USE OF THE DESIGN STRUCTURE MATRIX IN THE IMPROVEMENT OF AN AUTOMOBILE DEVELOPMENT PROCESS

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Abstract

Improving the efficiency of a process has gained considerable attention, especially in the automobile industry. While efficiency improvement may be approached from either a task orientation in which the individual tasks are made more efficient, or from a systems orientation in which the interrelationships between tasks are improved, most analysis tools and their solutions are task oriented. The Design Structure Matrix, in contrast, takes a systems orientation, allowing the entire system to be considered. It shows, in compact notation, the interrelationships between tasks. Marks placed in specific places in the matrix show, for each task, from which tasks inputs are received and which tasks information is supplied to. In addition, feedback loops which play a significant role in most processes, are clearly identified through the use of the matrix. Controlling the communication between the tasks in a feedback loop is vital to the timely and accurate execution of the process.

This analytical tool was applied to the automobile development process, with concentrated emphasis on the first half of the process. From this analysis several major feedback loops were identified; two major loops constituted the first half of the process. Based upon the matrix and knowledge of the development process, several options for improvement were formulated. The changes to the system vary from the most radical option of changing process milestones to simpler changes to individual tasks. In addition, the tool itself was introduced to the sponsoring company for its application to subprocesses.

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CHAPTER I
INTRODUCTION

The difficulty U.S.-based automakers have had in the past decade highlights the extent of the changes that have taken place in the global vehicle market. The pace of this market has quickened for the competitors, requiring them to be more aware of consumer wants and needs, to deliver a new vehicles to the marketplace with lower price tags and higher quality and reliability, to ensure that their vehicles are passenger- and environment-friendly, and to accomplish this feat of designing and building the new vehicle in a shorter time. Not surprisingly, the complexities of vehicle design turn the development process into a formidable task. In addition to the thousands of parts to be tracked throughout vehicle development, the tens of thousands of people working on the several vehicles in development at a time, each at a different stage, must be coordinated. The challenge of channelling the efforts of these people into several vehicles in a minimum amount of time and cost is far from simple. Furthermore, as much as 80 percent of the cost of developing a new vehicle is committed during the first 20 percent of that vehicle's development time. The efficiency of an automaker's development process, consequently, has become one of the stronger competitive advantages in this transformed market as demonstrated by such Japanese automakers as Toyota and Honda.

In an effort to improve the efficacy of its design process while making better use of its resources, one automaker is making great strides in the unification of its engineering and manufacturing staffs. Nonetheless, this company continues to seek new opportunities for improvement. The development of new ideas to improve the efficiency of the current process is critical.

The work described here presents an approach to this fundamental problem. The problem may be thought of as reducing development time (the so-called “time-to-market”) to increase responsiveness to the market. Consequently, it can be considered in terms of either the tasks accomplished in the process or the interrelationships between those tasks. Most process analysis tools considered for this project focussed on the tasks in a process; they showed the tasks along the “critical path”, the time during which the execution of tasks overlap, and the bottleneck tasks among other things. Since these tools were widely used, the process was already well known and documented from a task orientation. Therefore, the interrelationships between tasks--the *design structure* of the development process--was examined since the coordination of efforts from several different segments of the organization also contribute heavily to the development of a superior vehicle.

1.1 Context

This work was undertaken in the context of the Leaders for Manufacturing (LFM) Program. The LFM Program is a joint effort between the Massachusetts Institute of Technology (MIT) and 11 manufacturing firms , and represents a partnership between academia and industry. The purpose of the internship is to apply the understanding of fundamental principles to contemporary business situations.

1.2 Literature Survey

The literature consulted for this effort can be classified into two categories:

1. Information on the automobile industry, the development process, and analysis tools

2. Information on organizational behavior

By researching these two fields, a broader scope of the design-structure problem *and* a better idea of the implementation issues of a solution were achieved.

1.2.1 The Industry and Analysis Tools

The analysis and examples of vehicle development processes and a study of process analysis tools served as the foundations for this work.

Clark, Chew, and Fujimoto's work [7] served as an excellent basis for an understanding of the global industry and presents a framework in which they characterize the various components of "efficiency". Among the components they cite are the time to market, the number of common parts among vehicles, the amount of involvement downstream activities have in upstream tasks, and the number and timing of engineering design changes. Of these four components, only the time to market and the participation of various departments could be modelled in the scope of this project.

In his work, Shaffer [12] describes the development process at one automaker with greater attention to the later tasks than the earlier ones. His paper was instrumental to the piecing together of the information flow.

In the University of Michigan paper [11], a framework for classifying design processes into sequential development, simultaneous engineering, and simultaneous development was presented. Sequential development, according to the paper, is the classic "throw it over the wall" batch process in which huge amounts of data are transferred from one functional organization to the next. Each organization processes the data separately and sequentially. In simultaneous engineering, one "wall" is torn down: the engineering functions of the design and manufacture for the vehicle are combined. A simultaneous development process is one in which all the "walls" are torn down. Marketing, finance, design, manufacturing, and engineering all develop the vehicle together. The paper stresses that while simultaneous engineering significantly reduces costs compared to sequential development, even greater savings and better designs may be manufactured using a simultaneous development process.

Nunokawa [10] describes the vehicle development processes at Honda in great detail and contrasts it with product development at Toyota. While the two companies use a team approach, they differ in organizational structure and operation. Nevertheless, both processes may be classified as simultaneous development.

In his book, Steward does not examine a particular process but rather describes as method in which *any* process may be analyzed. Steward suggests a compact notation equivalent to a flow chart. The notation, called a "Design Structure Matrix", can be used not only in critical path analysis but also in systematically reordering the tasks in a process, unlike flow charts.

Eppinger, Whitney, Smith, and Gebala's paper [8], and Eppinger's and Whitney's comments [15] develop Steward's idea of the Design Structure Matrix further. The suggestions made in the paper are aimed at presenting data in greater detail. In one of their variations on the Design Structure Matrix, for example, numerical values to classify the amount of interdependence between two tasks replaces the "marks" in Steward's version. Eppinger [15] also suggests using the dimensions of the matrix to convey timing data while Whitney [15] suggests combining the Gantt chart with the Design Structure Matrix.

Finally, Black's thesis [4] applies the Design Structure Matrix to the development of an automotive brake design. Both the thesis and the paper by Black, Fine, and Sachs [14] describe the design of a brake system and the various considerations and interdependencies involved in the decision-making.

1.2.2 Organizational Change and Behavior

The literature consulted for organizational behavior towards change helped in formulating the implementation described in Chapter V.

Allaire and Firsirotu [1] presented a framework for organizations to use when considering changes to their structure. The framework is used to describe several scenarios in which the firm's current state is compared with its intended future state and how this change affects the organization's relationship to the "outside world".

Block's paper [5] centered around selling ideas in an organization. It consisted of checklists and advice geared primarily toward consultants, to help the idea-seller win supporters. The considerations Block presents helped to highlight areas in which any suggested change and implementation plan may be resisted.

Lawrence [9] attempts to explain how change is viewed by various people in an organization and why change is resisted through an example he presents. Lawrence considers both the technical and social aspects of change. The example emphasizes the importance of developing a team spirit while attempting change and of communicating the need to change.

Bryant's work [6] primarily lists different aspects of change in an organization. He addresses factors that influence attitudes toward change and procedures to effect change, among other things.

Ancona and Caldwell's paper [2] describe what they see as the four main functions in a team. The functions of ambassador, task coordinator, scout, and guard are explained. Their work suggests that well-performing teams have people who fulfill these functions either officially or unofficially. In her other work, Ancona [3] elaborates further on the relationship between the team and the remainder of the organization. She cites a study which showed that processes external to the team and the composition of the team also had a profound effect on team performance.

1.3 Organization of this Paper

In this thesis, the efficiency improvement of a vehicle development process is examined. Instead of using analysis tools that focus on the individual tasks, a Design Structure Matrix was developed and used tot look at the tasks in a different way.

