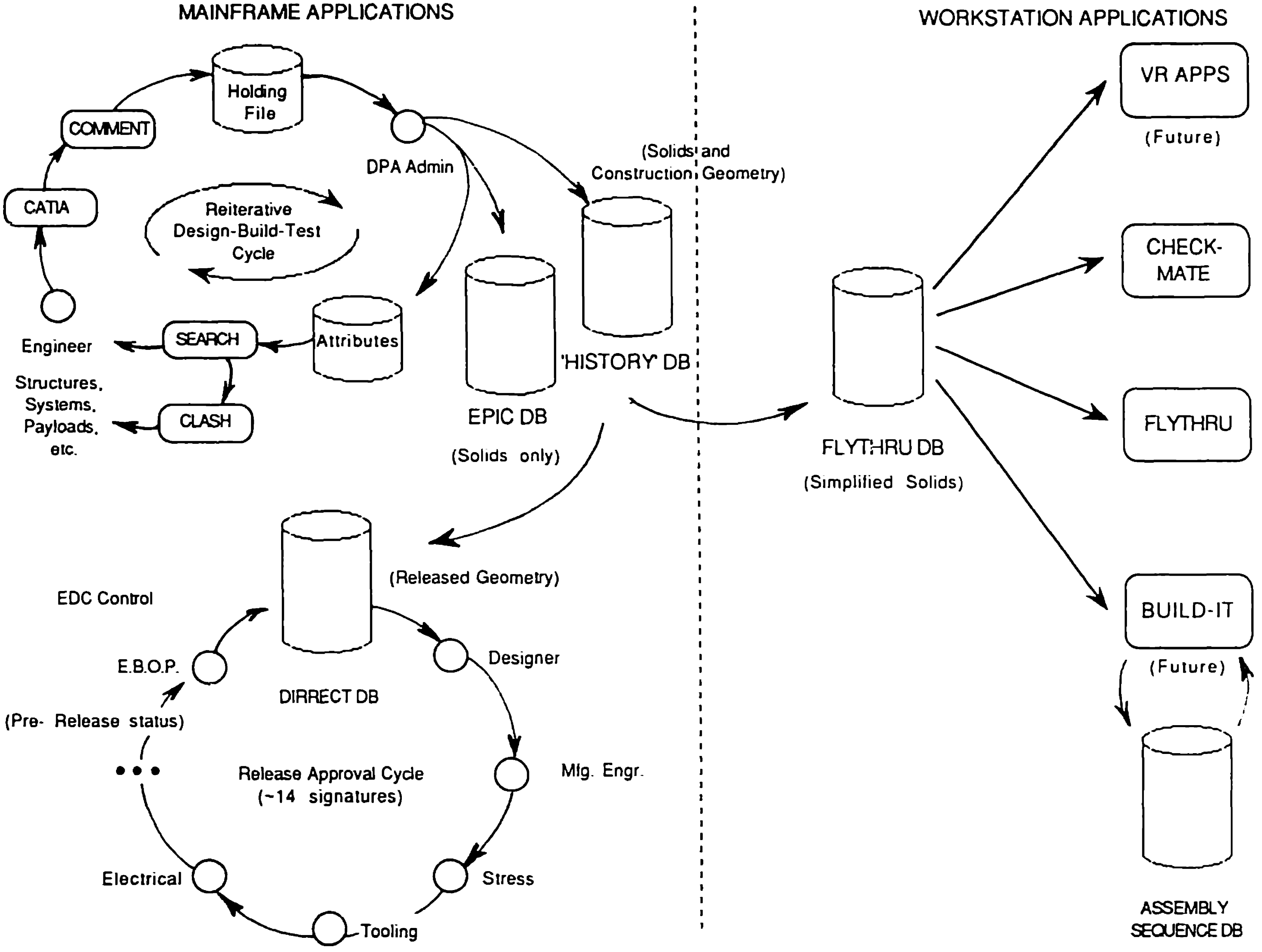
  Hardware Variability Control referred to an increased attention to the critical characteristics of the design and the contribution of process variation to the overall performance of the design. Under this initiative, critical assembly level dimensions were identified which were decomposed to the individual 'key characteristics' of components that contributed to the overall variation. This flowdown of requirements was a critical factor in focusing process control efforts and was responsible for much of the savings in fit up problems that were achieved on the 777.

Although *all* of the above initiatives were instrumental in the success of the 777 development, since this paper focuses on the use and implementation of analytical prototypes, the Digital Pre-Assembly process deserves a more detailed description. By separating the initiatives of DPD and DPA, Boeing managers highlighted an important distinction between the use of 3-dimensional solid modeling to develop part geometry, and the integration of those designs to produce an interference-free, producible design. In the former initiative (100% DPD), the use of 3 dimensional solid modeling to create component designs would have only resulted in the creation of a *collection* of *focused* analytical prototypes. It is actually the DPA process which enabled the integration of these focused analytical prototypes into a much more useful creation of a *comprehensive* analytical prototype.

As shown in Figure 4-3, many systems were required to make this comprehensive prototype a reality. It should be also be noted, that although CATIA is often mentioned as the enabling technology for this undertaking, this system only comprises a small piece of the overall DPA process. In this process, CATIA is simply used as the means of generating the 3D digital product data as an input to the system. The significant benefits of the DPA process however, was in the integration of these designs. In this regard, the Boeing proprietary systems which allowed the efficient management and sharing of information can be viewed as the enabling technology for the success of the program.

As discussed above, the DPA process was effective due to its ability to integrate and share designs. At the center of this process was the EPIC database (Electronic Pre-Assembly Integration on CATIA) and, later in the program, the FLYTHRU database (described later). This process begins on the far left of diagram 4-3 with engineers and designers from various functions. Using a commercially available solid modeling system (CATIA), product designs are generated and represented in a 3-dimensional solid model. To provide the non-geometric information essential to information sharing and communication, the designer then adds attribute information such as the name and phone number of the responsible engineer, effectivity information, location on the aircraft, etc. This model and

Figure 4-3: Boeing DPA System



associated comments are then forwarded to a holding area where DPA administration personnel can evaluate the model for the use of proper conventions and prepare the model for sharing. [2] In this step, any additional construction geometry or 2 dimensional drawings are removed so as to minimize the memory requirements when models are overlaid upon one another for interference checking. In addition to this 'stripping' of unnecessary data, the volume extents of the model are calculated in airplane coordinates and added to the attribute data for the model. The original model is then stored in a history database, and the 'stripped' model is shared in the EPIC database for integration with other models.

The DPA process consists of the reiterative sharing and evaluation of product geometry. Thus far, we have described the means by which designs are shared. The second part of this cycle however, is where the true benefits of the system lie. This portion is also driven by the individual engineers and designers who utilize the searching ability of the EPIC system to identify all models in the region surrounding the part or component for which they are responsible. Since the volume extents for each component have already been calculated in global aircraft coordinates, the extents of the component in question are known and can be used as search criteria for additional parts which occupy or intersect that volume. This list of parts can then be retrieved and batched to an interference detection utility (CLASH) to identify any conflicts with adjacent parts. Using this information, the engineers and designers can update their design(s) as necessary, and the cycle begins again.

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[2] This function has subsequently been automated and no longer requires the use of administrative personnel. However, as discussed in the following chapter, the DPA administration function also served a process feedback loop which cannot be easily replaced.

Although this process was very effective in integrating the design, it also had its limitations. The chief limitation was the inability to combine more than approximately 20 models in the same session due to memory constraints. Therefore, in complex areas of the aircraft where more than twenty models were located, all combinations of the models had to be independently checked for interferences. This problem was overcome, however, with the development of a proprietary system known as FLYTHRU. To overcome the memory constraints, models from the EPIC database were simplified into faceted solids which could be used to visualize much larger zones of the aircraft. Models that were shared to the EPIC database were automatically converted to this new format each night and were made available to a network of high performance graphics workstations on which this new system operated. These workstations were easily accessible to all design build teams and enabled team members to retrieve and 'fly through' the electronic mockup of their 'zone' of the aircraft.

This final addition to the DPA process was a critical step toward the creation of a comprehensive analytical prototype. It not only provided a means of visualizing large portions of the design, but also provided an improved interference checking capability as well. Interference checks that would have required hours or even days on the previous system now only required minutes. This system also enabled automatic clearance detection which could detect violations of design rules such as the minimum separation of electrical and oxygen lines. Since the time of the 777, the integrative capabilities of this system have also been expanded to include manufacturing and tooling functions. With the addition of this assembly sequence functionality, Boeing expects to achieve additional savings which rival those already attained by the 777 program.

4.2 The Ford Design System

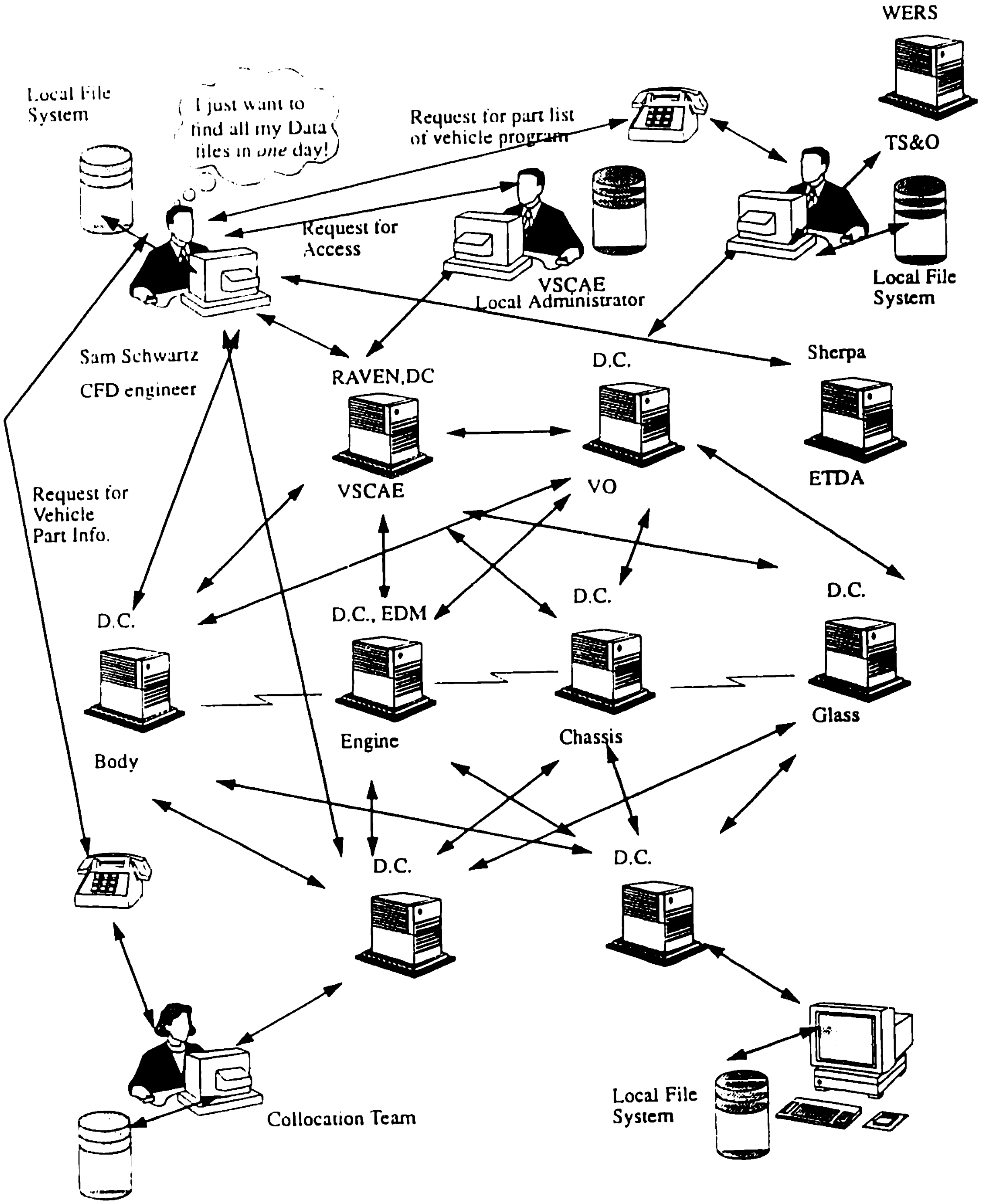
The design system in use today at Ford is not as archaic as the mylar processes used at Boeing prior to the 777, however it is also not nearly as integrated as the digital pre assembly process that is in use today. The principal design system in use at Ford is a proprietary system known as the Product Design Graphics System (PDGS). This design system originated in 1968 as a three dimensional wireframe and surfacing software developed for the body engineering function. When this system was first developed, it represented the state-of-the-art computer-aided design system. Whereas other auto manufacturers at the time were developing 3-dimensional drafting tools, the new Ford system took this a step further and enabled mathematical representation of surfaces. In the early eighties this pioneering continued through the development of a data collector architecture and local ring network for the storage of part information, a precursor to the client-server technology widely used today. As the use of the system grew rapidly in the mid eighties, additional data collectors were added until a global network with which to share data was created. Today there are over 6,000 PDGS workstations in use at Ford and its suppliers joined through the PDGS network which operates in over 20 countries worldwide.

This network provides an electronic means to share geometric data, however the environment in which this network evolved makes this very difficult. Until recently, the Ford design organization was very functionally oriented, similar to the structure of Boeing design functions prior to the 777. Separate organizations existed for Body Engineering, Chassis, Plastic Components, Glass, Climate Control, and Electronics. As a result, each division came to own and control access to its own data collectors on the network. Today, when designs from these individual component groups have to be brought together to integrate the vehicle level design, a complex web of data collectors must be navigated to obtain the necessary information. This difficulty has become conveniently known as the 'Sam Schwartz Get Data' problem throughout Ford, due to the efforts of a vocal Computational Fluid Dynamics (CFD) engineer to bring attention to this problem.

An example of the complexity of locating and obtaining access to information is shown in the illustration in Figure 4-4. As typified by the struggle of this CFD engineer, many engineers and designers are routinely faced with the laborious non-value-added task of: 'calling-around' to identify the responsible persons for neighboring parts, requesting CAD filenames and access to servers, and in some instances, using a third unrelated data collector to transfer the information to its final destination. Even when the data is eventually obtained, the engineers do not always understand the complex ancillary information contained in the files, and are not confident that they have the latest revision or that they will be updated if the design should change in the future.

As a result, integration of the vehicle design is not easily accomplished using this system. Due to this difficulty, the use of physical prototypes still comprises a large portion of the vehicle development process. This was illustrated in the previous chapter which described the various types of prototypes that are used in this process. Throughout a development program, hundreds of these physical prototypes are created, with some prototypes costing hundreds of thousands of dollars. As a Ford design manager stated following a comparison of the Ford and Boeing design processes: "Ford's prototyping process is equivalent to Boeing's production process... we probably build more prototypes in a year than they make

Figure 4-4: Typical Product Data Search[3]



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[3] Figure obtained from Ref.[5]

while in production". Of course, the reduced complexity and higher production volumes in the automotive industry warrant the use of more physical prototypes, but the advantages to integrating the design before the prototype construction should be just as important.

As of this writing, efforts are now underway to correct this problem. In an advanced engineering pilot project at Ford a vehicle is now being designed and 'pre-assembled' exclusively through the use of 3 dimensional solid models. Solid modeling systems have been used by various functions throughout Ford, but this project represents the first time these systems have been used on this larger scale requiring integration of all subsystems on the vehicle. Although this vehicle is not currently scheduled for production, this pilot project is providing a basis for which to develop the critical processes and procedures for managing the product data in a comprehensive electronic design environment.

5.0 Lessons learned from the 777 Implementation

As shown in the previous chapter, Ford is now at the point where it is ready to apply these new computer-aided tools to a full-scale vehicle program. Although the specific hardware and software used at Ford and Boeing will be different, there are some lessons learned from the Boeing implementation that are universally applicable. This chapter will describe the critical success factors in the Boeing implementation, as well as the difficulties encountered, so as to avoid repeating the same problems.

5.1 Implementation Problems

Although the implementation of the digital pre-assembly process was highly successful, it was not accomplished without difficulty. A diagram illustrating some of these difficulties is shown in Figure 5-1. This figure represents problems with the 777 process that were voiced in interviews with individuals who participated in the program. The individuals interviewed represented a broad cross-section of the development team, including product engineers, manufacturing engineers, DBT leaders, computer services personnel, and data coordinators. The comments which were extracted from the interviews represent the most commonly cited examples of difficulties. These are arranged in an affinity diagram to collect similar problems under a common theme. Although not all of the problems will be discussed in detail, the most important and frequently cited problems are described in the paragraphs which follow.

Figure 5-1: DPA Implementation Problems

Difficulty Obtaining Buy-In

- Engineering Managers were uncertain of their control of a design process which was frequently changing.
- Manufacturing Managers did not believe engineering could create a producible design without a physical mockup.
- The new design process required more effort from the designers, but the benefits were elsewhere in the process.
- The major suppliers [JAI partners] did not understand the DPA requirements when they committed to the program

Lack of Tooling Integration

- The tooling organization did not actively participate early in the design process.
- Conventions for including tooling models in the DPA were not adequately established.
- Tool-to-tool and Tool-to-part interfaces were not always checked for interferences.

Unclear Definitions of DPA and 100 % DPD

- Engineers initially regarded the EPIC system as a data repository rather than a digital prototype.
- It was unclear as to whether detailed items such as fasteners were to be modeled in the system

Underestimated Resources

- Managers believed that DPA would 'automate' the design process & did not account for extra time to create solid models.
- Integration tasks that were previously done on the physical mockup now required time on workstations.
- In the new process, integration tasks occurred much earlier and required 'front-end' loading of resources.
- The impact of training and new team members was underestimated.

Lack of Tooling Integration

The most commonly cited problem with the Boeing 777 development was the lack of involvement by the tooling organization. Although tooling engineers were included in the design-build teams from the inception of the program, their active participation did not begin until the program was well under way. This late start placed the tooling organization behind the learning curve of the new system, and as a result, the disciplines and procedures for integrating tooling designs with the product were not adequately developed. Consequently, it was unclear what coordinate systems were to be used to locate the tools in the design database, and different conventions were established. As a result, some tool-to-tool interferences and tool-to-part interferences remained undetected, thereby creating integration errors later in the process.

Underestimated Resources

In the early phases of the 777 program the amount of work required from the engineering functions exceeded the amount of persons budgeted for the effort. This problem occurred for several reasons. The primary reason was the fact that managers believed that they were 'automating' the design process, and had estimated that the new solid modeling software would actually increase design productivity. In reality, however, designing using solid modeling software actually required more time than using previous methods. Some of this added time was due to the fact that a new system was being used, but a large portion was due to the difficulty in creating and revising existing models. For many models, it was often easier to start the design from the beginning rather than attempt to revise the existing model.

Another significant reason for the underestimation was due to the new design process itself. In previous programs, a physical mockup was used to develop designs and integrate various parts of the aircraft. This integration step usually occurred later in the process and was handled by an entire staff of individuals that were responsible for the mockup. In the new process, this integration was occurring much earlier. Therefore, estimates of 'ramp rate' for resources that were based on managers' experience on previous programs were inaccurate. In addition to this shift in resource timing was the amount of engineering personnel required. In previous programs, much of the integration effort was accomplished on the physical mockup with the assistance of the mockup personnel. In the new process, these mockup personnel were not necessary and the integration activities which formerly occurred in the mockup shop were now occurring on the designers' workstations. Unfortunately however, the absence of the mockup personnel's contribution was not reflected in a commensurate increase in engineering resource.

The amount of training and the impact of new hires also exacerbated the resource problem. Although the CATIA design system had been used elsewhere in the company prior to the 777 program, many of the designers and engineers were unfamiliar with the system. For veteran designers, the transfer to the new design system required a significant change in thought process. Many designers who had spent their careers using 3-view drawings were unprepared for the 3-dimensional work environment. According to one account, several designers adopted the practice of using traditional drafting methods to develop the part prior to creating the three dimensional solid model. Another designer, when faced with a problem, printed hardcopies in the format that he was familiar with and used the comfort of his drafting board to solve the problem. This practice obviously resulted in twice the effort as was anticipated.

Lastly, the impact of new members of the design team was also underestimated. Although the need for training was anticipated, the disruption of the design process was greater than expected. In addition to the use of the CATIA system, new team members also had to learn the procedures associated with the Digital Pre-assembly process and the new Design Build Team organizational structure. As new members joined the team, those who had already been trained and were most experienced were often called to assist the new members. Since new team members continued to arrive throughout the first half of the design process, there was a significant time period where the workforce was not able to achieve full productivity.

Unclear definitions of DPA and 100% DPD

Although eventually remedied, in the early part of the design process, there was not a consistent understanding of the objectives and scope of Digital Pre-assembly (DPA) and Digital Product Definition (DPD). The misconceptions about DPA dealt with the objective of the EPIC database which stored the solid model designs. Initially, some groups viewed the EPIC database as an electronic repository of data rather than an electronic mockup of the aircraft. Models were stored on the database, but the integrative abilities of the system were not fully utilized. As described earlier, one of the capabilities of the EPIC database included the ability to search for models in a given coordinate space. The results of this search could then be overlaid upon each other and interference checks could be performed automatically. Some design groups used this effectively, however others simply stored their models to be used by others. Some managers, in an effort to achieve "efficiency' assigned the task of interference detection and integration to certain members of their team. Although this may have been done with good intentions, it violated the basic philosophy of data sharing intended by the DPA process. By separating the engineers and designers from how their components interfaced within the design space, they did not have a first hand appreciation of how to best integrate with other designs. This problem was remedied during the 777 program with the addition of the Boeing 'Flythru' system. Whereas the interference detection system used at the beginning of the program was tedious to use and could only operate on 20 models at a time, this new system utilized simplified, faceted geometry and could visualize and interference check larger aircraft sections. With the ability to visualize large portions of the aircraft, the electronic database was finally able to be perceived as an electronic version of the physical mockup.

The uncertainty surrounding '100% Digital Product Definition' deals with a small, but nevertheless important detail. Although the term 100% DPD suggests that all parts must be modeled on the design database, there were inconsistencies as to how literally this was to be interpreted. As a result, some design groups included fasteners in their definition of DPD, others did not. Still other groups which were under time or resource constraints included some types of fasteners but omitted others. Subsequently, many of the integration errors that occurred on the 777 were due to interferences, misalignments, or the inaccessibility of fasteners.

Difficulties in Obtaining Buy In

As one Boeing manager voiced in retrospect at the success of the 777 design system, "The changes which enabled the success of this program were 80% cultural ". As with any cultural change of this magnitude, a certain degree of resistance is to be expected. Centers of resistance included manufacturing management, middle-management within engineering, and designer/drafters.

Manufacturing resistance could be best characterized as skepticism with the new design system. To fully understand this reaction, it should be recalled that manufacturing had traditionally relied upon the physical mockup as the only means of verifying engineering designs before production. In addition, the physical mockup provided a mechanism by which manufacturing engineers could identify and communicate producibility information to the design process. Ultimately, manufacturing was responsible for producing the new design, and based on experience with previous programs, they had no evidence which indicated that engineering could produce a 'one off' design that was producible. Therefore, removing this 'first defense' against the engineering design exposed manufacturing's lack of confidence in the engineering-manufacturing interface. As a result, manufacturing managers insisted that a physical prototype of the 41 section of the aircraft be constructed to confirm the new process.[4] During the construction of this prototype it quickly became apparent that the design was accurate and producible, and manufacturing support was obtained without having to complete the prototype.

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[4] This section, which consists of the flight deck and forward section of the aircraft was chosen because it is one of the more complex segments of the aircraft where packaging space is limited and interferences are likely.

Another center of resistance originated in the middle management ranks within engineering. The source of this resistance was primarily due to the uncertainty and feeling of loss of control which was associated with using a new design process. To understand their position, it is necessary to realize that managers at this level had been 'raised' in the organization on the use of the former design practices. In fact, they were promoted to their positions because of their expertise and ability to succeed under the rules of the old system. Therefore, a large part of their feeling of control was based on this experience. Because the new process was being developed and revised concurrently with the design, individuals at the lower levels of the organization, who were using the new process every day were most familiar with the procedures.

Further compounding this uncertainty was the lack of tangible evidence as to the progression of the design. In the past, the physical mockup served as 'proof of progress' of the development effort. By visiting the mockup area, managers could quickly assess the level of completion of the design and take corrective action where necessary. This problem was mitigated somewhat by the two week design freezes which occurred following each of six design stages. During this time, all changes and additions to the design databases were suspended, allowing a 'time-out' for which to evaluate the design. The addition of the FLYTHRU™ system also dispelled some of this uncertainty in that large portions of the aircraft could then be visualized simultaneously on a workstation monitor.

Lastly, another important group of individuals that experienced resistance to change were the designers who were actually responsible for creating the solid model designs of the components. As mentioned above, the use of the new system required these individuals to adopt entirely new thought processes. After years of designing in a 2-dimensional projections, they were suddenly thrust into a design environment which required them to think in 3 dimensional space. In addition to this drastic change, the new system actually required more work to complete and revise designs. Since the benefits of this extra work were realized by the larger design process and downstream functions, it is understandable that these individuals did not have much incentive to initially embrace the new system.

5.2 Implementation Success Factors

Using the same approach as for the problems, a diagram summarizing the critical success factors for the Boeing 777 implementation is shown in Figure 5-2. The factors which are discussed below represent the attributes that were most frequently cited in the interviews.

Management's Strategic Commitment

Perhaps the most frequently cited factor for accomplishing this drastic change was top management commitment and support. Due to the large investment required for a new aircraft and the new design system, program managers understood the importance of remaining committed to the new process. This commitment began at the outset of the program by including process initiatives as the five major thrusts of the new program. As the program progressed, these initiatives were continually reiterated and any compromise was not tolerated. In the beginning of the program, the commitment to the DPA process was challenged by some chief engineers and managers, but it was quickly made clear that there would be no place for 'disbelievers' of the new system on the new aircraft program.

Figure 5-2: DPA Implementation Success Factors

Management's Strategic Commitment

- Five process-related improvements became the key initiatives for the 777 program.
- Top management continually reiterated their support of the new process and did not tolerate disbelievers.
- Data from early pilots indicated the potential savings and was instrumental in obtaining managment committment.

Tactics used to Drive the Development Process

- Initial design freezes forced design groups to populate the system early.
- Design freezes allowed management to assess the progress of the design and identify/resolve conflicts.
- The 'degrees of development' fostered early sharing of designs and indicated the detail required in each stage of the process

Synergy of Initiatives

- The Design Build Teams (DBTs) encouraged cross functional participation which complimented the DPA process.
- The Hardware Variability Control (HVC) process increased awareness of key characteristics of the design

Communication of Process to Build Confidence and Support

- The on-site-DPA Administrators communicated and enforced the new procedures as they were developed.
- The 'preferred process' handbook removed uncertainty as to how the new system would change individual's daily work.
- The on-site DPA Administrators served to feedback suggestions from the DBTs for improving the process.
- The catch phrases "Share early, often", "If its not in the computer, not in program" effectively communicated the DPA philosopy.

Communication of the Process to Build Confidence and support

As stated in the previous section, one of the problems associated with the new DPA process was that procedures were still being developed and refined while the program was in progress. This could have had disastrous effects were it not for efficient communication of the new process. Some mechanisms that were essential to this success were the on-site DPA Administration personnel, the proliferation of instructional 'catch phrases' and the 'Preferred Process' Handbook.

The DPA Administration function was chiefly responsible for the DPA process and consisted of two groups each containing approximately 40 individuals. The groups were divided into a central DPA Admin function which maintained the DPA database, and a group of DPA administrators that were co-located within the individual design build teams. This latter group of individuals proved to be an essential communication link for the development of the new process. Being co-located with the design teams, these individuals were able to provide immediate support to the engineers, ensure that the correct procedures were being followed, and communicate any changes to the process. In addition to providing this top-down communication and control, these individuals also provided a vital feedback link to the central group which was developing the process. Being involved with the daily activities of particular design build teams, the on-site DPA personnel had an intimate knowledge of how well suited the procedures were to the tasks of the groups. Since it is unreasonable to assume that all procedures can be predicted prior to an implementation of this magnitude, this communication and feedback link is essential.

Another successful mechanism for institutionalizing the new process was a document known as the "Preferred Process" Handbook. This handbook provided a common reference for the entire design team which documented the major process initiatives on the 777. This document was effective because it not only described the new process, but also articulated the reasons behind the need for change, and the goals of the new process. Many volumes of detailed procedures for the mechanics of the process were available, but without this overview to tie the entire process together many of the cultural change aspects of the implementation would not have been addressed. By containing the signatures of all key program managers, this document served as a mechanism to communicate management commitment. Furthermore, it was written in a manner which could be easily understood, and clearly described how each type of role was to change under the new process. This eliminated some of the uncertainty of how the 'big-picture' changes would affect individual's daily activities, and assisted in overcoming their resistance to change.

Finally, another tactic used by management to communicate and institutionalize the importance of adhering to the process was through the use of simple 'catch phrases'. The simplicity of these phrases resulted in reiteration among the design team, thereby ensuring widespread communication of the messages. In fact, even after the 777 has entered its production phase, these phrases are still ingrained in the culture and are still frequently quoted. Specifically, these phrases were "Share early, Share often" and "If its not on the computer, its not in the program". Although these may be very simple statements, these phrases were effective in that they directly addressed what was anticipated to be the two most probable causes of failure of the new process.

The "Share early, Share Often" phrase was meant to address the 'perfectionist' tendency of engineers and their unwillingness to share their work with others until complete. Since computer models can be 'assembled' even if not fully detailed, one of the primary advantages of the Digital Pre Assembly process was that it provided the ability to share designs and identify integration errors much earlier than would be possible if physical prototypes were constructed. This benefit could not be realized, however, if engineers believed that it would reflect badly on them if they were to share their designs too soon. Therefore, the widespread acceptance of this phrase, in effect, legitimized the sharing of incomplete models without the fear of undue criticism from peers.[5]

The latter phrase "If its not on the computer, its not in the program" was designed to address the possible tendency to return to the use of previous design methods in times of crisis. This was of particular concern in the beginning of the program when engineering resources were constrained and resistance to change was highest. Although this may seem trivial, if some designs were allowed to exist outside of the system, the entire DPA process would have been doomed to failure at the very start. Since the primary objective of the DPA process is to detect integration errors between components, a fundamental requirement of the system is that all of the components are contained in the database. If all parts were not contained in the system, there would not have been any confidence in the interference checks performed, and the DPA process would have degenerated into merely an electronic repository of data. By refusing to recognize designs that

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[5] It should be noted that although there was unanimous buy in to the need to 'share early and often' this did not always occur. This was primarily due to the difficulty of revising models in CATIA however, rather than an unwillingness to share information. Since revisions were very time consuming, small changes were often allowed to accumulate before sharing with others.

did not use the new process, management forced the early creation of a critical mass of design information which enabled the DPA process to gain acceptance.

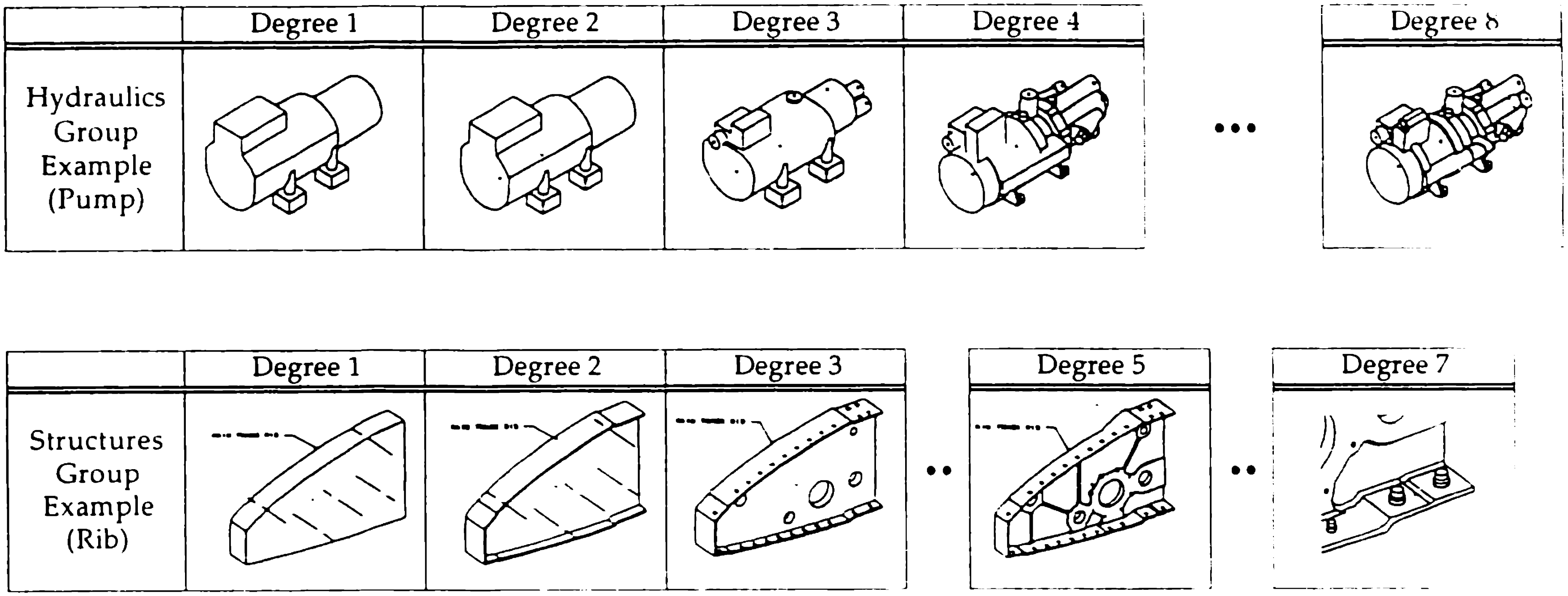
Tactics Used to Drive the Development Process

As mentioned previously, one of the primary functions of a prototype is its role in the management and pacing of the development process. In an environment utilizing physical prototypes the development process was primarily driven by the need to create physical parts to meet the build schedule for the prototype. Therefore, if the design effort was to stay on schedule management only needed to manage the requirements for prototype production. In an environment based on electronic prototype, these build requirements do not formally exist. As a result, several electronic prototype 'build points' were created in the development process. At each of these build points, the electronic model was frozen and no changes were allowed for a period of two weeks. This not only provided an opportunity for management to evaluate the design, but also provided milestones for the development team to work toward.