In Chapter II, the analytical tools that are available are described with special focus on the Design Structure Matrix and its implications. In Chapter III, the process framework is described and modelled using the tools in the previous chapter. The analysis of the models and the implications highlighted by them, in addition to options for improvement, are explained in Chapter IV. Chapter V discusses the implementation of the option, while a critique of the Design Structure Matrix itself and the conclusions of this thesis is provided in Chapter VI.

CHAPTER II

TECHNIQUES for MODELLING DESIGN STRUCTURE

Of the several techniques available to represent the design structure of a process, three are useful in the analysis: Flow Charts, Gantt charts, and Design Structure Matrices.

2.1 Flow Charts

In general, flow charts highlight the path(s) of a job through a process. Steps, or milestones, can be represented by a shape (circle, square, etc.) or by an arc between two shapes. In this thesis, the information flow through the vehicle development process was modelled. The steps in the process are boxed and arrows show the direction of the information flow in the flow chart shown in figure 2-1.1.

Because of their clarity, flow charts conveyed the sequence of steps well. They were especially useful in the data collection stage (see section 3.1 for further explanation of data collection and classification), since many people could interpret them easily. In addition, the representation of well known information loops was trivial. More subtle feedback loops, however, could not be represented easily. For example, if a particular task only rarely affected an up-stream task, the arc was omitted from the flow chart (see section 3.1). The feedback, nevertheless, existed. Consequently, information could be lost by using flow charts exclusively. Data collection and classification is treated in greater detail in section 3.1.

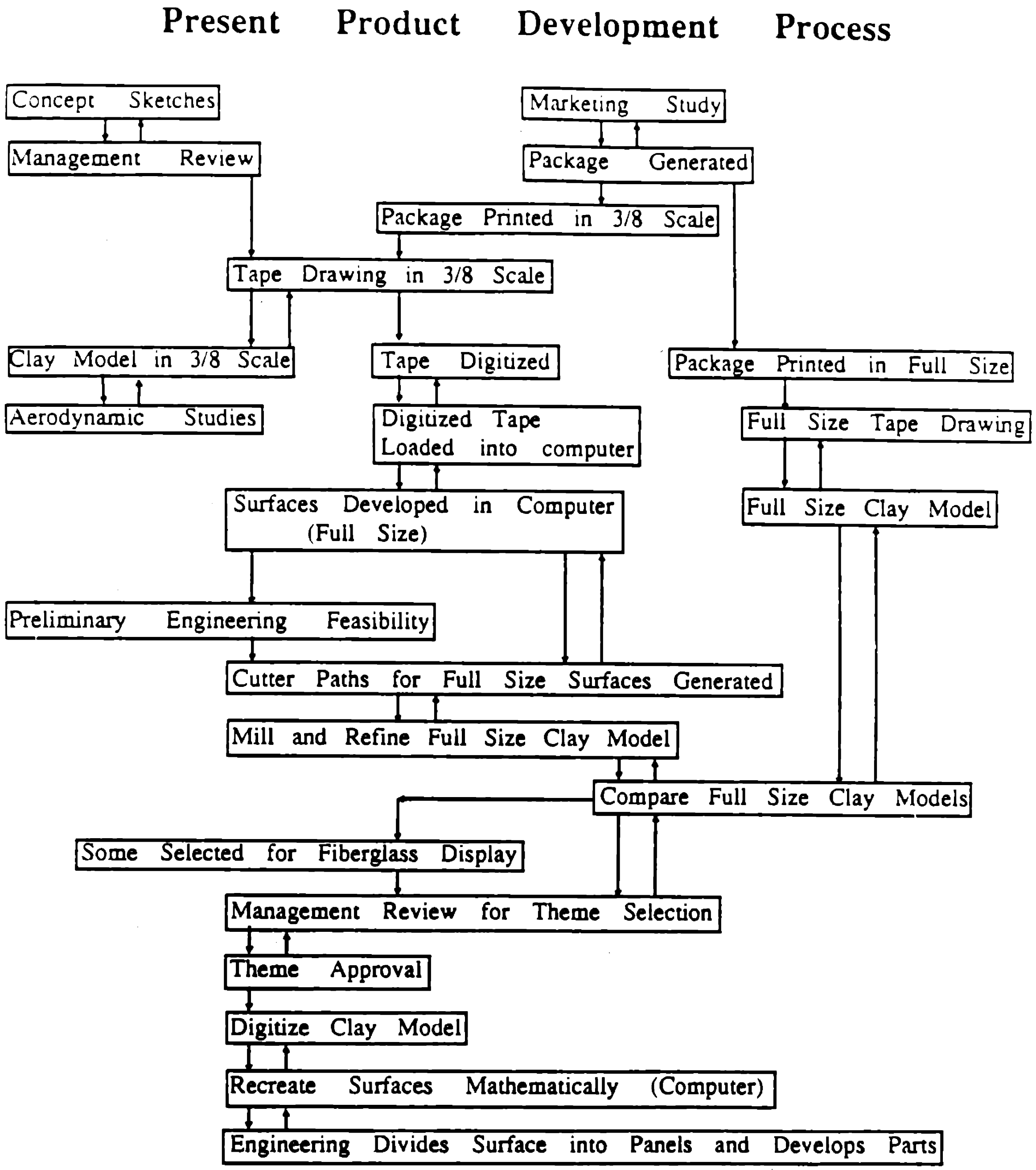


Figure 2-1.1 Flow Chart of Present Product Development Process

2.2 Gantt Charts

Gantt charts are used to depict the relative start and finish times for each process step. This not only shows the amount of time each step occupies but also easily identifies the steps that overlap. For example, in the Gantt chart in figure 2-2.1, steps 5 and 6 overlap between weeks 159 and 148, since both of their time blocks cover those weeks. While they show the amount of time necessary for the completion of a task, or a process, they do not represent information flows well. Simply looking at a Gantt chart as in figure 2-2.1 will not reveal the informational needs of a particular task. Thus, if Task 11 in figure 2-2.1 required information from Tasks 4 and 6, the Gantt chart does not explicitly show this dependence. To show feedback and dependence, arrows may be used as in a flow chart, although these may create more confusion.

2.3 Design Structure Matrices

Design Structure Matrices represent the inputs needed for and outputs supplied by each process step. By illustrating where and when in the process the information for each step comes and goes, they help to uncover feedback loops, or sometimes, the lack of them. In addition, they may suggest alternate ways to order the steps in a process and can provide insight into the actual working of the process.

2.3.1 Matrix Construction

The construction of the matrix begins with the identification of each discrete task in a process flow and the listing of these tasks on both the horizontal and vertical axes. The next step involves coupling the tasks with each other according to informational needs. This coupling is accomplished by marking the columns of the tasks which contribute