It is still debatable whether or not the design freezes were necessary to the success of the DPA process. From the interviews in this study, most individuals agreed that the early design freezes were effective in driving the development process. It appeared that primary benefit of these early freezes was that they forced the design teams to populate the database early, even if only with their future intentions of designs. This served to 'jump start' development process in the early stages when progress was occurring very slowly. There were mixed responses as to the need for these freezes later in the design process, however. Many persons believed that the two week freezes at end of the program placed unnecessary holds on the progress of the program, and could not understand any reason to restrict the sharing of changes which were inevitable. Based on this information, in future implementations of the DPA process (or similar processes at Ford) design freezes should be incorporated into the design schedule, but only in the early phases of development.

A final success factor associated with driving the development process was the method used to categorize the level of completion of a design. Although a relatively simple concept, this was effective in that it helped to legitimize the early sharing of information. This method, referred to as "Degrees of Development" is illustrated in Figure 5-3. As shown in the figure, for each type of subassembly, a rough indication of the level of completion required for each degree is shown. This method was particularly effective in that it *graphically* depicted what information was required at different levels of design. Taking advantage of the cliché, "A picture is worth a thousand words" this allowed engineers from all functions to quickly internalize a common understanding of what information they could expect from different subsystems. Combined with the concurrent product definition schedule, this categorization was then used to drive the development cycle.

Figure 5-3: Degrees of Development



Degree	Requirement
0	Basic Datums in 3D Space
1	Simple Envelope Solids
2	Simple Shapes with Structure Interfaces
3	Simple Shapes with All Interfaces
4	Component Envelope Defn. (for Vendor Specs)
5	Dimensionally Correct Solids
7	Complete Detailed Part Definition (Fillets, chamfers, etc.)
8	Detailed Vendor-supplied Part Definitions

5.3 Summary of important lessons

Although all of the above lessons will be important to consider, several of these in particular may represent problems for Ford. Based on observations of approaches used on a pilot implementation of a similar system, the following areas will be particularly important:

- **Importance of tooling/manufacturing integration**
  One of the key problems experienced during the 777 development was the inadequate involvement of tooling in the DPA process. Since that time Boeing has recognized this weakness and is now investigating ways to extend the process to more readily integrate manufacturing. The pilot project being used to develop a 'Ford DPA process', may also suffer from this same weakness. Since the project which is being used to develop this new process is not scheduled for production, there is very little input from manufacturing. As a result, the systems which are being developed are very heavily oriented towards engineering and analysis. Since production readiness is even more of a concern in high volume auto manufacturing, it is essential that product *and process* integration be the focus of any new procedures that are developed.
- **Early and frequent sharing of information**
  Until recently, product development at Ford has typically been a very functionally oriented process. Although this is now changing with the creation of program teams for new vehicle programs, residual behaviors from this old functional culture may continue for some time. Under this old culture, designs remained in their functional engineering 'silos' such as

chassis, body, electrical, etc. until they were nearly perfected. Even when sharing did occur, it was often on a 'need to know' basis where it was the responsibility of the user to 'track down' all necessary geometry and re-solicit this information periodically to check if changes had been made. New habits must be formed in which this information is actively made available by the originating individuals early in the design process and immediately following any changes in the their design. To accomplish this, managers may want to include several 'electronic build points' in the process to drive the early sharing of information, and a system similar to the 'degrees of development' to legitimize the sharing of incomplete designs.

- **Management commitment**

  Another strength of the Boeing implementation was the strong commitment of the program management to the new process. This was facilitated by the fact that the 777 team was a semi-autonomous organization which was given the responsibility for its own process development. Therefore, the 'champions' for the new process could also be the management of the program. If such a system is implemented throughout Ford, the process will likely be developed by a central organization and 'applied to' new programs. As a result, program managers will have the role of 'customers' of the new system, rather than the 'champions' leading the organizational and cultural changes which are required.

- **Communication of Process**

  Lastly, another important issue will be the communication of the newly developed processes. If the method of process development on the Ford pilot project is any indication of the methods which will be used for a larger implementation, the process will be developed and implemented in a 'top down' approach. New procedures will be developed in 'closed door meetings' and then thrust upon the organizations which must follow the processes. Although it is unreasonable to expect that processes can be developed with the participation of the hundreds of individuals that will use the process, what is needed is a better method of communication and feedback of the process. A system which was effective at Boeing was the use of 'process experts' (DPA On-site Administrators) as adjunct members of the various product development teams. These 'process experts' are deeply involved with the process development and can be used to communicate and enforce the new process, but are also in the position to feedback the suggestions of how the procedures can be made to better suit the needs of individual units.

6.0 The Evolution of Design Systems

Thus far in this thesis, we have discussed the similarities and differences between Boeing and Ford, provided a description of the current design systems in use at each company, and documented several lessons which can be learned from Boeing's recent implementation of the Digital Pre-Assembly process on the 777 program. The purpose of this chapter is to assimilate this knowledge into a larger context of the general trends in electronic prototyping systems. In the first part of this chapter, a timeline will be presented which illustrates the progression of design systems until this day. This timeline is based on the past and present systems used by the companies and illustrates the ambitious leap accomplished during the 777 program. In the second part of the chapter, the functions of prototypes are explored in detail, and opportunities for the use of analytical prototypes are evaluated. Finally, in the last section, the timeline is extrapolated upon to illustrate possible steps in the future evolution of design systems. This extrapolation is based on the prototyping needs which are not currently being addressed, future development activities occurring at each company, and commercial software which is now becoming available.

6.1 Historical Progression of Design Systems

As a basis for this timeline, we will refer to the method used to characterize prototypes found in the literature review section of this document. Recalling from Chapter 3, prototypes can be characterized along two dimensions: the degree to which it is either physical or analytical and the degree to which it is focused or comprehensive. For reference, a matrix illustrating some of the primary examples of prototypes within the auto industry is shown in Figure 6-1.

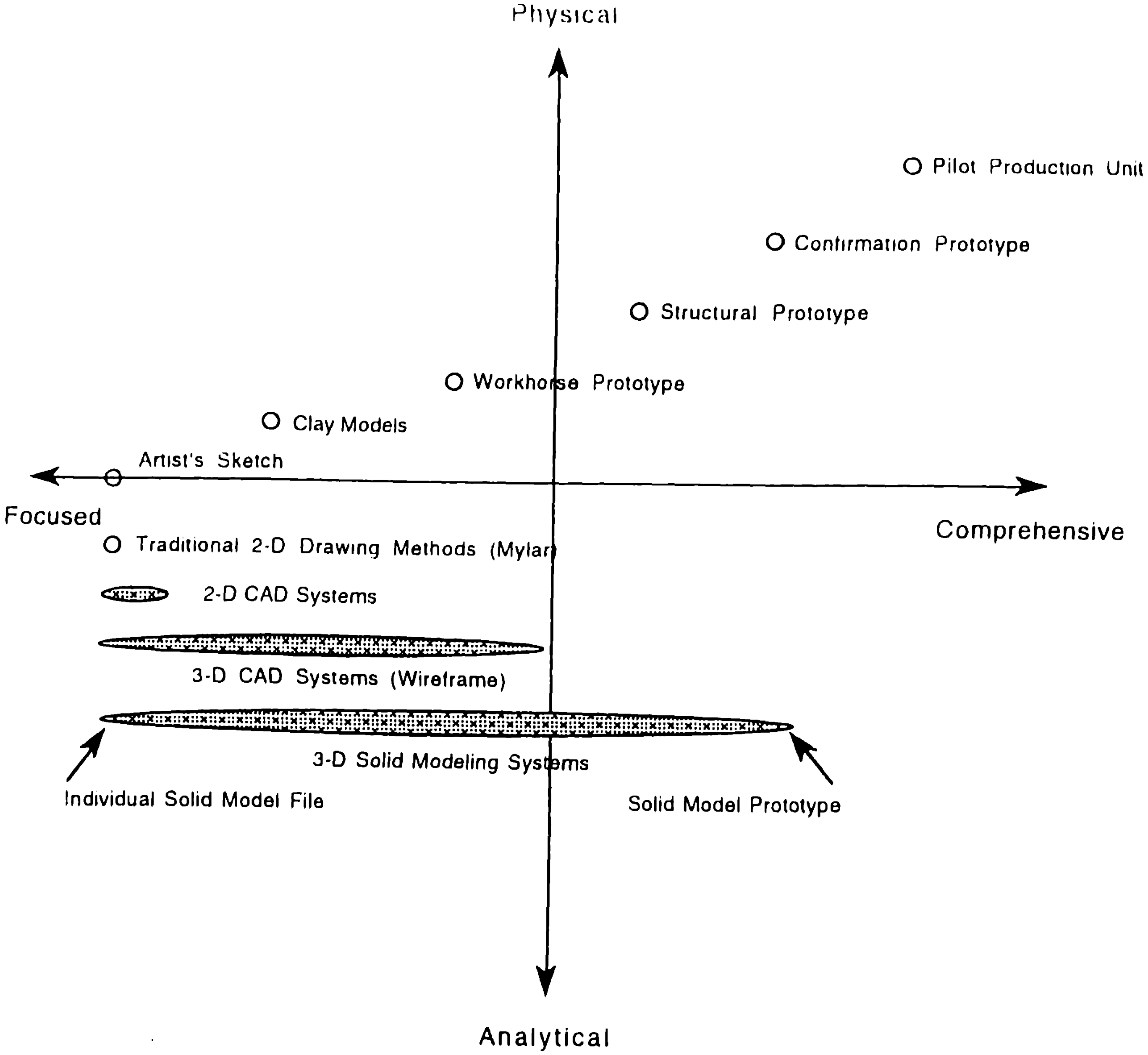


Figure 6-1: Perceptual Map of Prototypes and Design Systems

Also included in this diagram are broad classifications of the types of design systems which have been or are currently in use at the companies under study. As this diagram shows, successive generations of design systems are enabling the 'production' of increasingly comprehensive analytical prototypes.

This progression begins with the traditional design process based on 2-Dimensional mylar drawings. Such drawings were created by hand using conventional drafting tools and were essentially a more analytic version of an artist's or engineer's sketch. Although they can be considered to be more analytic than a sketch, they are similar in the degree of complexity (or comprehensiveness). Due to the need to represent the third dimension via orthographic projections or section drawings, this method is severely limited as to the amount of information which can be contained without becoming confusing to the reader.

The next 'generation' of design systems, 2-D computer aided drafting, was essentially an automated method of producing drawings by the above method. This process was not much more analytical than a mylar drawing (except for the medium used), but had the potential to be slightly more comprehensive. In its basic form, a 2-D CAD drawing can be as focused as its mylar predecessor, however, the power of the computer to easily make changes, create layers, and copy geometry enabled somewhat larger, more complex geometry to be combined in a single file or drawing.

Much greater advances in the degree of comprehensiveness were made with the advent of 3-D wireframe CAD systems. First used by auto companies in the early '70's, these systems were the first to enable engineers to visualize large assemblies of parts. With the addition of the third dimension, it was no longer necessary to create projections and sections to verify the fit of adjacent components. Utilizing the tool's ability to rotate and view the computer generated images, the task of integration was greatly simplified.

Since this system can be used to model a single component as well as a large assembly, the degree of comprehensiveness of this system is expressed as a range on the diagram. This range extends to the level of a workhorse prototype because such a system is not practical for very large assemblies. Although wireframe systems are *capable* of displaying many parts simultaneously, there is a practical limit to the complexity which can be interpreted by the user. In complex designs, foreground and background lines are difficult to discern from each other, and the image can appear inverted from what is intended. In addition to being more comprehensive, wireframe systems are also classified as more analytical than their predecessors. The introduction of wireframe systems was also accompanied by the ability to create mathematical representations of surfaces and finite element meshes for use in computer aided engineering (CAE) analyses.

The latest generation of computer aided design tools have greatly expanded the degree of comprehensiveness and have provided increased analytical capabilities as well. One of the limitations of wireframe modeling described above was the ability to interpret the confusing masses of lines required to define a large assembly. When viewing a large assembly constructed of 3 dimensional solid models, interpretation of complex assemblies is no longer a difficult task. Through the use of oblique light sources, shading, and rendering, depth cues are provided which communicate the third dimension easily.

As was the case for wireframe systems, the degree of comprehensiveness for solid modeling systems is also shown on the diagram as a range. This range extends from the most focused use of solid modeling to depict a single part, to the most comprehensive which may consist of a solid model prototype of the entire vehicle.[6] It is important to note however, that even a fully defined solid model prototype of a vehicle cannot be considered to be a fully comprehensive prototype. This is due to the type of information that is learned and conveyed by late stage physical prototypes such as confirmation prototypes and production prototypes. Much of the knowledge gained from these prototypes is derived from the assembly processes and manufacturing processes used during their construction. Therefore, the upper range of comprehensiveness for solid modeling systems is limited to be less than that of a confirmation prototype.

In addition to the increased range of comprehensiveness, solid modeling systems have increased analytical capabilities as well. Since parts are defined as solids, volumes of parts are easily calculated, which, when combined with the material density, can be used to automatically determine the weights of parts or assemblies. Furthermore, these systems provide the ability to automatically search for interferences within assemblies and can calculate and display the volume of intersection. Many of the new commercially available solid modeling packages also are integrated with finite element analysis capability which allows the seamless transfer of design information to engineering analysis.

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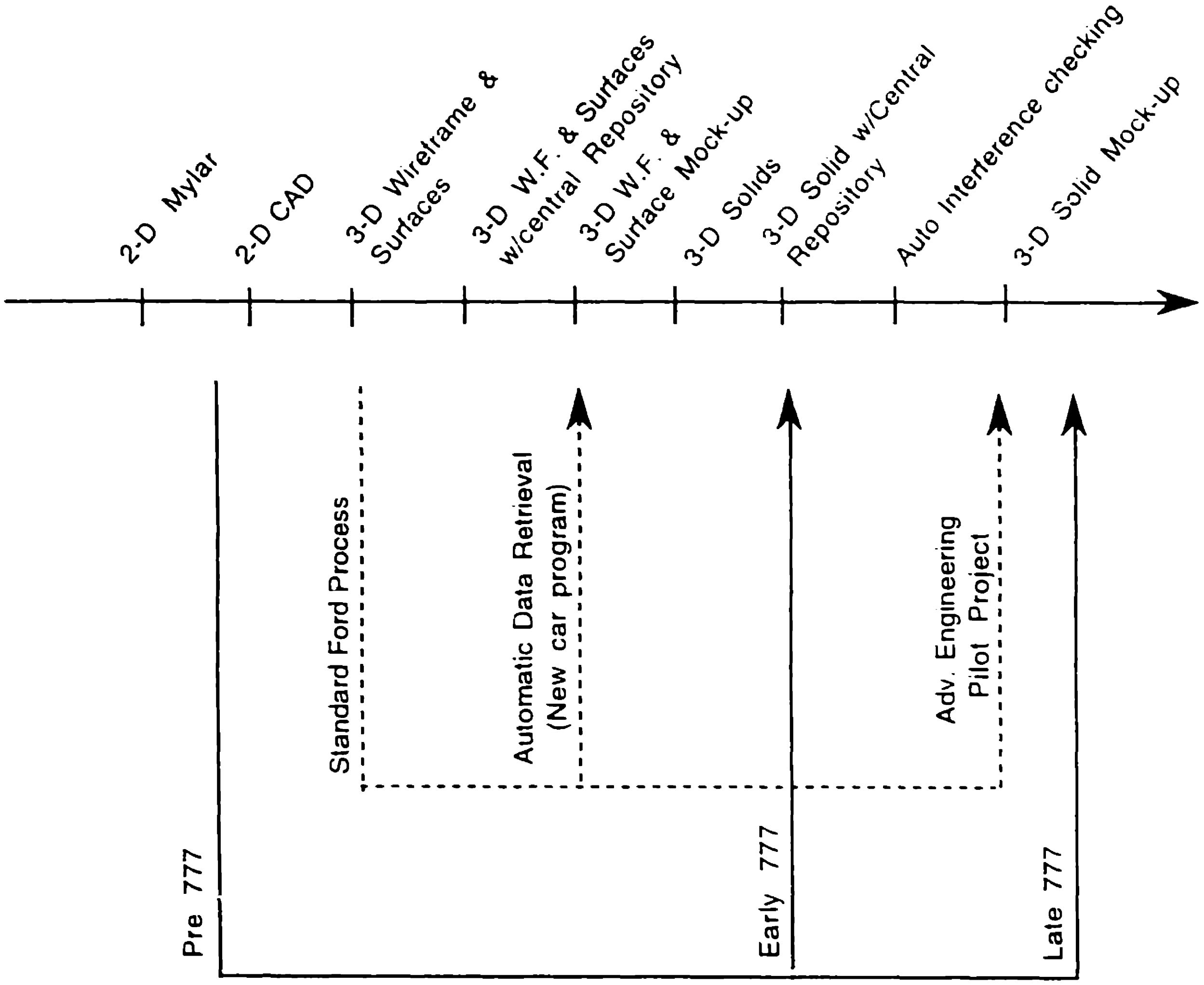
[6] Although in terms of interpretability a complete solid model prototype may be possible, very large assemblies may be constrained by the memory and storage capacity of engineering workstations. However, with the rapid increases in performance of engineering workstations, this constraint is rapidly disappearing. Furthermore, if simplified faceted solid models are used, very large assemblies are possible. This was evidenced by the Boeing 777 program which routinely used such a system to visualize large portions of the aircraft.

To better illustrate the progress which has occurred at each company, this evolution in design systems is shown in a simplified, timeline format in Figure 6-2. In this diagram, the range of comprehensiveness for each system is divided into three broad categories. The first category encompasses the basic use of the system (wireframe or solid modeling) to model individual parts or small assemblies. The next level of comprehensiveness involves the use of the system in conjunction with an electronic repository for the central access to design data. The third level of comprehensiveness is a digital prototype, which involves the large scale sharing and *assembly* of *all* design data.

6.2 Progress of Boeing and Ford on the Implementation Timeline

As shown in Figure 6-2, the use of solid modeling on the 777 program represented a significant leap forward for Boeing. Although there was some use of solid modeling and computer aided drafting within Boeing prior to the 777, the primary tool which had been used at the company for previous programs was 2 dimensional mylar drawings. Due to the ambitious initiatives for their new aircraft, the primary design tool in use during the early part of the 777 program could be considered as 3-D solid modeling with a central repository. Although it was intended to be used as an electronic prototype, the initial practices of the engineers using the system treated it as merely a central database of information. This was primarily due to the inability to perform interference checking on 'assemblies' of more than twenty models simultaneously. Without

Figure 6-2: CAD Evolution Timeline



the ability to 'assemble' and check all components in a given area, it therefore was difficult to regard the system as a replacement of the physical prototype.

It was not until later in the program, that the system could truly be considered as a complete solid model prototype. With the introduction of Boeing's proprietary system for visualizing simplified solid models, much larger assemblies could be assembled on the computer. This system enabled computer aided interference checking of large segments of the aircraft and visualization capabilities which could replace the role of a physical prototype in the design process.

The position of Ford's design system is also shown on the timeline. Although commercially available solid modeling software is used in some functional groups at Ford, the dominant system which is being used for current vehicle programs is the Ford Product Design Graphics System (PDGS). In recent years, this system has incorporated a rudimentary solid modeling ability, however, as of this writing, the majority of current programs have not yet adopted the widespread use of this capability. Therefore, the current state of Ford's system is classified primarily as a 3 dimensional wireframe system with a central repository. As discussed earlier, the central repository of information is actually not centralized, but instead consists of an extensive network between data collectors for each function. Under this system, electronic exchange of design information is possible, but there is no formal process for electronically 'assembling' the most current design.

Several new projects are underway however, which will move the Ford design system toward the type of system which was employed on the 777 program. Within a current new vehicle program, efforts are underway to create a central data library consisting of the filenames and network locations for all current CAD geometry for the vehicle. With the use of parent collector drawings, all CAD wireframe geometry for a particular region of the vehicle can be retrieved on demand. This automatic retrieval and assembly tool will provide the necessary functionality to allow the resulting system to be considered a 3-D wireframe prototype of the vehicle. Although this will achieve great benefits in the reducing non-value-added time acquiring current geometry for neighboring parts, the actual benefits of a 3D wireframe prototype remains to be seen. As mentioned earlier, complex wireframe models are often difficult to interpret, and it is therefore questionable as to what degree of learning can be gained from such a system.

Much greater advances are being made at Ford through an advanced engineering pilot project. As discussed in Chapter 4, one of the objectives of this project is to utilize solid modeling design tools to produce a complete solid model prototype of a next generation vehicle. This project utilizes a central product data management (PDM) system which contains the latest, production intent solid model geometry for the new vehicle. Comprehensive solid model prototypes are then constructed from this data, enabling the early detection and correction of any interferences or integration errors. If this system is successful, and is implemented throughout Ford, this will bring Ford's design system to be comparable to that which was used on the Boeing 777 program.

7.0 Future Evolution of Design Systems

As the above timeline illustrates, both companies have made great progress in the use of advanced design systems. However, if Ford is successful in implementing their latest advance they will only have implemented a system with the same basic functionality that was used on the 777 several years ago. It is true that the new Ford system will be able to take advantage of more powerful hardware and software that has become available since the time of the 777 commitment, but fundamentally, the systems will be very similar. What is important to Ford, therefore, is to understand what the next generation of design tools will entail and position their current strategy accordingly.

7.1 Current functions of prototypes and future needs

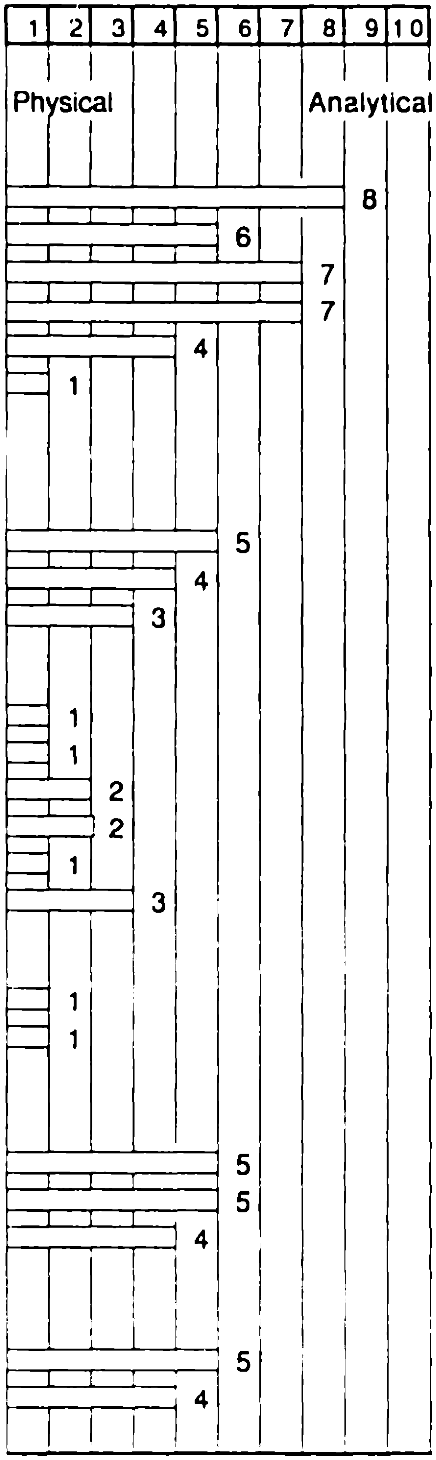
To determine what the next generation of design system should be, it is necessary to analyze what functions that prototypes currently serve and determine what needs are not being adequately addressed. Recalling from Chapter 3, there are four principal functions that prototypes serve:

- Learning and Feedback
- Outside Evaluation
- Information Sharing and Integration
- Monitoring and Pacing of the Development Process

This framework has been used to organize a list of the detailed functions that a prototype currently serves in the automobile development process. An extensive list of the functions by category is shown in Figure 7-1 on the following page. For each of the functions that a prototype performs, a rating is provided

Figure 7-1: Functions of Prototypes In Vehicle Development

Dependence Upon Physical vs. Analytical Prototypes



		Primary Mode
Learning and Feedback		
Stress / Reliability Analysis	8	FA
Noise, Vibration and Harshness (NVH)	6	FA
Styling	7	FA
Thermal / Airflow Testing	7	FA
Safety / Crash Testing	4	CP
Component Functionality Testing	1	FP
Communication and Information Sharing		
Engineering Integration		
Packaging Confirmation	5	CP
Design of 'Systems' components (i.e. wiring)	4	CP
Occupant Ergonomics	3	CP
Manufacturing Integration		
Manufacturing Variation (Component)	1	FP
Assembly Interferences	1	CP
Assembly Sequence	2	CP
Assembly Variation	2	CP
Assembly Ergonomics	1	CP
Tooling Access and Removal	3	CP
Servicability Integration		
Dissassembly Sequence	1	CP
Service Ergonomics	1	CP
Outside Evaluation		
Management Review and Approval	5	CP
Marketing Evaluation	5	CP
Customer Evaluation	4	CP
Monitoring of Development Process		
Design Reviews	5	FP
Program Management	4	CP

FP = Focused, Physical FA = Focused, Analytical CP = Comprehensive, Physical which illustrates the degree to which the particular aspect of the design is dependent upon physical or analytical prototypes. A rating of 0 indicates that the particular activity is completely dependent upon learning gained from a physical prototype, and a rating of 10 indicates that the learning is obtained solely through the use of analytical prototypes. Also included in the figure is an indication of the primary type of prototype(s) which are employed.

As is shown in Figure 7-1, analytic prototypes already have become an integral part of many design activities but are relatively absent from others. In particular, analytical prototypes are depended upon quite extensively for the activities classified under learning and feedback. In the opposite extreme, functions relating to information sharing and integration, particularly manufacturing integration, are still highly dependent upon physical prototypes. In the paragraphs below, a brief overview of each of the major types of functions is given and the degree to which the increased use of analytical prototypes is appropriate.

Learning and experimentation

Many of the activities included in this classification are very closely related to engineering analysis and are therefore well suited to the use of focused, analytical prototypes. The analytical prototypes used for these purposes include a wide variety of Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) software packages that are commercially available. This early analysis can be used to predict the behavior of the components or system and improve the chances of success when the physical prototype is eventually constructed.[7]

Other activities, such as styling development are also accomplished with the use of focused, analytical prototypes in the form of Computer-Aided Industrial Design (CAID) packages. These CAID software tools enable designers to rapidly develop many styling concepts efficiently and cheaply on the computer. These styling concepts are then electronically rendered to produce a photorealistic image for evaluation purposes. Precise clay models are then machined for only the successful, refined concepts using three dimensional surface geometry generated by the CAID system. In this way, much of the iteration and learning for the styling design is performed analytically, and the physical, clay prototype serves only as a confirmation of a perfected design.

Exceptions to the extensive use of analytical prototypes in this category are crash testing and functionality testing. Although engineering analysis software can be used to estimate crash-worthiness during the design, the dynamic, somewhat unpredictable nature of a crash necessitates the construction and testing of physical prototypes. Even if analytical prototypes are able to model this situation more accurately in the future, it is still reasonable to assume that due to the liability involved with occupant safety, that physical prototypes will still represent a large portion of this activity.

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[7] Although these computer aided engineering analysis tools are widely used in the automobile design process, a significant difference was observed in the way that these tools were used in the aircraft development process. At Boeing, analysis tools were used much earlier in the design to determine target stress requirements for components based upon system level requirements. At Ford, engineering analysis tools are often performed after the fact, to verify that the design will meet the system level requirements. Often due to schedule constraints, this is done simultaneously with the construction of a physical prototype, and the learning gained is too late to be useful.

The other exception, functionality testing, is conducted to determine if a component or subsystem serves the purpose intended and assess its ability to withstand use. Due to the inability to model all of the properties of the component and its interaction with the environment, this activity also necessitates the use of physical prototypes. In the future, analytical systems may be able to model this detail, however, since the primary mode used is a focused physical prototype, the cost of construction is generally low, and is justified for the fidelity of the resulting information.

Outside Evaluation

The outside evaluation function of prototypes consists of the communication of progress to upper management, customers, or related functions such as marketing. The primary modes by which this occurs differs at various stages of the design process. At the early stages of the design, the predominant mode of communication is through analytical prototypes such as CAID systems that were described above. Later in the design process however, physical prototypes are used because of their ability to concisely visualize all of the design effort to that point. Since the primary goal of this activity is to give an overall perception of the design and its progress rather than communicate technical details, it is reasonable to assume that as analytical prototypes are more extensively used, that they will also satisfy the needs for outside evaluation.

Management and pacing of the development process

This function of a prototype is evident at the level of design reviews as well as major program milestones. At the level of the design review, a combination of detailed deliverables and prototypes are used to drive the development process. Although focused physical prototypes may be periodically created by the design team for communication purposes, equally important deadlines also may be to have completed an FEA or CFD analysis of the design.

At the overall program management level however, the major milestones are still predominantly governed by the physical prototype build dates. These build dates are effective as milestones because they mark the culmination of a program-wide design phase in the design-build-test model of development. In a future design environment, where only analytical prototypes are 'produced' there are no such naturally occurring divisions between design stages. In a design environment such as this, design-build-test cycles are repeated continuously and the design remains flexible. This flexibility may be a great advantage for functions such as integration, but unfortunately it also makes analytical prototypes less appropriate for accomplishing the program management function. This role of prototype should not be forgotten if analytical prototypes are to be used to reduce the overall development cycle time. 'Artificial' electronic build points and requirements may have to be introduced to provide the necessary milestones by which to drive the development process.

Information Sharing and Integration

The greatest opportunity for the use of analytical prototypes lies in the function of information sharing and integration. As discussed earlier, the majority of the benefits of Boeing's digital pre-assembly process were related to the early and frequent sharing of design information between the various design groups. As

Figure 7-1 shows, however, many of the integration activities in the automobile development process are still highly dependent upon physical prototypes.

As shown in Figure 7-1, the information sharing function is divided into three primary types:

- Engineering Integration
- Manufacturing Integration
- Serviceability Integration

Engineering Integration encompasses the ability of the prototype to bring about the systems level integration of the various subsystems of the design. In the most basic sense, this refers to ensuring that subsystems designed by different design teams fit together without interferences. In the Ford process, much of this integration takes place in the PDGS system, however lack of current design information between various groups often results in integration errors which are not detected until the physical prototype is built. Due to the difficulty in detecting interferences in a wireframe system, many other interferences simply pass through undetected. This is particularly important for subsystems such as electrical wiring harnesses which interface with many parts of the design. For these types of components, the physical prototype is often used to develop the design and routing patterns. With the use of advanced solid modeling tools and their interference checking capability, many of these integration errors can be detected in the analytical prototype before the expensive, comprehensive physical prototype is constructed.

Manufacturing integration refers to the use of the prototype to develop assembly processes and confirm the manufacturability of the design. Although manufacturability is a major concern during the design process, the majority of the learning related to this activity is obtained during the assembly of the physical prototypes. Since the primary mode for this activity is the comprehensive physical prototype, this represents a very costly means to identify problems . If errors are detected at this phase, considerable redesigns may be necessary which may compromise the quality of the design and result in delays in the development process. If analytical models were used to develop assembly sequences and calculate assembly variances concurrently with the product design, many of these costly late-stage design iterations could be avoided.