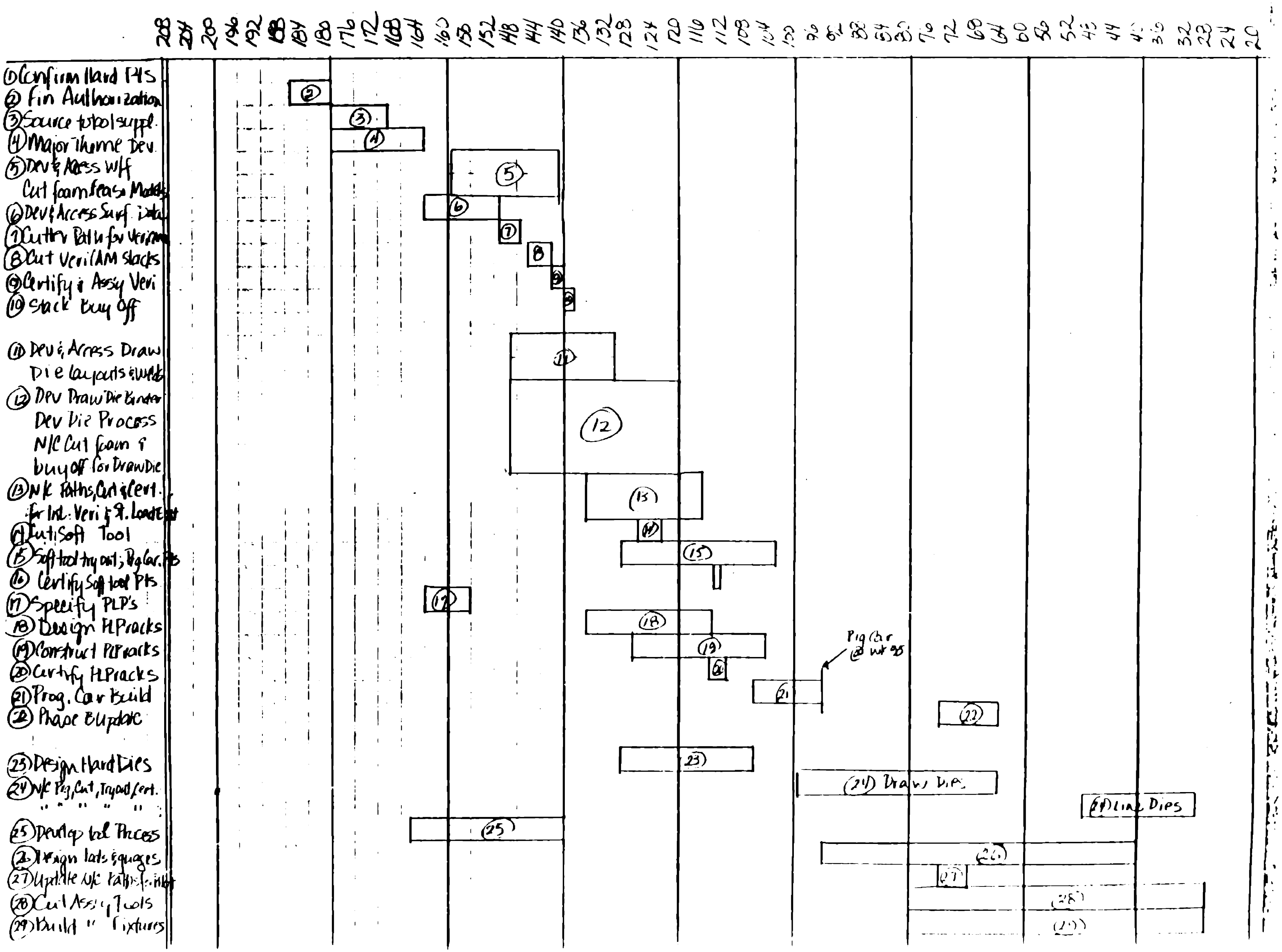


Figure 2-2.1 Gantt Chart of Vehicle Development Process Flow
Source: Shaffer [12]

information for the completion of the step in question. The figure below contains an illustration of Steward's original binary marking system. By considering only the rows, this matrix shows that Task 1 depends upon information from Task 3 for proper completion, Task 1 supplies information to Task 2, Task 3 requires information from Tasks 1 and 2, and Task 4 needs information from Tasks 1 and 3.

	Task 1	Task 2	Task 3	Task 4
Task 1	•		X	
Task 2	X	•		
Task 3	X	X	•	
Task 4	X		X	•

Figure 2-3.1 Binary Marking System

At the same time, the columns of the matrix indicate output destinations: Task 1's output is used by each of the other three Tasks, Task 2 gives its output to Task 3, Task 3's output is required by Tasks 1 and 4, and Task 4 does not feed any information to the other tasks.

2.3.2 An Example

Perhaps the best way to explain the myriad intricacies of a Design Structure matrix is through an example:

2.3.2.1 Basics

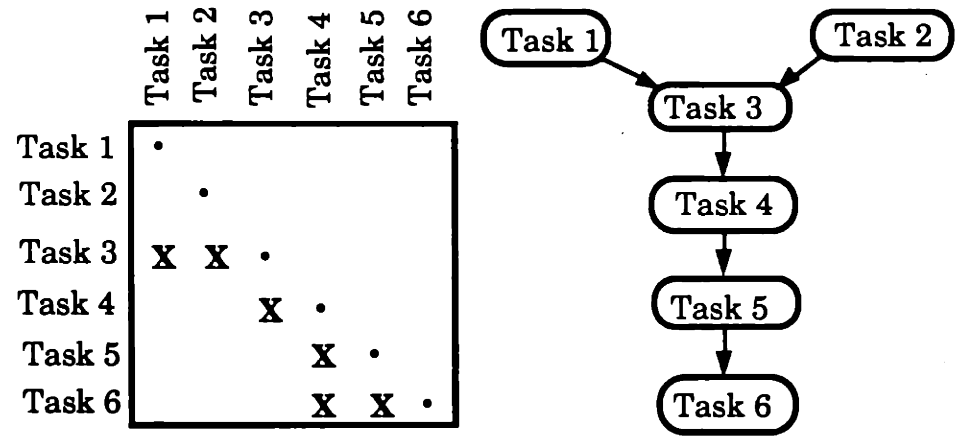
Consider the making of a subassembly at a job shop. The table below lists the steps involved:

Table 2-1

Tasks:

1. Procure and set up welding equipment and racks
2. Procure stamped parts
3. Load parts into racks
4. Weld parts together to form subassembly
5. Unload subassembly and place on pallet
6. Move subassembly pallets to assembly area

With the steps placed in this order, the precedence relationships depicted below show that Tasks 1 and 2 must be completed before Task 3 can begin. Task 3 must be completed before Task 4 can begin. The output from Task 4 is required for both Tasks 5 and 6, but Task 6 cannot begin without the result of Task 5.



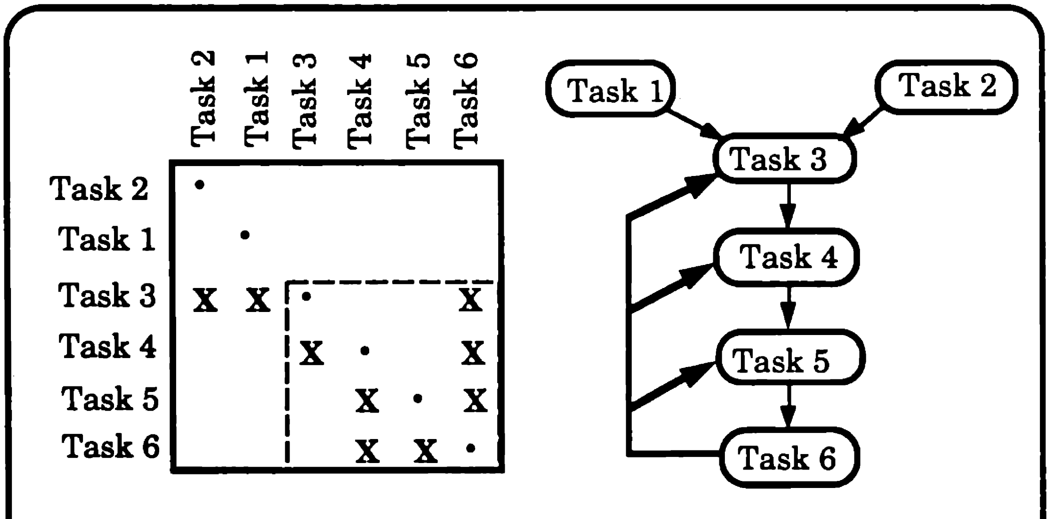
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
Task 1	•					
Task 2		•				
Task 3	X	X	•			
Task 4			X	•		
Task 5				X	•	
Task 6				X	X	•

Figure 2-3.2 Precedence Relationships for Subassembly Example

2.3.2.2 Feedback

The Design Structure Matrix displays feedback information more clearly and compactly than a flow chart. Rather than using arrows for information flow, the matrix notation makes use of precisely-placed marks to convey the same data. Furthermore, displaying even the slightest dependence of one task on another can be easily accomplished without creating a confusing model. Thus, every feedback loop, whether officially part of the process or implicitly guiding information flow, is displayed.

The process above contains "feedback loops". Yet Table 2-1 and figure 2-3.2 above are probably what the process is identified as. An observer will be informed that if the subassembly does not meet the assembly line's (customer's) needs, the subassembly-maker at the job shop will be notified. In the event that the subassembly is not up to standards, the subassembly-maker can alter the way in which other steps are performed for the next subassembly, such as loading the parts into the racks using different reference points (Task 3), welding the parts in a different order to avoid certain shape deformations (Task 4), or loading the subassemblies onto pallets in a different orientation (Task 5). Implicit feedback loops are drawn in figure 2-3.3 below, as X's above the dots on the diagonal of the matrix.