Serviceability integration is very similar to that of manufacturing integration. Although serviceability is a factor which is reviewed in the design, there is not any effective means to evaluate the serviceability until a comprehensive physical prototype is constructed. Serviceability is actually much more complicated than manufacturability because it is not merely the reverse order of the manufacturing process. An oil filter or timing belt may be very easy to assemble on an engine while it is built off-line, but one would not want to remove the engine from the vehicle to replace these components. In the current design process, the only means of assessing serviceability prior to the physical prototype is through the use of sketches and storyboards which illustrate conceptually how service will be accomplished. Due to the difficulty in obtaining current design information, this task is usually done too late in the design process and serviceability errors are detected on the physical prototype.

Lastly, a common element in all of the above integration tasks is that of ergonomic evaluation. This element is present in engineering integration in the form of occupant ergonomics, and in manufacturing and service as the ergonomics associated with assembly or disassembly. In all of these instances, ergonomic evaluation is still very highly dependent upon physical prototypes. The greatest use of analytical prototypes in this regard is in the area of occupant ergonomics where occupant safety and reach zones are defined on computer and 'packaged' along with the other components of the interior. Although this prevents violating basic human space requirements, a large portion of ergonomic evaluation is still dependent upon human perception and 'feel'. As a result, analytical prototypes still fall short in their ability to satisfy this function.

In Figure 7-1 and the above discussion, it is apparent that there are several aspects of the design process where analytical prototypes are not yet employed extensively. The objective, however should not be merely to replace physical prototypes with analytical prototypes. The true basis for this replacement should be driven by the reduction in development cycle time and cost.

One of the primary drivers for development cycle time is the late detection of integration errors and the subsequent design changes which must occur. Included in Figures 7-2 through 7-4, are design change data for several vehicle programs at Ford. The actual quantity of design changes and timing of build dates have been disguised to protect proprietary information, however a qualitative relation between design change activity and prototype construction can still be observed. As shown in these figures, the quantity of design changes surges to two to 4 times the steady-state level coinciding with or immediately following a prototype build event. This spike in design changes can be considered beneficial in that it indicates learning is occurring as a result of the prototype build, however it is unfavorable in that the errors had to wait until the build to be discovered.

Figure 7-2

Program 'A' Engineering Changes vs. Time

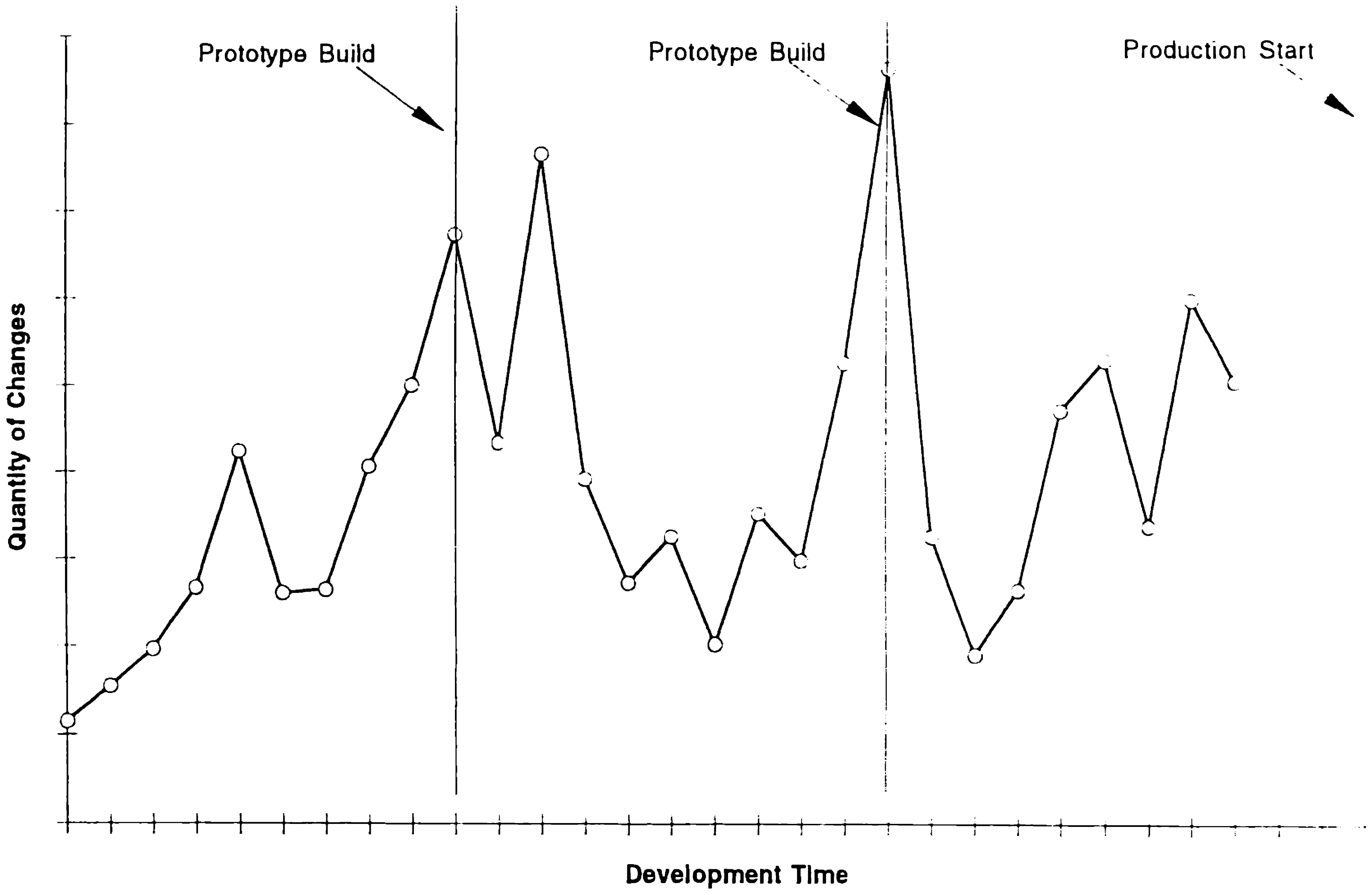


Figure 7-3

Program 'B' Engineering Changes vs. Time

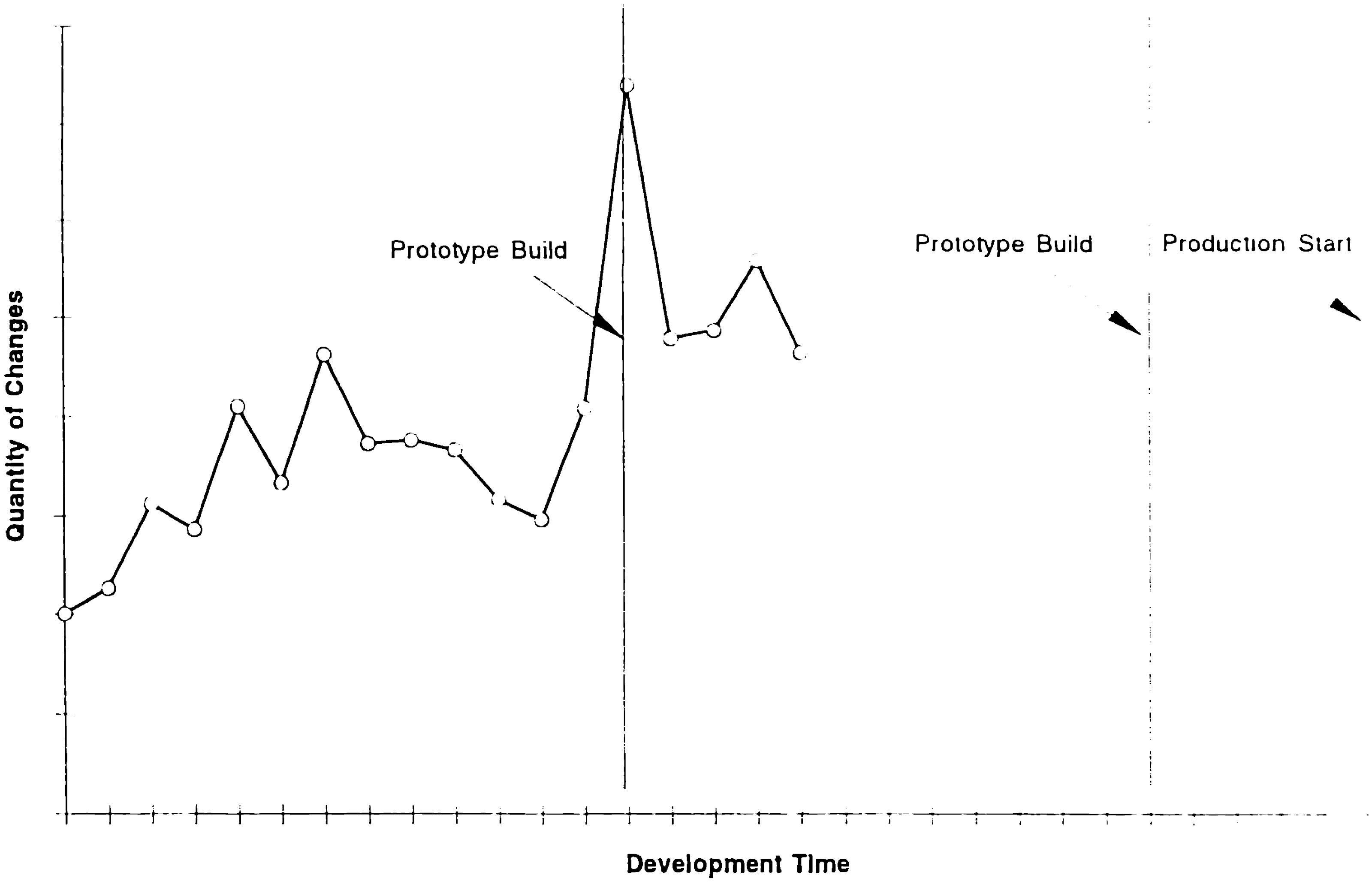
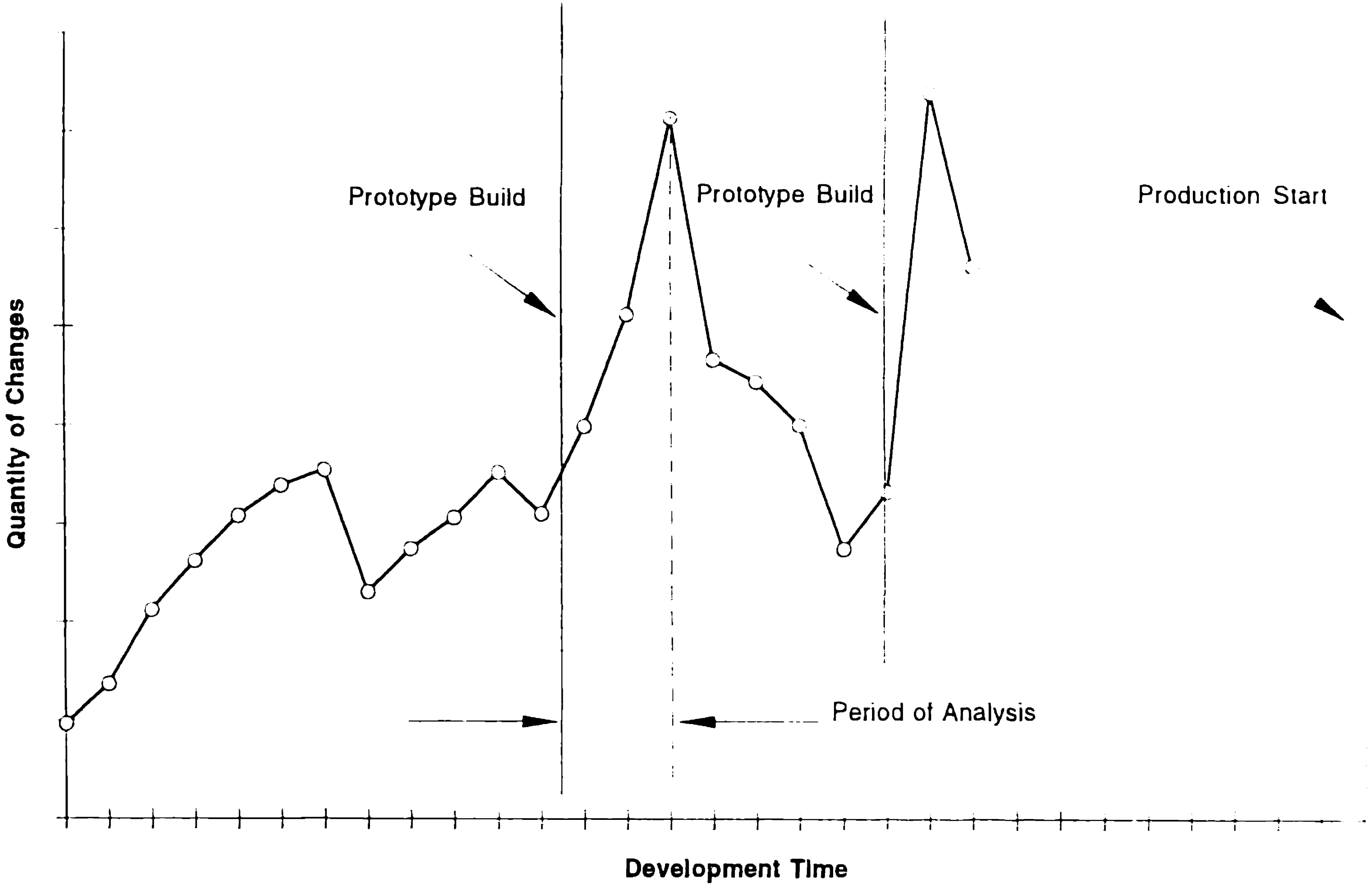


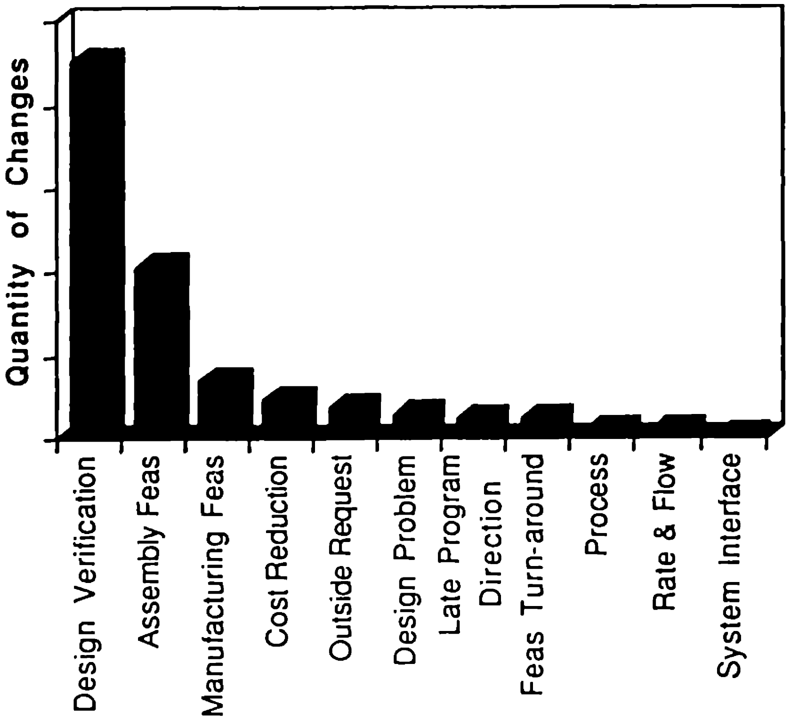
Figure 7-4

Program 'C' Engineering Changes vs. Time



Additional information can be gained from a detailed analysis of the types of design changes which occur immediately following the construction of a prototype. The pareto analysis shown in Figure 7-5 represents the causes of engineering changes for the period following the first build event in Figure 7-4 (area indicated in the figure)

Figure 7-5: Causes of Engineering Changes



As shown in the above figure, the primary cause of engineering changes is due to inadequate design verification. This category encompasses problems related to the nominal packaging of components as well as poor performance of the design to expectations. As shown by the improvements witnessed on the 777 program, many of these problems (particularly those related to packaging interferences) can be eliminated through the use of a solid model prototype. According to data from Boeing, there was a 75 % reduction in integration errors as a result of the frequent sharing involved in the DPA process. With Ford's implementation of a solid model prototype and associated product data management system, it is expected that similar improvements in this area can be achieved.

As far as future needs for design systems are concerned, the next largest cause of changes presents a great opportunity. This category, assembly feasibility, primarily includes problems related to interferences during assembly, assembly variation, and assembly ergonomics. As indicated in Figure 7-1, these areas are also where analytical prototypes are currently least employed. If these problems could be identified and corrected much earlier in the design process through the use of analytical prototyping, this costly late-stage reiteration of the design can be avoided.

7.2 Future Generations of Design Systems

Based upon the above needs of the prototyping process and the current uses of analytical vs. physical prototypes, this author proposes that the next stage in the evolution will be typified by assembly-centered design processes. The objective of such processes will be to extend the capabilities of the analytical prototype to address the needs of assembly feasibility. As shown in Figure 7-6, these processes will require a new type of design system which builds upon the limits of the 3-D solid model prototype. Such a system will have to incorporate a fourth dimension, time, with which to model the assembly sequence of the components and tools. Due to the ability to model the 'process' dimension of the product, this new type of system is classified on the diagram as more comprehensive than three dimensional solid model prototypes. This comprehensiveness is expressed as a range in the diagram because, as explained in the following chapter, the

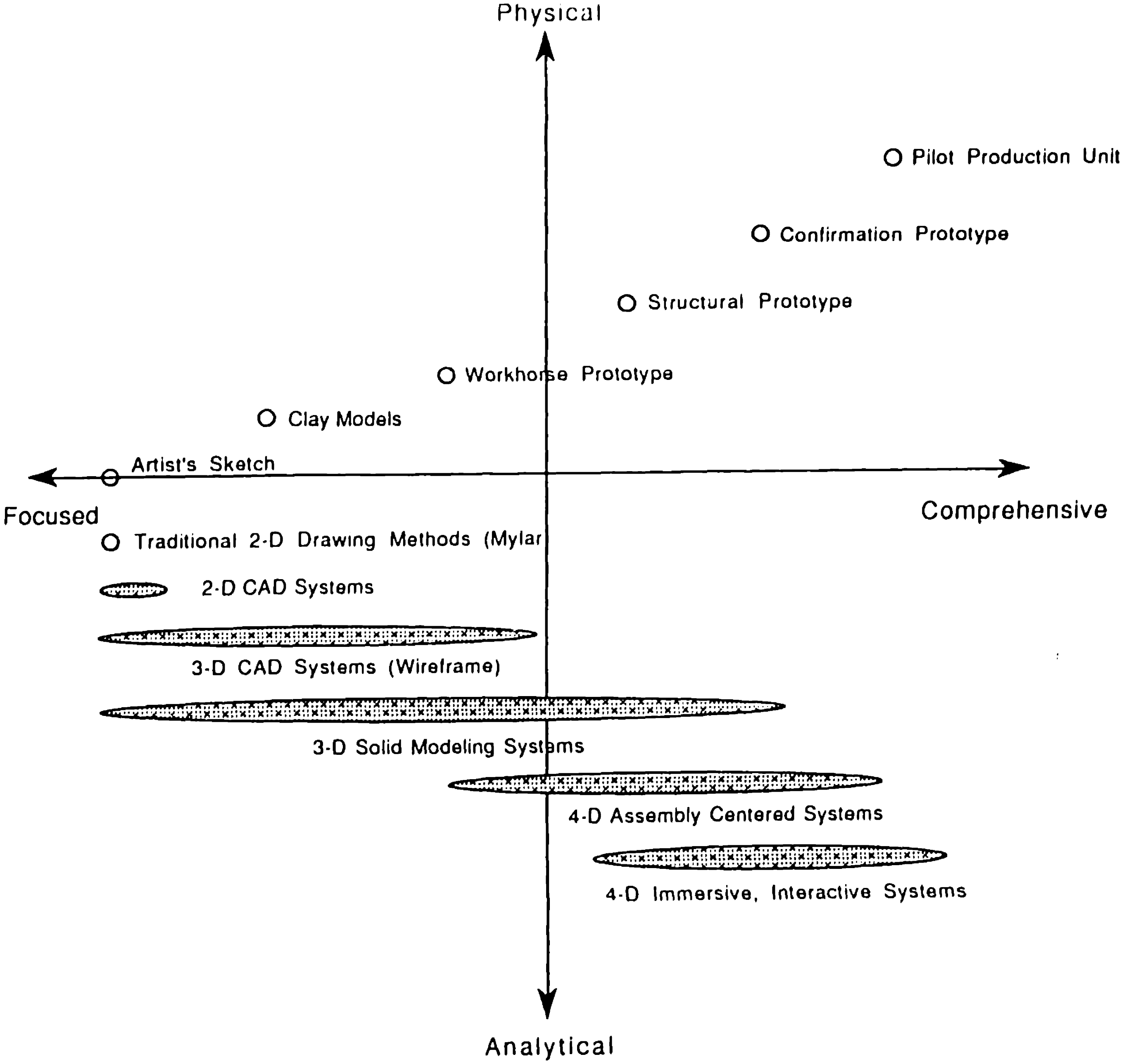


Figure 7-6: Perceptual Map of Future Design Systems

implementation of such a system can be accomplished in a series of logical steps, each building upon the amount of process information contained in the model. Additionally, since four dimensional systems will enable the automatic calculation of assembly interferences and assembly variances, this type of system is also classified as being more analytical than preceding systems.

If four dimensional systems and their associated processes are implemented successfully, the needs of assembly interference detection, manufacturing variation, and assembly variation will be addressed. The one element that will still remain missing in analytical prototypes however, is that of ergonomic evaluation. The principal barrier to assessing ergonomics with an analytical prototype lies in the inadequacy of the human/computer interface. Currently, the only method to adequately assess this personal interaction with the design is through the use of physical prototypes. In the future however, improvements in computer hardware and software will enable this problem to be overcome. It is proposed that the subsequent generation (although 5-10 years in the future) will be that of Immersive and Interactive (i.e. virtual) design systems. With the ability to evaluate the ergonomics of use as well as the ergonomics of assembly and service, these 'virtual prototypes' will extend the comprehensiveness of analytical systems to nearly that of a comprehensive physical prototype. This is not to say that physical prototypes will not still be a part of the development process. Instead, these systems will provide increased insight during the design stage, so as to make best use of the physical prototype to test designs which are more nearly perfect.

In the following chapter, the proposed next 'generation' of 4 dimensional design systems will be explained in more detail. A timeline illustrating a suggested sequence of implementation will be presented and the justification for the ordering of the implementation steps will be discussed.

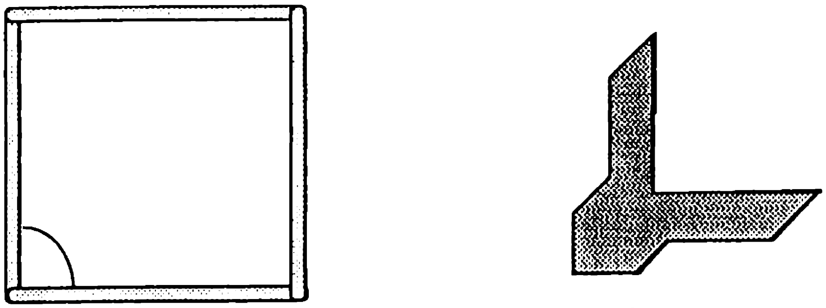
8.0 The Next Generation: 4 Dimensional Systems

As briefly mentioned above, a 4-dimensional design system is a design system incorporating the three dimensions of geometric space associated with present systems combined with the added dimension of time. Obvious questions to then ask are, "Why should time be selected as this additional dimension?" and "Is another dimension necessary to achieve the next step?"

To answer these questions, consider the example shown in Figure 8-1. As shown in this figure, there is an example of a very simple assembly consisting of four bars joined at their ends. Hypothetically, it is desired to determine what the assembly variation will be in one of the angles formed by adjacent bars. As this figure indicates, this value is impossible to determine without first knowing what tooling is used and the tolerance that it can maintain. Even when the tooling information is known however, a different assembly variation is obtained depending upon the assembly sequence used during construction. This assembly sequence information is therefore a critical factor in determining assembly variation.

In a 3-dimensional system, there is not any means to capture the sequence of operations to produce the product and there is not any meaningful way to incorporate tooling geometry with product geometry. In order to do so, an additional dimension is required. Time is selected as this critical dimension not only because it is essential to capture assembly sequence information for the calculation of assembly variances; but it is also necessary to capture assembly path information for the detection of interferences *during* assembly (4-D interferences), and assembly-level design features.

Figure 8-1: The Importance of Assembly Sequence

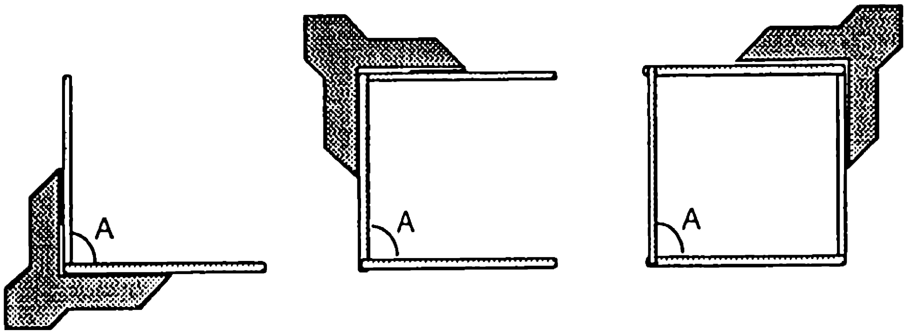


Assembly

Fixture

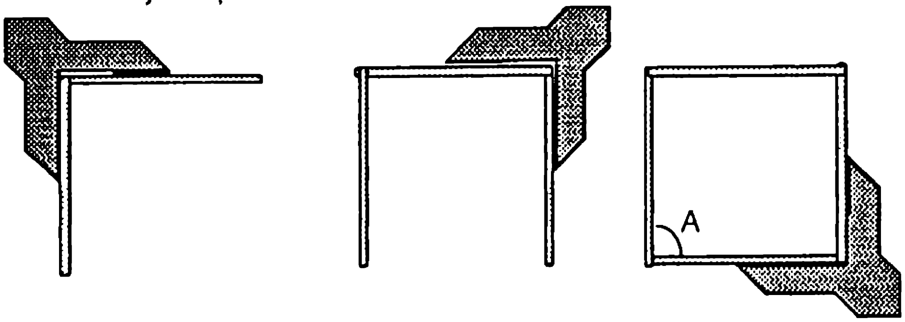
Problem: Four bars are to be joined at their ends. If the fixture to be used can maintain a tolerance of 90 +/- .1, what is the assembly variation in angle A?

Assembly sequence 1:



A= 90 +/- .1

Assembly sequence 2:



A= 90 +/- .3

*Example derived from Ref.[6]

As evidenced above, four-dimensional systems can be used for a variety of purposes. Included in figure 8-2, is a proposed implementation plan to progressively achieve these purposes. The implementation for 4-dimensional systems can be broken down into four incremental steps:

- Assembly Sequence Modeling
- Feature-Based Assembly
- Variation Modeling
- Variation Optimization

As shown in the figure, Boeing has already begun work on the most fundamental type of 4-D system to model assembly sequence information. As you may recall from chapter 5, one of the most frequently cited problems with the Boeing 777 development was the lack of tooling involvement and the difficulty in incorporating tooling in the DPA process. This system is intended to address these issues and provide a link by which to communicate assembly process information directly to the manufacturing floor. If successful, this assembly modeling system is scheduled to be used in the DPA process for the 737 redesign which is already underway at the time of this writing.

The sections which follow explain each of the implementation steps and the potential benefits associated with each step. For reference, a summary of the this information is illustrated in Figures 8-3a and 8-3b.

Figure 8-2: CAD Evolution & Future 'Roadmap'

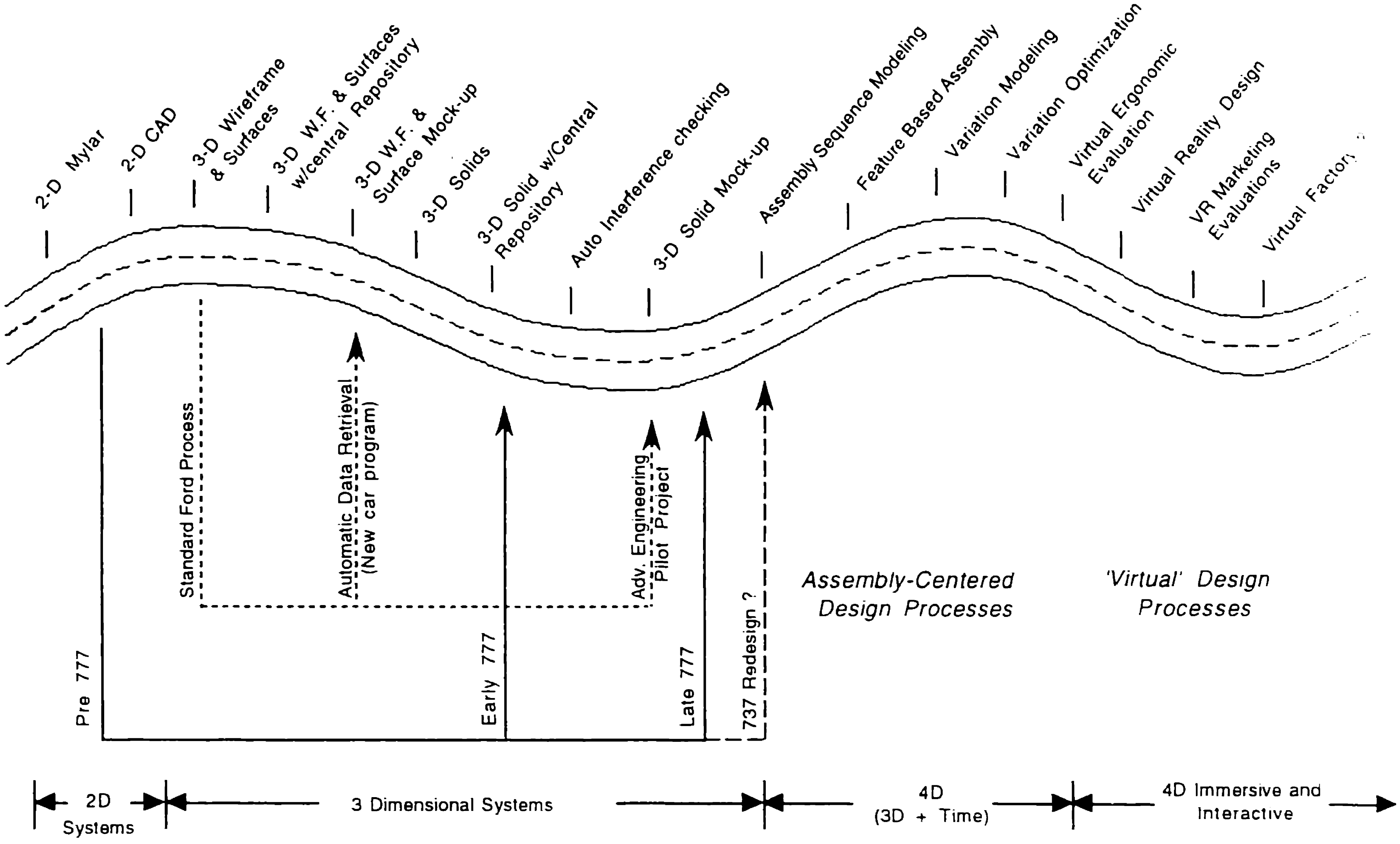


Figure 8-3a : Incremental Steps in the Assembly Centered Design Process

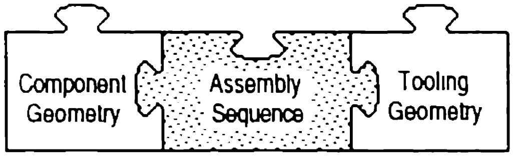
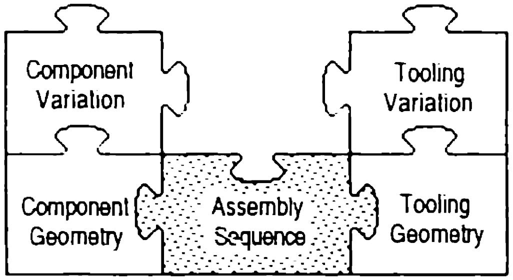
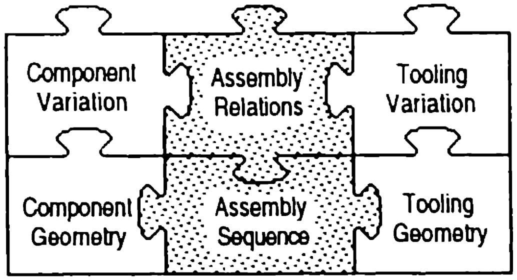
		Comments
	'Current' System Solid Model, Nominal Dimensions	Difficult to incorporate tooling and component geometry in the same model Only nominal dimensions are modeled, in their final assembled position
	Add Assembly Sequence to Model	Provides an environment where components and tools can coexist logically Provides an unambiguous method for communicating the intended assembly process Allows for assembly level design (i.e. drilling a hole into assembled parts) Enables detection of 4-D Interferences (i.e. interferences *during* assembly Two levels - Assembly Tree Information (i.e. order of appearance - Assembly Path Information
	Add Component Mfg. Variation and Tool Variation	Provides a mechanism that manufacturing can use to communicate estimates of variation to engineering during the design process

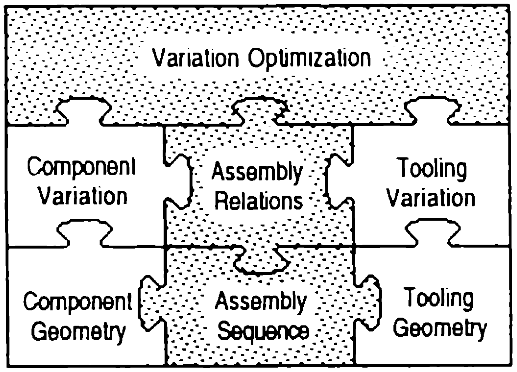
Figure 8-3b : Incremental Steps in the Assembly Centered Design Process

Comments



Add Feature-Based Assembly

Establishes the mating relationships between part features such as holes, locating points
Feature relationships combined with variation and assembly sequence enables the automatic calculation of assembly variation.