	Task 2	Task 1	Task 3	Task 4	Task 5	Task 6
Task 2	•					
Task 1		•				
Task 3	X	X	•			X
Task 4			X	•		X
Task 5				X	•	X
Task 6				X	X	•

Figure 2-3.3 Design Structure Matrix with Feedback

Another kind of implicit feedback occurs between successive runs through a process. For example, an experienced subassembly-maker knows exactly which equipment and rack designs will be most useful and how best to assemble the subassembly. An inexperienced subassembly-maker, however, may not necessarily know that a pin placed in a certain location of a part is best for orienting that part, for example, and may try to orient the part on the racks without pins, for example; or the subassembly-maker might try to weld all the large parts first before deciding that welding some of the smaller pieces with the larger ones and then placing the welded parts together is a better method. Commonly, these iterations are referred to as "learning curve" effects. In this analysis, they and iterations like them, are considered to be feedback loops.

Knowledge of the feedback, both implicit and explicit, in a process permits the task sequence to be examined. Eppinger, Whitney, Smith, and Gebala [8] identify three possible design sequences for two process tasks: dependent or series tasks in which one task receives input from the other; independent or parallel tasks in which both tasks receive the same input and operate on it simultaneously and independently of each other; and interdependent tasks in which both tasks receive the same input and operate on it but also receive input from and supply to each other. These three types are illustrated in a flow chart below:

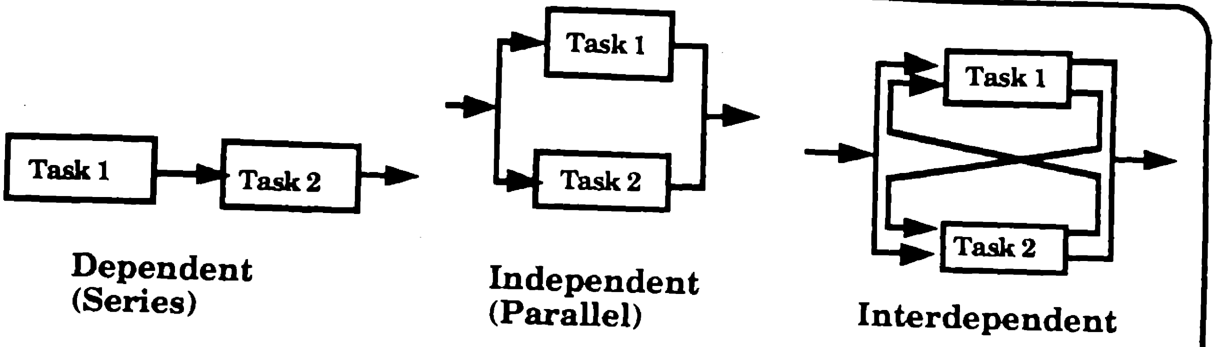
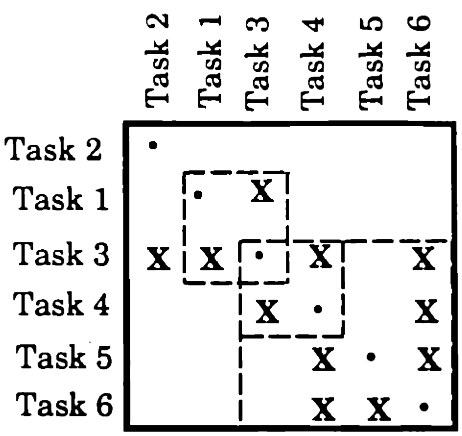


Figure 2.3.4 Task Sequencing
From: Eppinger, Whitney, Smith, and Gebala [8]

Returning to the example, in figure 2.3-3 above, marks in the upper triangle of the matrix--the part of the matrix above the diagonal dots--identify feedback to individual steps. In these cases, to reiterate, an earlier task needs input supplied by a later task. For example, the feedback that Task 4 (welding parts together) supplies to Task 3 (loading parts into racks) is indicated by a mark the 4th column of row 3. Hence, the marks in each column represent the tasks that depend upon output from that column's task; Tasks 3, 4, and 5 depend upon output from Task 6, as indicated by the X's in column 6 in those rows.

Notice also that the ordering of the tasks has been changed; Task 2 precedes Task 1. Since Task 3 requires input from both of these tasks and since they are independent of each other (see figure 2.3-4), switching the order of these two tasks has no impact on the final outcome of the process. In his book, Steward [13] discusses tearing and partitioning of Design Structure Matrices to achieve a lower diagonal matrix--that is, to reorder the tasks so that all the marks fall below the dots in each column.



	Task 2	Task 1	Task 3	Task 4	Task 5	Task 6
Task 2	•					
Task 1		•	X			
Task 3	X	X	•	X		X
Task 4			X	•		X
Task 5				X	•	X
Task 6				X	X	•

Figure 2-3.5 Design Structure Matrix

When several tasks are interdependent, they comprise a "block" of tasks in a feedback loop. The dashed-line blocks drawn on the Design Structure matrix in figure 2-3.5 show the steps involved in each of the three feedback loops. The timely execution of the process depends upon the quick and accurate relay of information between the tasks in these blocks, suggesting that the subassembly-maker and the assembly line must communicate. Should the assembly line fail to tell the subassembly-maker that the subassemblies are below expectations, the assembly line will be faced with the choice of suffering with the poor quality subassemblies or shutting the line down. Similarly, if the assembly line requests subassemblies that are structurally unsound, the subassembly-maker at the job shop must either convince the assemblers that such constructions are impossible or face a dissatisfied customer. In both cases, the assembly line--the customer in this example--ultimately loses when information between the tasks in the feedback loops is not conveyed.

In the discussion of this example so far, it has been assumed that only one person makes the subassembly. In most complex processes, however, several people are responsible for a portion of the whole process. Communication between these people critically impacts process improvement. In the example, suppose that the person who welds the subassembly is not the same as the person who purchases the tooling and equipment. Communication between these two involves each one relating to the other the problems in the tasks: the welder may find working with particular equipment models to be far easier and thus may want the purchaser to obtain these models, while the purchaser may experience extreme difficulty in finding this equipment. If the welder merely asks the purchaser to obtain the model, the response may be that it is too expensive. On the other hand, if the welder relates what attributes this model has that markedly improve the efficiency of his task, then the purchaser, who may be able to obtain a different model with the same attributes just as easily can help the assembler without jeopardizing his own performance. The communication necessary is not simply a statement of wants but rather a description of *constraints*.

Finally, a superior design structure matrix requires the inclusion of *every* task. Consequently, this example does not superlatively represent the process because it omits the task in which equipment is maintained. Again, the single subassembly-maker lists the tasks in this process, quite likely this step will be forgotten. In a complex process with several people, however, the omission of this task could cost opportunities for process improvement. For instance, if using an arc welder at a certain power level welds the subassembly quickly while damaging the sparking element, the equipment maintenance crew might suggest an alternate power level at which the life of the are welder is prolonged while acceptable welds are provided in an acceptable time frame. Thus, the entire process is improved for while the subassembler has maintained his efficiency, the equipment maintenance crew has improved theirs.

The Design Structure Matrix may be applied to any process: it would have been equally applicable to a far simpler process such as sandwich-making, using the same concepts. An important realization, however, is that identifying the process requires the knowledge of the people in the process as well as the understanding and insight of the observers/modelers.

CHAPTER III
MODELLING the PROCESS

The framework presented below describes one automaker's current vehicle design process which has evolved over decades. In modelling this process, we aim to identify opportunities for improvement. The following description of the vehicle development process is admittedly rather focussed on the upstream tasks. This is, however, the area focussed on. Knowledge and understanding of the downstream tasks is important to comprehension of the true mission of the earlier tasks. Consequently, the entire process will be presented, with greater focus on early tasks and enough background on the later steps for adequate understanding.

3.1 Data Classification

The process flow was unearthed by interviewing several people in the design, engineering and manufacturing areas of the company. Due to the scope of the project, only manufacturing staff, and not plant personnel were interviewed at length. Data was gathered from these interviews in two ways. First, a process flow chart was developed. This flow chart was shown to all the interviewees during the interview and was later circulated to re-check for accuracy. Any incorrect information was discussed and corrected in a follow-up interview before issuing the next revision. Second, notes were taken during the interviews. These notes recorded timing data when it was estimated, informational needs, and information flows in the event of a design failure or approval denial. The data from these notes served as the basis for the Design Structure Matrix.

In the process of gathering information, confusion over the "currently followed", the "should-be followed", and the "will-be followed" processes developed. To separate these different ideas, the will-be followed process was labelled the "future process" while the currently followed process was considered to be the "present process". The should-be followed process was the ideal version of the present process. The currently followed process was modelled in the Design Structure Matrix and its related network; the flow chart circulated to the company people modelled the should-be process.

A variation of Steward's [3] binary marking system was used for the Design Structure Matrices. Eppinger, Whitney, Smith, and Gebala [8] discuss possible variations to assign classifications to the interdependencies between tasks. The dependency classification system we developed categorizes the dependencies into 4 groups: self, primary, secondary, and tertiary. A self dependency (•) simply indicates the diagonal of the matrix. A process step that has primary dependence (**1**) upon another cannot begin until information from that step arrives. A secondary dependency (**2**) signifies that the process step may begin without the information from the other step, but its completion nevertheless hinges upon data provided from that step. Tertiary (**3**) dependence means that the information provided to the step in question serves as helpful, but not crucial, information. By categorizing the value of the information in this way, the truly important feedbacks could be discerned from the less important loops.

While Gantt charts helped to understand the subtleties of the process, finding the information for them, if it existed at all, was more difficult.

Although the people performing the task could give a rough estimate of the time their tasks took, no log charting the actual use of time was available. Several interviewees suggested using the corporate Master Timing Schedule, which gave the deadlines for the milestones of the project, in place of logs. Other than the interviews, the only other source of timing information was Shaffer's work [12] which provided little data on the earlier process tasks.

3.2 Framework: the Process Flow

The term "vehicle program" refers to the development of a series of vehicles using the same platform, or understructure. While the process flow for each program differs slightly to incorporate improvements, a generic process flow can be thought of as having four major milestones: concept development, theme development, part development, and tooling development. (See figure 3-2.1 below).

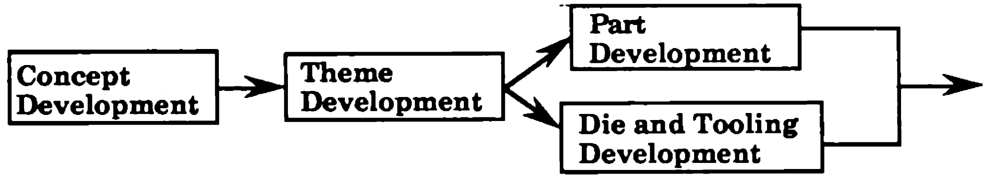


Figure 3-2.1 Milestones in the Process Flow

The relationships between these milestones can be illustrated as shown in figure 3-2.2 below. Note the additional subprocess, Task 2a, which represents the "Computerize Surfaces" step (to be explained later). This task is deleted in the future process but is being performed in the present one, idealized or otherwise.

		1	2	2a	3	4
Concept Development	1	•				
Theme Development	2	X	•			
Computerize Surfaces	2a		X	•		
Part Development	3			X	•	X
Die and Tooling Development	4			X	X	•

Figure 3-2.2 Design Structure Matrix Representing Major Milestones

3.2.1 Concept Development

Beginning with a marketing study and ending with concept approval, the concept development stage takes approximately one year. The goal of this first activity is to determine the strategy for the program, which includes specification of vehicle and engineering dimensions, market timing, production targets, stamping and assembly plant identification, and possible parts and tooling vendors. A design structure matrix for this part of the process is shown in figure 3-2.3 and explained below.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Marketing Study	1	•														1
Package Study & Generation	2	1	•			1								2	1	1
Concept Sketches	3	2	1	•	1	2										1
Mgmt Review of Designs	4	2	2	1	•			2					2			
Package Selection	5		1	2	1	•		2					2	1	1	1
Scale Tape Dwg Generation	6			1		1	•									
Scale Model	7			1	2	2	1	•	2							
Aerodynamic Tests	8							1	•				2			
Scale Tape Digitized	9						1			•						
Computer Design Developmt	10			2				2	2	1	•		1	2		
Cutter Paths Generated	11										1	•				
Full Size Clay Models Milled	12											1	•	2		1
Engr Preliminary Eval	13							2			1		2	•	2	1
Package Approval	14		2			1							1	1	•	1
Concept Approval	15	1	2	1		1							1	1	1	•

Figure 3-2.3 Design Structure Matrix for Concept Development

The marketing study provides information on demographics, brand names, and other marketing parameters. These data are then used to develop the product concept--a product plan and profile which include strengths and weaknesses of the new vehicle and serve as an aid in the development of approximately 20 "packages". A package specifies vehicle parameters, such as wheelbase length; location of the driver's heel, hips, and head; and height and width of the vehicle. The marketing study also provides useful information on styling issues which the design studios use to begin work on preliminary "concept sketches" (Task 3) that will later be more fully developed and mated to a package. This is represented by a "2" in row 3 column 1 of figure 3-2.2 above.

The process of choosing five or six packages (Task 5) from the 20 or so involves two parts: an engineering feasibility check and a three dimensional "spatial" check. In the process, some of the packages are developed into full size, three dimensional clay models from the tape drawings, to convey the size and shape of the package better.

Tape drawings (Task 6) are used to help designers translate their two dimensional sketches into three dimensional clay models. Once these package parameters are known, a scaled drawing of the critical dimensions is printed on mylar. Designers, or "stylists", then use black tape to transfer their concepts from the sketches to the package drawing. The "tape drawing" serves as a basis for engineering and model development. Drawings of side and front views of the package with a general outline of the vehicle help in the preliminary evaluation of a concept. The figure below is a schematic diagram of a side view tape drawing.

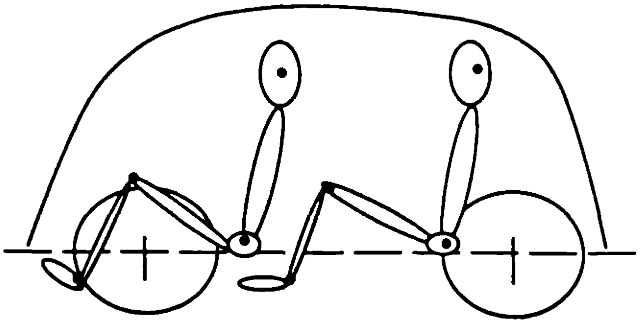


Figure 3-2.4 Schematic of a Tape Drawing showing head, heel, and hip points over a sketched shape of the vehicle

While clay models may be cut either by hand or by numerically controlled (NC) machine, all models developed for package assessment are full size and NC machined since spatial dimension visualization is critical, since only a rough idea of the shape is needed and since time constraints preclude elaborate manual fashioning. Clay is the preferred material for conveying these spatial concepts since it can be either milled or designed manually and yet holds its shape. To NC machine the model, several points on tape drawings of several views are "digitized", or assigned spatial coordinates. The computer then uses these points to construct a surface for which cutter paths (Task 11) for a full size three dimensional clay model can be generated and used to machine (Task 12). Since the software can enlarge three dimensional shapes, only the scale tape drawing is necessary, saving digitizing time. In addition, the surfaces can find uses in other tests such as aerodynamic and structural analyses.

At the same time that these full-scale rough models are made, designers and modelers fashion three-eights scale models (Task 7) from three-eights scale package and tape drawings. The smaller models' surfaces are smoothed since they are used for marketing purposes and internal idea-selling, and also to provide valuable experimental data for aerodynamic studies (Task 8).

Engineering evaluation (Task 13) at this time consists of dividing the surface into panels which will later be stamped from sheet metal. While final surface data is necessary to begin part design and the tooling development process, this initial engineering look at the vehicle will ensure that, at least theoretically, the vehicle can be stamped and assembled.