Add Variation Optimization

Calculates the contribution of each variation to an overall assembly variation
Provides a means for engineering to make intelligent, cost effective tolerancing decisions
Identifies cost effective locations for adjustment points and slip planes

8.1 Assembly Sequence Modeling

In traditional, serial design processes, drawings for product components were created by a specialized engineering function and were handed 'over the wall' to a downstream manufacturing function to develop the necessary tooling and processes to create the product. In the past decade however, great improvements have been made through the adoption of concurrent engineering practices. In such an environment, manufacturing input is solicited much earlier in the design process, and manufacturing plans are conducted 'concurrently' with product design. Usually, the method to accomplish this is to include manufacturing representatives on the design teams along with product design engineers or to invite manufacturing evaluation during design reviews.

Unfortunately however, little has changed with the medium of communication between these functions. Although advanced computer aided tools are now used to create geometry, designs are still typically shown in the form of a fully assembled product and without the necessary tooling required for manufacture. Manufacturing engineers on the team are thus placed in the difficult role of having to 'imagine' the assembly process and tooling requirements; and in this imagined scenario, must identify and communicate potential problems to the team. As a result, manufacturing input on the design is often based on previous bad experiences with designs and personal knowledge of existing processes.

Assembly sequence modeling addresses this communication barrier by providing a medium with which to combine tooling designs with product designs. By incorporating the time dimension of assembly sequence, tooling and product geometry can occupy the same location at different times without causing confusion or interferences. Assembly sequence modeling can take two forms. In its most basic form, (such as that being developed at Boeing) it involves merely capturing the assembly sequence of the design. This appears as an assembly hierarchy indicating the order of appearance (or disappearance, in the case of tools) in the assembly. This sequence can then be 'played back' on the computer to visualize components and tools appearing in the proper location and time. In this most basic form, this is useful in that it provides an unambiguous method for communicating and documenting the intended production process. Also, in cases where complex fixturing is required, this system can also be used to detect errors created when parts must be assembled where a fixture is temporarily located.

A more advanced version of assembly sequence modeling consists of modeling the assembly *path* in addition to the assembly sequence. The added information that this provides is useful in the detection of 4-dimensional interferences (interferences between parts or tools *during* assembly). This is very similar to the previously described system, however when the assembly sequence is 'played back' on the computer, objects do not merely appear in the proper location. Instead, computer animation techniques are employed which visualize the entire motion of the objects and can calculate interferences at increments along the assembly path. Such systems have been used extensively in robotics programming applications, but have not found widespread application as a tool to be used during the design process for design for assembly (DFA) evaluation.

8.2 Variation Modeling

One of the drawbacks of the DPA process used on the 777 and current solid model prototyping efforts is that these systems are only used to model nominal dimensions. Unfortunately, the real world dimensions are not always perfect and some degree of variation is always to be expected. The purpose of variation modeling therefore is to capture these dimensional variations in the definition of the solid geometry. In today's parametric, feature-based CAD systems this is easily accomplished by attaching a variance term to the parameters defining a particular feature. This variance term can be the actual process variations from production, or, in the case of newly developed parts, can be estimates of variation from manufacturing.

Although this variance information can be included in analytical models today, it lacks application if used in a system which is not capable of recording assembly sequence information. As discussed above, the assembly sequence information and tooling variation are critical elements for determining assembly variation. For this reason, variation modeling should only be implemented following the step of assembly sequence modeling.

8.3 Feature-based Assembly

Although the previous steps of variation modeling combined with assembly sequence modeling are necessary factors in determining assembly variation, an additional element is necessary before these calculations can be performed automatically by the design system. As shown in figure 8-3b, this missing 'piece' is the assembly relationships between mating parts and tools. Without these mating relationships, it is impossible for the computer to determine which dimensions and variances to use in calculating the assembly variance. In feature based CAD systems, this is easily accomplished by selecting mating features such as surfaces, holes, and locator pins on adjacent components. In fact, many solid modeling packages currently provide the ability to create assemblies of components using a such a feature-based approach[8].

8.4 Variation Optimization

After feature based relationships are established within the computer model, automatic variation analysis and variation optimization are made possible. At a basic level, assembly variance can consist merely of a tolerance stack up analysis. In this type of analysis, only the extreme values of variance are considered, resulting in a worst case assembly deviation. A more indicative measure of assembly variance however, is to take into account the probabilistic distributions of each of the contributing dimensions.

This is especially important for complex assemblies of many parts. In this instance, the worst case analysis may result in a very large theoretical deviation due to the stack up of many variations, but the occurrence of this condition may be very unlikely. In such a situation, the power of the computer can be utilized to determine the *distribution* of assembly variance. As Figure 8-4 illustrates, a monte-carlo simulation can be used to empirically determine the assembly distribution. In this method, several hundred 'experimental parts' are created

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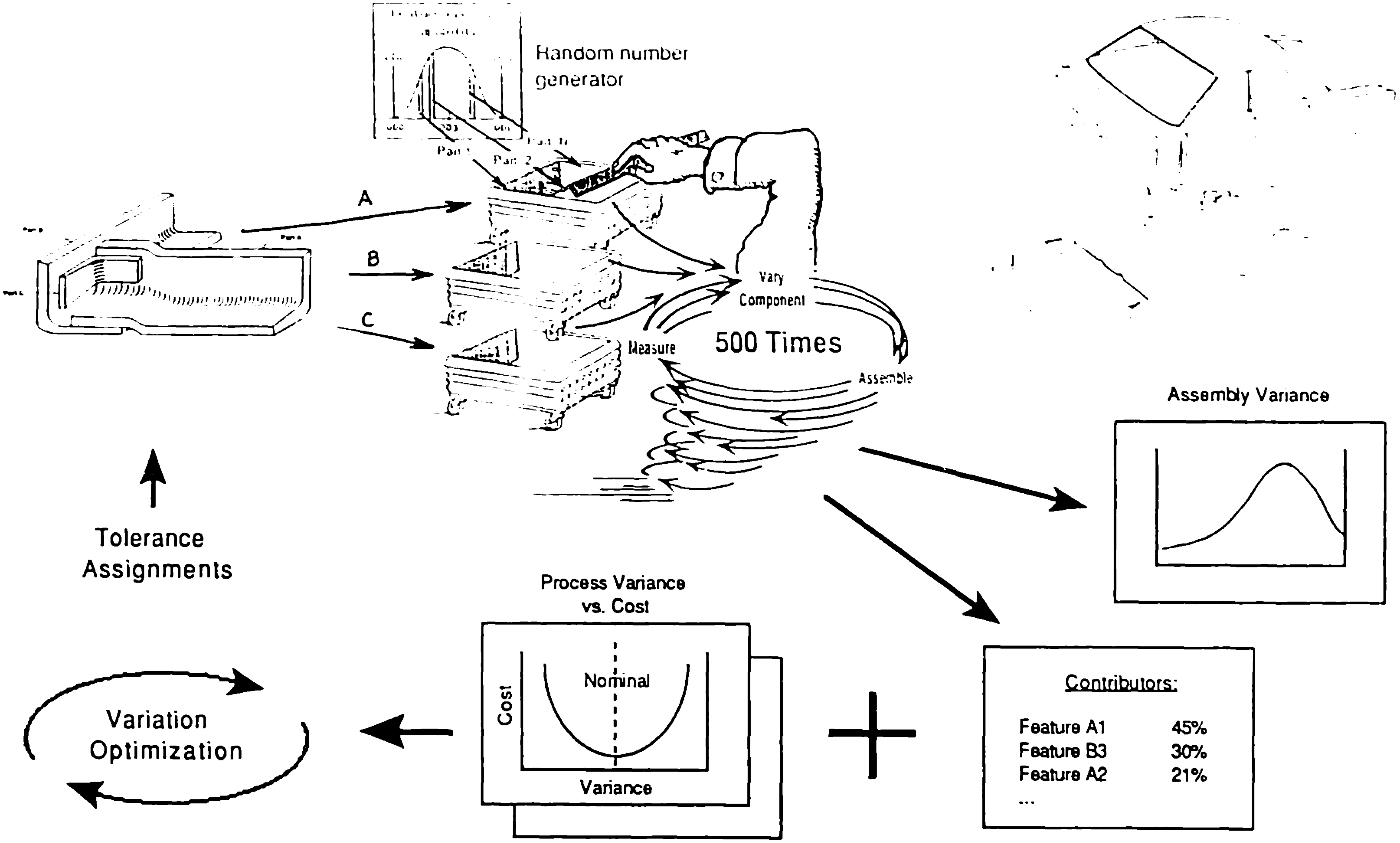
[8] This method of assembly is not frequently used however, because of the complex feature dependencies that it creates in the design. Due to the frequent change which occurs early in the design process, parts and features may be deleted for which other parts of the design are dependent. Therefore, this method is most appropriate for use in small assemblies where the interdependencies can be managed, or in the middle to late stages of a more complex assembly when the design becomes more stable.

Figure 8-4 : Variation Simulation and Optimization



within the computer according to the distributions entered for the contributing variances. These 'parts' are then randomly assembled and measurements are calculated for the assembly dimension under evaluation. After many reiterations of the assembly process, a distribution of assembly variance is thereby obtained.

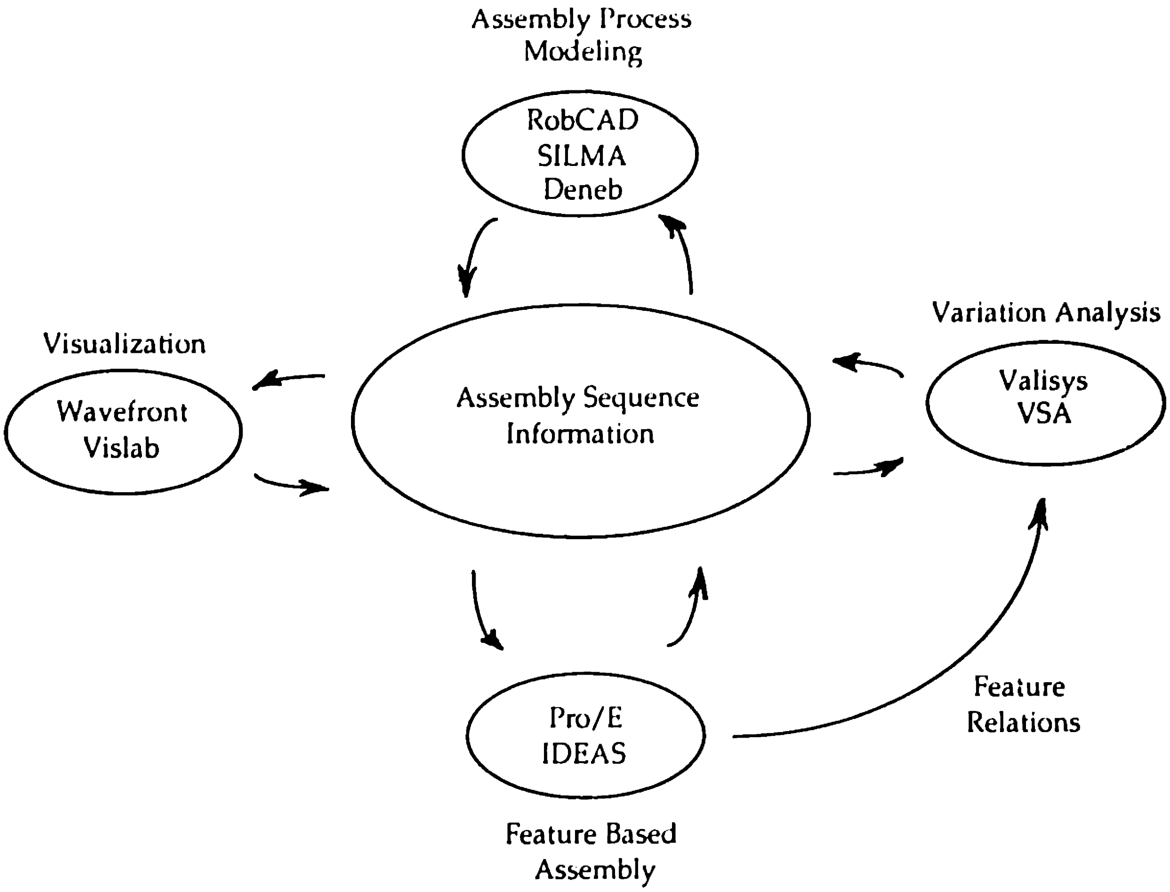
Variation optimization takes this analysis one step further. Due to the geometric differences in the way each dimension relates to the overall assembly dimension, some variances will contribute more to the assembly variance than others. Since this contribution can be calculated from the simulation, this can be combined with cost data for various types of manufacturing tolerances to determine the most cost effective assignment of tolerances in the design.

8.5 Existing 4-Dimensional Systems

As mentioned above, Boeing has already begun work on developing a basic form of 4D system that will enable assembly sequence modeling. Although this is a proprietary system exclusively for internal use, similar software is now becoming available commercially. In fact, many 'pieces' of what is envisioned for 4D systems are now commercially available. Assembly sequence software packages such as CIMSTATION™ from SILMA allow the recording of assembly tree and path information for the proveout of assembly sequences and for the detection of assembly interferences. Other packages, such as RobCAD™ and systems from Deneb Robotics provide suites of software which allow modeling and optimization of both robotic and human assembly processes. Several other packages, such as Vislab™ or Wavefront™ also provide similar capabilities, however, these tools are primarily used for the purely aesthetic visualizations of processes.

Additionally, commercial applications are also available in the area of variation analysis. Tools such as Valysis or VSA are able to capitalize on the feature-based modeling abilities of solid modeling software such as Pro/Engineer to develop linkages between mating features. Using input process variation data and monte-carlo simulation techniques, these packages are then able to calculate the assembly variances of the design as well as and the contribution of individual variances.

Figure 8-5: Integral Role of Assembly Sequence



As illustrated above, many parts of an assembly-centered design process already exist in various applications which are commercially available. What is lacking however is an integration among these tools and a method for incorporating them into the larger design process. Most of the difficulty in accomplishing this is in the management of data between these different specialized 'pieces' of the process. As shown above, a common thread that all of these systems share is the assembly sequence information. What is needed, therefore is a comprehensive data management architecture which allows the sharing of this assembly sequence information along with geometric data, so that a single, commonly understood process can be used in each part of the system.

9.0 Strategy For the Future

Thus far in this document, we have described the design systems in use at each company, documented lessons which can be learned from Boeing's use of Digital Pre-assembly practices, and have theorized future needs and applications of analytical prototyping. As this has shown, analytical prototypes will continue to become more complex as 4-dimensional and 'virtual' design technology becomes available. The question which now remains to be answered is: How should companies approach this increasingly complex area of product development?