Using the engineering preliminary evaluations (Task 13) and full scale rough clay models (Task 12), each of the five or six packages chosen for further development is checked against the marketing studies' evaluations and the goals for the program. From these five or six semi-final packages the one package that will be completely developed is chosen. The concept is reviewed and ratified before financial support for the program is allocated and the program is officially begun. The package is then sent to the design studios for theme development, and major engineering work and tooling and material sourcing begins.

To simplify the Design Structure Matrix representing this quarter of the process, the Design Structure Matrix including only the more important tasks is shown below (figure 3-2.5):

		1	2	3	5	12	13	14	15
Marketing Study	1	•							1
Package Study & Generation	2	1	•		1		2	1	1
Concept Sketches	3	2	1	•	2				1
Package Selection	5		1	2	•	2	1	1	1
Full Size Clay Models Milled	12					•	2		1
Engr Preliminary Eval	13					2	•	2	1
Package Approval	14		2		1	1	1	•	1
Concept Approval	15	1	2	1	1	1	1	1	•

Figure 3-2.5 Simplified Design Structure Matrix for Concept Development

By regarding only the primary dependencies, this matrix yields the network shown below in figure 3-2.6.

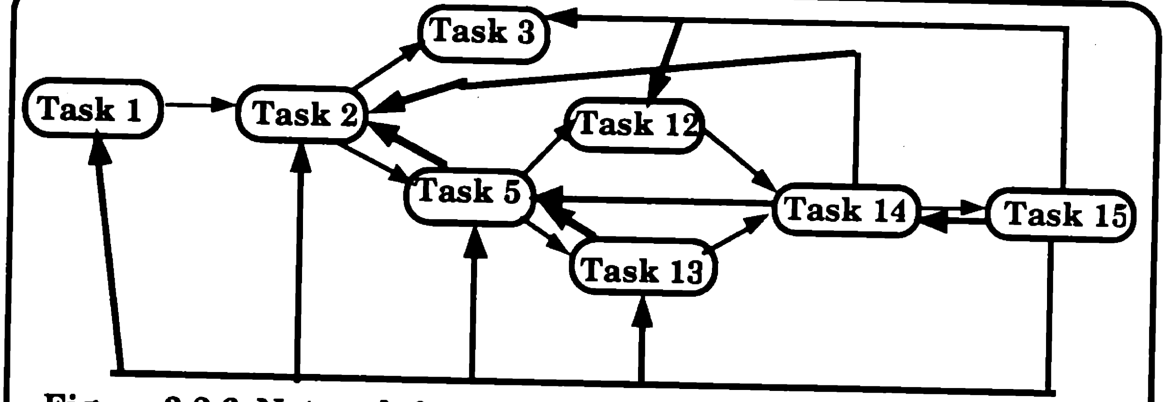


Figure 3-2.6 Network from Simplified Design Structure Matrix

3.2.2 Theme Development

During theme development, which takes over one year, the style of the vehicle is fully developed, finalized and approved by all functions of the company. While concept development took place in the pre-production studios, development of the theme is carried out in the production design studios. The design structure matrix that follows lists the steps described in this section and their interrelationships.

		16	17	18	19	20	21	22	23	24	25	26	27
Concept Sketches	16	•	3	3	2		2						2
Scale Tape Drawings	17	1	•										
Full Size Tape Drawings	18	1	2	•	2								
Full Size Clay Models	19	1		1	•							1	1
Scale Tape Digitized	20		1			•	2		3				
Computer Design Developed	21	1	2			1	•	2	2	2			
Cutter Paths Generated	22						1	•	2				
Full Size Models Milled	23	2						1	•			1	1
Engr Feasibility Evaluation	24				2		1		2	•			
Theme Selection	25				1				1		•	1	1
Models Refined by Hand	26										1	•	1
Theme Approval	27										1	1	•

Figure 3-2.7 Design Structure Matrix for Theme Development

The production design studios begin by developing several more concept sketches, this time more closely correlated with the now-completed package and with more of a marketing slant. Three-eights scale and full-size tape drawings are made for these new sketches. At this point, the clay model may either be completely moulded by hand or may be NC machined for a rough cut. Again, the scale models are surface-smoothed primarily for use in aerodynamic analysis and for marketing purposes, while the full scale models better convey proportion and absolute spatial dimensions. Unlike concept development, modelers will then smooth the final, full size surfaces and fashion the features of the clay vehicle under the direction of the concept designer. The models fashioned at this stage represent the vehicle in far more intricate detail than the previous ones used in the concept development. Important at this early stage, details in the final vehicle impact total engineering time, marketing strategies, and manufacturing processes and schedules.

Smoothing any conflicts about the styling that may later create problems in any of these area is critical to the successful, on-time launch of the vehicle. Thus, designers, design engineers and manufacturing engineers alter this exterior surface until it meets all manufacturing, engineering, safety, and aesthetic requirements. The considerations now consist of ensuring that the fenders will clear the tires; creating functional hinging and flanging that maintain the desired surfaces; choosing the materials and process used to stamp the panels; maintaining even gaps between panels; and how the differences between different models of the same vehicle will affect the assembly process. If the styling is deficient in any area, the designer will change it to alleviate the problem while maintaining its aesthetic beauty. If such a compromise cannot be reached, then the problem must be resolved by choosing either aesthetics or function over the other. The marketing strategy helps to guide this decision by relating the importance of the feature to the overall vehicle. Any changes made to the clay model after its initial milling are done manually.

At the same time that major theme development begins, the tool sourcing committee chooses the vendors to manufacture the tooling--the dies and assembly fixtures. Overall pricing quote, vendor location, program timing, vendor CAD system compatibility and usage, and work quality considerations serve as the basis for the choice of vendors from the approved vendor list. Panel definition at this point, although not yet begun, becomes significant because the chosen vendor must be kept current with any changes in the design. The plant in which to assemble the new vehicle as well as the various plants in which to stamp each panel are also decided at this time.

Upon the completion of several clay models, theme selection begins. Like the package selection, the choices of the final styling are narrowed until one is chosen for production. During this step, design management may suggest changes to or combining the styles to obtain a superior-looking vehicle. When these alterations are made, the final few theme selections are presented to top management for theme approval. Top management selects one of the designs for production. This chosen surface is then known as a "production surface".

A simplified Design Structure Matrix to represent theme development is shown below along with its corresponding primary dependence network:

		16	18	19	21	23	24	25	27
Concept Sketches	16	•	3	2	2				2
Full Size Tape Drawings	18	1	•	2					
Full Size Clay Models	19	1	1	•					1
Computer Design Developed	21	1			•	2	2		
Full Size Models Milled	23	2			1	•			1
Engr Feasibility Evaluation	24			2	1	2	•		
Theme Selection	25			1		1	1	•	1
Theme Approval	27						1	1	•

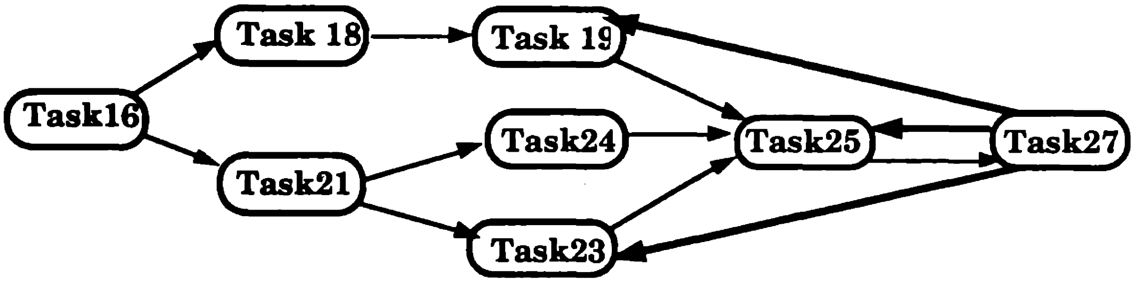


Figure 3-2.8 Simplified Design Structure Matrix and Network for Theme Development

3.2.3 Part Development

In the part development stage, engineers use the model that top management selects to divide the surface into its finalized panels and to design parts that, when assembled, will yield the approved surface. To ensure that the manufactured surface maintains its spatial integrity, the surface is first verified for accurate transfer from the clay and checked for aesthetic value. Once the production surface is verified, the engineering work on the part design begins. In the Design Structure Matrix in figure 3-2.9 below, the block comprised of Tasks 34 through 37 represents surface verification and the block of Tasks 31 through 33 represents part design development. Tasks 28 through 30 in figure 3-2.9 form a block representing "Computerize Surfaces", Task 2a, in figure 3-2.2.

		28	29	30	31	32	33	34	35	36	37
Digitize Model	28	•	2	2							
Generate "Redlines"	29	1	•	2							
Generate Surfaces	30	1	1	•	2						
Engr Part Development	31			1	•	2	2				1
Feasibility Models	32				1	•					1
Structural Analysis	33			2	1		•				
Cutter Paths for Ext Surfs	34			1	2			•	2	1	1
Mill, Stack Foam; Apply Decal	35							1	•	1	1
Evaluate Verification Model	36								1	•	1
Approve Surfaces	37				2		2			1	•

Figure 3-2.9 Design Structure Matrix for Part Development

3.2.3.1 Surface Verification

The clay model identified for production must be translated into CAD software. The translation occurs via "digitizing" or taking points from the three dimensional model to create a three dimensional equivalent surface in the computer. This is the same process as digitizing the tape drawings except for the added third dimension; a probe measures points on the surface of the approved model. These points, mapped into a coordinate system, can then be used to generate "redlines", or character lines. Redlines, from which production surfaces are generated, can be sent to engineering departments, via electronic means, to enable design engineers to begin part development. When completed, the surfaces are also sent from the design studios' digitizing area. In an ideal process, production surfaces cannot be further altered.

Once in the computer system, the surface can be transferred to any part of the company, allowing part and tooling design not only to become easier but also to be performed simultaneously. The master set of surface data points is carefully guarded since it guides these efforts and ensures their compatibility.

At the same time that design engineers begin designing parts, surface verification continues with cutter paths created from production surfaces. The model of each panel is NC machined from foam *separately*, covered with a shiny black sheet-decal, and then stacked with the others to reconstruct the entire surface that was approved in clay. To ensure the foam's smoothness, the NC cutter path spacing is decreased; this prevents large ridges in the machined surface although eliminating the ridges entirely is essentially impossible. This "verification model" verifies the transferred surface's integrity and tests the continuity of the surface across the panel boundaries. Evaluation of the verification model consists of viewing the highlights created by rows of fluorescent lights reflected off the black sheet-decal. Highlight lines that have waves or discontinuities indicate problematic areas in surface.

A design or an engineering problem may motivate alteration of the verification models. The correction makes use of one of two methods. In the first method, the new surfaces developed by manual changes made directly to the verification model are redigitized and recreated on computer. In the second method, the mathematical surface is modified directly in the computer. In both cases, the new surface must have cutter paths developed for it. The verification process then repeats using the corrected surface. Milling, stacking, and decal application take approximately 12 weeks. Usually, a good verification surface takes two millings: the first run with the original production surfaces and then a second to incorporate feedback. Sometimes, however, a good surface requires three or four tries, and consequently takes more time to accomplish.

The approval of the verification model marks the end of the surface definition stage. The process takes approximately one year from concept approval to verification model approval.

3.2.3.2 Part Design[1]

While vehicle parts have been designed simultaneously with surface verification, the approval of the production surface prompts the adjustment of part designs to conform to surface requirements. As parts are altered, their effect on adjoining parts must be calculated and taken into

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[1] See Scott Roodvoets, An Evaluation of the Influence of Platform Team Organization on Product Development Performance, M.S. MIT Thesis, ©1991.

consideration. In addition, part changes must be relayed to tooling sources to allow them to keep up with their development.

Critical to part design, feasibility model development takes place parallel to the development and evaluation of the verification model. Instead of representing the surface, however, feasibility models are intended to model the actual part, which includes hinging, flanging, and access holes. As changes are made to the verification model, corresponding changes are effected on the feasibility model. Should one of these changes be infeasible, styling, design engineering, and manufacturing engineering managers work together to solve the problem or develop a compromise solution. In addition, structural analysis, which tests the engineering soundness and crash worthiness of the design as well as the noise, vibration, and harshness[2] inside the vehicle, also depends upon feasibility models and CAD part designs. Proper structural analysis simulations require the actual design of the part to be used.

The simultaneous approval of the verification and feasibility models implies the verification of the transferred production surface and the completion of part development. Only in an ideal process execution do these events occur simultaneously; time lags must be anticipated due to the milling, stacking, and engineering analyses which must be done. (No data exist with which to determine if surface verification is more likely to be completed first.)

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[2] Harshness refers to the low frequency noise heard when the vehicle travels over gravel or other pitted surfaces. Decreasing the harshness of a vehicle means minimizing this extra noise. Harshness and whistling are due, in large part, to manufacturing access holes.

3.2.4 Tooling Development[3]

Tooling here refers to stamping dies and holding fixtures used in body production. These change more with each new platform than welding or conveyance systems. Consequently, their development is also critical to preparing the vehicle design for high volume production. The Design Structure Matrix in figure 3-2.10 below represents die development as the block of tasks 39 through 43 and tooling development as tasks 49 through 52. The other tasks that are included in this matrix are intended to show the complexity of the process for only the more important tasks are shown in this matrix.

		38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Draw Developmt & Approval	38	•															
Die Process	39	1	•	2			1					1	3				
Die Design	40	1	1	•		2	1										
Hard Die Cutter Paths Dev'd	41			1	•	1	1										
Die Pattern Developed	42			1		•	1										
Parts Released	43			1	1		•					1					
Dies Cast	44					1	1	•	3								
Dies Machined & Constructed	45				1			1	•	1							
Tryout	46								1	•							1
Soft Tool Development	47		1	2							•	1					
Soft Tools Proved	48										1	•					
Build Program Car	49		2	2								1	•		1	1	
Identify Principal Locating Pts	50													•	2	2	
Des, Constr, Certify PLP Racks	51													1	•		
Des&Cut Tools, Guages, Fixt's	52												3	1	2	•	1
Pilot Operations	53									1					1	1	•

Figure 3-2.10 Design Structure Matrix for Tooling Development

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[3] See Franz Drees, Comparative Analysis of Best Practice in the Manufacture of Hard Dies for Automotive Stamping Operations, M.S. MIT thesis, ©1991. and Joseph Presing, Simultaneous Engineering in Car Body Process Design, M.S. MIT thesis, ©1991.

3.2.4.1 Stamping Dies

Development of the dies actually begins during theme development, when the shape of the vehicle is decided. The figure below illustrates the sheet metal forming process briefly.

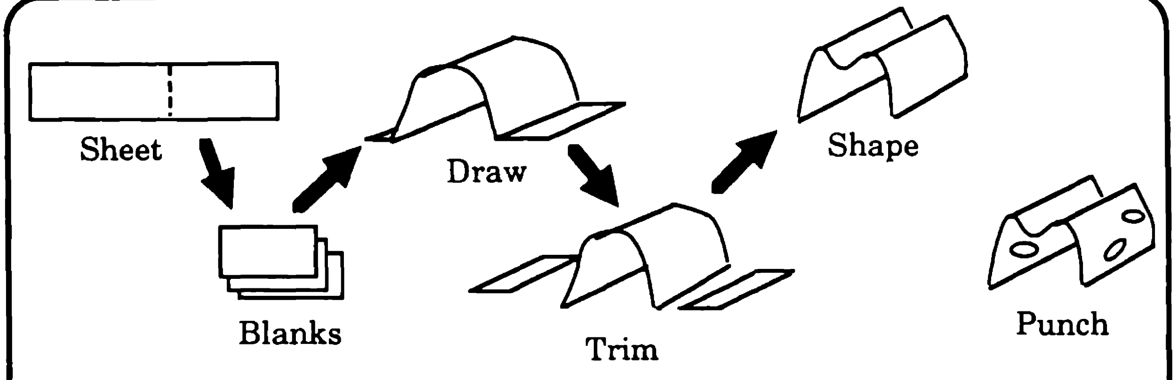

Figure 3-2.11 Sheet Metal Forming Process

Stamping engineers, by looking at the clay model, determine how easily a particular part of the vehicle may be stamped in high volume. If significant stamping problems are anticipated, the styling is changed to accommodate the concern.