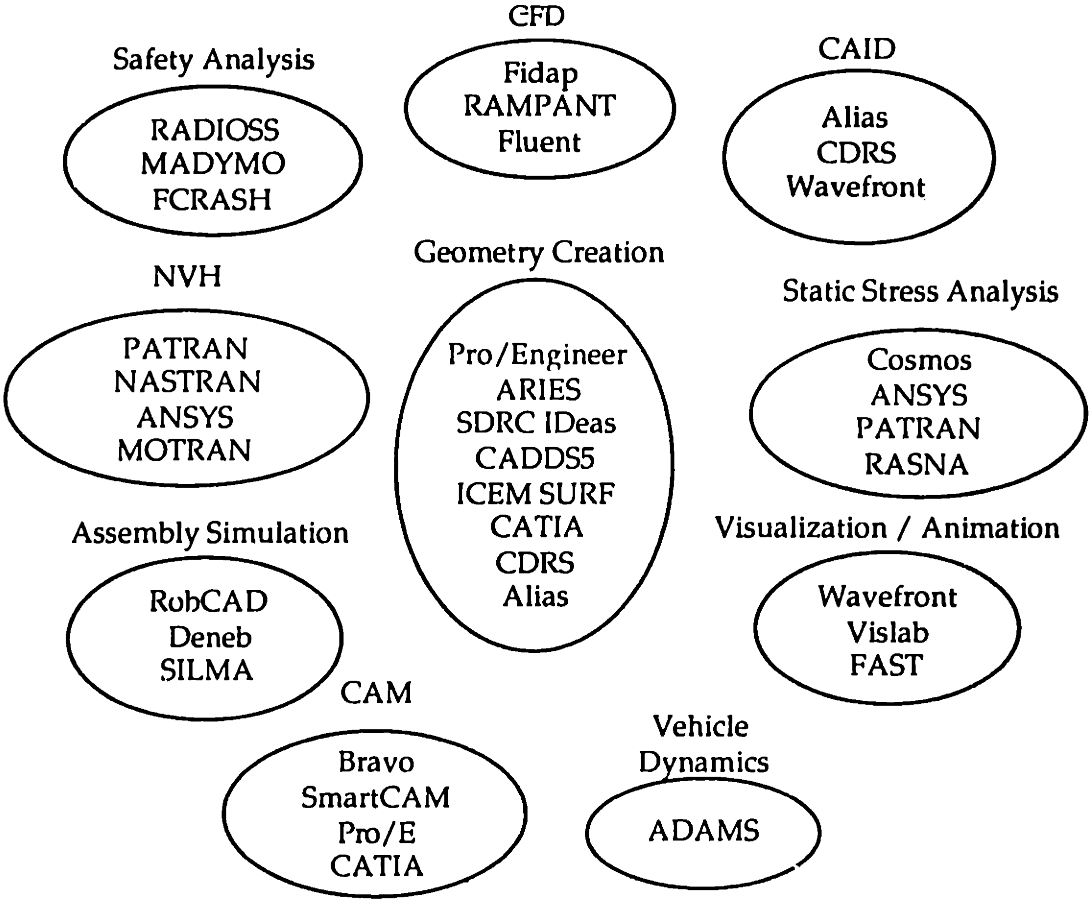
9.1 A modern definition of 'CAD'

The first approach to this matter is in the definition of 'computer aided design system' itself. As evidenced throughout this thesis, analytical prototypes can assume many forms within the product development cycle. When computers first came to be used in the development process, the term 'CAD' primarily referred to Computer Aided Drafting, since these systems were essentially a replacement of traditional drafting equipment. As these systems became more complex and capable of three dimensional design, their role in the process became more than simply a documentation of the design process and hence earned the title 'Computer Aided Design' systems. Since that time, specialized computer applications have become extensively used in all aspects of the development process, such as: Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), and Computer Aided Industrial Design (CAID).

As analytical prototypes have become more complex, the distinction between each of these systems has become blurred. It is now unclear where computer aided industrial design ends and computer aided design begins. Likewise, in today's environment of concurrent product and process development, the roles of Computer Aided Design and Computer Aided Manufacturing are also converging. In the future, these distinctions will become increasingly blurred as progressively more comprehensive analytical prototypes are made possible. Therefore, in this context of 'design system', a more holistic view of the term 'CAD' should refer to 'Computer-Aided Development', reflecting the all encompassing, integrated nature of these computer systems in the development process.

To illustrate the complexity of the situation and the interrelationships between the systems, an inventory of some of the popular computer aided development tools is shown in Figure 9-1. Although the details of each software package will not be discussed here, (which would require volumes) this chart illustrates the plethora of tools which are now commercially available to perform specialized tasks within the development process. It is important to also note that there are several tools which are capable of performing multiple tasks in the process. For example, Alias Paint software, which provides powerful sketching and rendering capabilities for CAID, can also be used for geometry creation directly from the computer rendered sketches.

Figure 9-1: Inventory of Computer-aided Development Tools



9.2 Competitive Advantages in Design Systems

Once a holistic view of the Computer Aided Development process and potential sources of tools are considered, the next step is to determine where internal resources and effort should be focused in this process. Ideally, internal resources should be applied where the most competitive advantage can be obtained; and external resources (i.e. outsourcing) should be sought for parts of the process where there is little advantage to proprietary differentiation, or the skills within the company cannot compete with alternative sources.

Based on Ford's current strategy of continuing to develop their own proprietary computer aided design system, it would appear that Ford regards their modeling system to be a source of competitive advantage. Although this is partially true, closer inspection reveals that it is not the modeling system itself which is important, but it is the role that this system serves in the larger "Computer aided Development" process. As shown in figure 9-2 (top), the geometric modeler (in this case, the PDGS system) serves two purposes in the overall process. At the basic level, this system is the primary means of generating product and tool geometry. In a larger context, however, this system provides the critical link by which information is stored and shared between various parts of the process and suppliers.

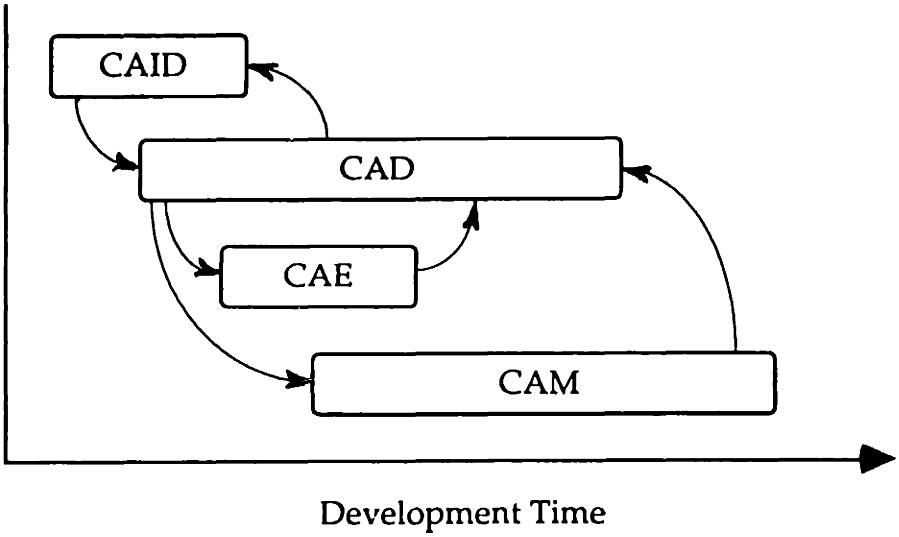
Although for a long period of time the geometric modeling capabilities of the PDGS system were regarded as state of the art, in recent years this system has struggled to incorporate functionality at the same rate as the commercial software market. This is evidenced by several internal Ford organizations which have begun to adopt commercially available solid modeling packages for their own internal use. Therefore, in terms of actual geometry creation, this proprietary system can no longer be considered a source of advantage. Where advantage is to be gained however, is in the integrative role that the PDGS system has served in the larger design process. As shown in figure 9-2, the CAD system is the central joining system by which various parts of the larger system communicate. This critical relationship was described in the comment below by a retiring CAD manager who had been involved with the PDGS system from its inception:

> " Over the years, the PDGS system and the Ford design process have evolved simultaneously .... and it now reaches into every activity of the design process. To remove the system would be to remove all of these links as well."

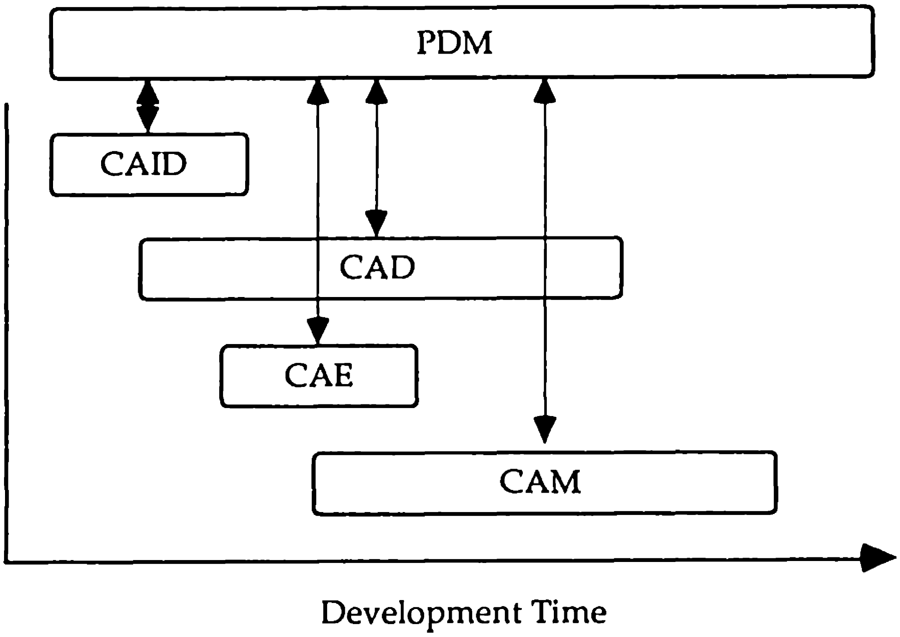
Therefore, the primary task at hand should be to maintain the capability to integrate the process, while capitalizing on the state-of-the-art tools which will continue to become commercially available.

Figure 9-2: Integral Role of CAD and PDM

Traditional CAD System as Integrator



Product Data Management System as Integrator



9.3 Future Focus of Internal Resources: Product Data Management

The above example suggests that the future source of competitive advantage for corporations will not be in developing state-of-the-art tools for specific parts of the process, but rather, in the most efficient integration of the best tools available. In an environment where all competitors are able to purchase commercially available software tools which rival those which can be produced internally, the company which can best incorporate the tools in a cohesive design system will succeed. Therefore, companies should focus their internal resources on developing integration strategies which are customized to their own product development processes, yet are flexible to the use of a variety of tools.

The enabling technology which can provide this integration, and subsequently will allow comprehensive prototypes to exist, is Product Data Management (PDM). It is not surprising then, that PDM software now represents the most rapidly growing area of design-related applications. In 1994, this sector experienced a growth rate of 30% and now includes solutions from a number of sources including: Sherpa, Metaphase, Centra2000 and an ever growing number of applications from CAD software vendors and hardware vendors.

Although many commercial solutions are available, the true advantage in this area lies in the customization of these packages to the company's particular design process. Whereas this integration and customization used to occur in the geometric modeling portion of the process, this customization now must occur in the product data management system. As analytical prototypes become more comprehensive, increasingly complex data management schemes will be required. The company which can best utilize these tools to create a logical data management architecture and supporting design processes will be able to deliver higher quality, better integrated products to market faster than their competition.

10.0 Summary of Findings

Based on the information contained within this thesis, it is apparent that there has been great progress toward the use of increasingly complex and more comprehensive analytical prototypes in the design process. This has been most clearly shown by the great strides made by Boeing during the development of the 777 aircraft. Due to the publicity of the 777 success and the increased availability of the necessary computer aided tools, many other companies such as Ford are also attempting to make use of comprehensive analytical prototypes in their design processes. This paper has documented the evolution of analytical prototypes, the lessons to be learned from the Boeing implementation of a comprehensive analytical prototype, and future opportunities for analytical prototypes. The following sections summarize:

- Key considerations in implementing a comprehensive analytical prototype
- Future evolution of comprehensive, analytical prototypes
- Importance of data management in comprehensive prototypes

Implementation Considerations

As Boeing individuals involved in the 777 program recall, "The changes involved on the 777 were 80% cultural". Acknowledging this, there are four principal areas which will be important for Ford to consider as it implements its own system:

- **Early and frequent sharing of information**

  One of the primary successes of the Boeing DPA process was that it provided a mechanism with which to share designs among the members of the development team. This ability is useless, however, if the culture of the organization does not support the early and frequent sharing of information. Although the culture is changing at Ford towards more collaborative vehicle development teams, there is still hesitation to share designs between the engineering subfunctions which existed in the previous organization structure. If the benefits of a comprehensive prototype are to be realized, these organizational artifacts and residual behaviors must be eliminated.

- **Management commitment**

  Another strength of the Boeing implementation was the strong commitment of the program management to the new process. Due to the fact that the 777 team was a semi-autonomous organization, program management was also given the role as 'champions' for their own new process development. If such a system is implemented throughout Ford, the process will likely be developed by a central organization and 'applied to' new programs. As a result, program managers will have the role of 'customers' of the new system, rather than the 'champions' leading the organizational and cultural changes which are required. To ensure that these changes occur, program managers should make an extra effort to understand the new processes and contribute some of their organizational power to support the team responsible for process implementation.

- **Importance of tooling/manufacturing integration**
  One of the key problems experienced during the 777 development was the inadequate involvement of tooling in the DPA process. Since that time Boeing has recognized this weakness and is now investigating ways to extend the process to more readily integrate manufacturing related information. Due to the high-volume production of automobiles, the role of manufacturing input should be even more important at Ford. Judging from the pilot project being used to develop a 'Ford DPA process', however, the systems being developed are very heavily oriented towards engineering and analysis. Since producibility is a critical element of vehicle design, it is essential that product *and process* integration be the focus of any new procedures that are developed.

- **Communication and Feedback of Process**
  Since it is unreasonable to assume that all procedures can be determined at the outset of an implementation of this magnitude, some process development and refinement will undoubtedly occur as the new system is first used on a development program. Therefore, an essential element will be to incorporate a communication and feedback linkage that can be used to institutionalize the new processes and suggest changes. A

successful method used on the 777 was to have DPA administrators co-located with the design team. These individuals' responsibility was shared between helping to create procedures and actually using the procedures within a particular design team. Currently at Ford, the addition of such individuals is considered unnecessary overhead on the process. In the long term this may be true, but in the initial implementation phase, these individuals can be instrumental in ensuring that new procedures are adopted quickly and are appropriate to the needs of all design groups.

Future Evolution of Analytical Prototypes

Given that Ford is successful in implementing a system similar to that used on the 777, they will have succeeded in integrating the engineering functions involved in the design. As recent developments at Boeing indicate and Ford data supports, there is an additional opportunity in the integration of manufacturing into the design system as well. In order to incorporate production process information however, future generations of analytical prototypes will have to include an added dimension of time. The components of these '4-dimensional' systems are as follows:

- **Assembly Sequence modeling**

  Assembly sequence modeling will provide the ability to capture the most basic element of the manufacturing process: the ordering of components and tools in the production process. At the most elementary level, this consists of simply recording the 'order of appearance', but in more advanced systems, this may also include the assembly 'path' as well. By recording this information, design teams can share a common understanding of the intended assembly process, adapt their designs to this, and detect any assembly-related interferences prior to production.

- **Feature-based Assembly**

  The use of feature-based assembly will build upon the assembly sequence information by recording the mating relationships between adjacent parts. This information can be used to locate components within the analytical prototype, but more importantly, will provide a necessary element towards determining the assembly variance within the analytical prototype.

- **Variation Modeling**

  Variation modeling will move analytical prototypes from the realm of purely nominal dimensions to more appropriately reflect the variability encountered in the 'real world'. Combined with the assembly sequence and mating relationships, the addition of statistical distributions for product and tooling dimensions will enable the automated calculation of assembly variances. This can be used to target and correct design features which significantly contribute to overall product variances affecting quality.

- **Variation Optimization**

  Variation optimization will allow the benefits of understanding variance to be applied to cost effective tolerancing decisions. By combining the cost of reducing variation in individual features with the contribution of those features to overall variance, it is possible to determine the least expensive allocation of overall assembly tolerances. This information can be used to drive the assignment of tolerances as well as process improvement efforts in manufacturing.

Importance of Data Management

Perhaps the most important element in the evolution of comprehensive prototypes has, and will continue to be effective product data management. This was evidenced on the 777 development where the DPA process was used to integrate product data from various engineering groups to produce a digital mockup of the current design. As analytical prototypes become more complex, they will not only integrate engineering functions, but manufacturing functions as well. As a result, increasingly complex data management schemes will be necessary to ensure that the most current product and process data is made easily accessible to all members of the design team. Due to the integral relationship between product information flow and the design process itself, product data management represents a significant source of competitive advantage. Ensuring the efficient transfer of current design information can result in significant reductions in design cycle time, quality and cost due to the elimination of non-value added time in the development process and costly late-stage design changes.

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