Draw development, during which the draw and trim conditions for each panel are determined, begins during part development. Drawing is the process by which the basic shape of the part is initially imprinted into the sheet metal piece. As the sheet metal is pulled over the male half of the die (by the female half), metal flows to relieve the planar stress induced. If too much material flows out of an area of sheet metal, tears or skid marks occur; too much material flowing into an area results in buckling[4]. After the part is

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[4] For a more detailed discussion of deformation processing, see Hosford and Caddell, Metal Forming: Mechanics and Metallurgy, Prentice Hall, Inc., © 1983.

drawn, the excess sheet metal is trimmed away. Draw development uses knowledge of the panel divisions and the resulting panel shape to determine material flow during the stamping of the part so that these defects may be avoided during full volume production. Figure 3-2.12 below shows a schematic representation of a draw die.

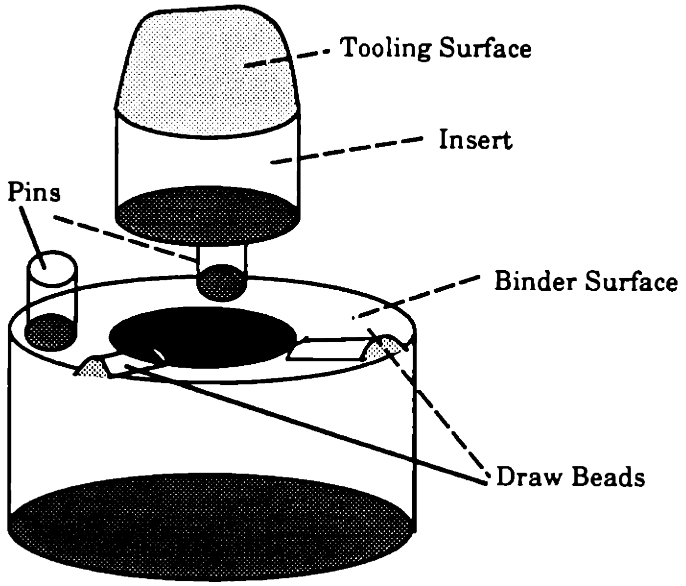


Figure 3-2.12 Schematic Diagram of a Draw Die

Upon draw approval, in which the draw development is accepted as feasible, die process engineers determine the actual stamping parameters involved. These parameters include specifying the number of dies required per panel; the press loading, material specifications, and mechanical handling for each operation; a general concept for what the dies will look like; and the sequence of the dies in the stamping line. In addition, the die process engineers interface with stamping plant engineers to gain process approval from the plant. Die design may begin with partial part information; hence, it starts during draw development when the details of the part may not be finalized. Die design makes use of the part geometry to determine the thickness of the [die] casting, the number of inserts and their placement, and the dimension of the dies, taking the sheet metal characteristics into account. From the die design, cutter paths for the surface of the final dies can be generated and later used for machining the die surface. While the cutter paths are generated, die patterns for each die are constructed. Like the verification and feasibility models, die patterns, too, are constructed from foam. They represent the final die geometry, the tooling surface of which is NC machined using the cutter paths generated. Again, engineering changes may change the shape of the die pattern.

At this time, a temporary set of dies is made. Figure 3-2.13 below illustrates where in the process the soft dies fit. Soft dies test the die process. They are fabricated from a low-melting-point alloy, which is much easier to machine than the cast iron "hard dies" used in full volume, and can be remelted. Soft dies have an average lifetime of approximately 200 parts. Parts stamped with soft dies are later used to test conformance to holding racks and location specifications in the pre-pilot vehicle build, which in turn tests the assembly sequence. Any problems in the stamping or final shape of the parts warrants a change in the die process or surface, or both. When the soft dies are approved, the pattern is approved and the parts are officially released. Hard die development continues with the patterns being sent to the tooling source[s] to sand cast the dies. Any changes from this point onward result in tremendous costs and significant lost time.

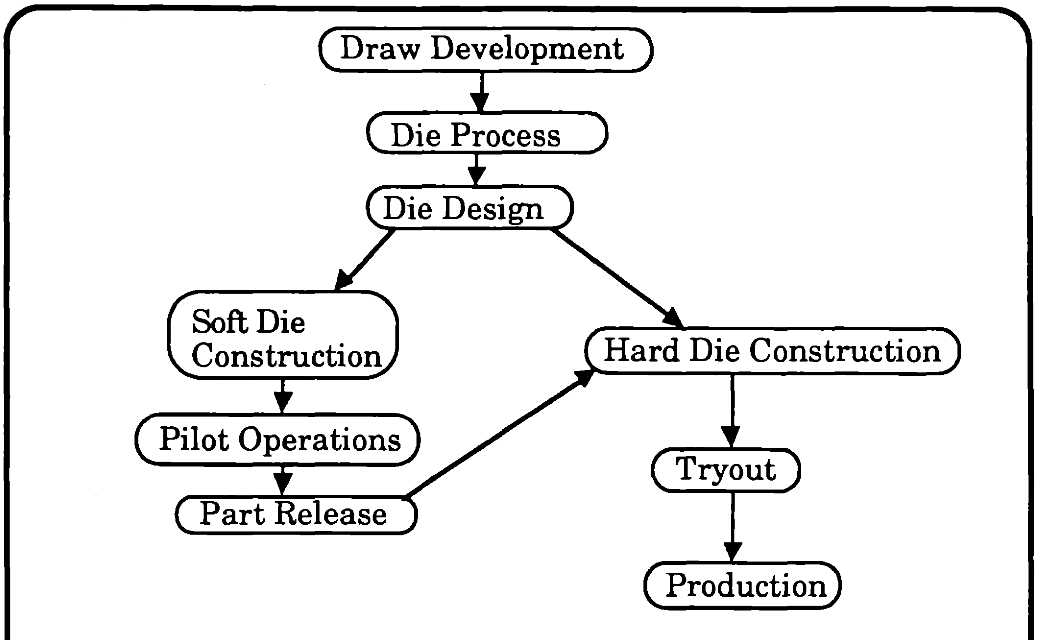


Figure 3-2.13 Hard and Soft Dies in the Process Flow

The tooling source casts the die from the die pattern, allowing an extra half inch on tooling surfaces, and sends the uncut die back to the automaker for final cutting and assembly. Upon completion, the die is "tried out", that is, several parts are stamped in the plant to test its performance. Any problems that arise here (usually) can be fixed manually. Tryout typically takes two to three months although periods as long as six months are not unheard of.

3.2.4.2 Fixtures

To ensure that parts and subassemblies are oriented properly for welding and assembly in the plant, fixtures must be designed and constructed. Fixture development requires part release, although it may begin sooner and incorporate changes. At least six principal locating points (PLP's) for each part are determined from the geometry. These points are used to determine the planes of a certain area in the part and the rotation of the part. Racks to hold and test the part for correct spatial orientation--and defects--can then be designed. (The material handling systems will reorient the part, if need be, during assembly. Programming the material handling systems is in the domain of the plant and will not be addressed here.) Parts from soft tooling development and tryout are used to test the racks for agreement with part geometry.

CHAPTER IV
OPTIONS for EFFICIENCY IMPROVEMENT

As explained in section 3.1, the framework presented in section 3.2 models the present process, specifically the currently-followed process. A Design Structure Matrix was constructed for the will-be-followed process and in section 4.1 is compared with the framework. Section 4.2 concentrates mainly on analyzing the aggregate of the matrices discussed in Chapter III. From these observations and analyses, follow the recommended options for process efficiency improvement, presented in section 4.3.

The recommendations fall into two categories: those that suggest a complete shift to a platform organization and those that maintain the functional organization with a few changes. These options illustrate the use of the Design Structure Matrix in process analysis and improvement. Indeed, people more familiar with this process may be able to use the information and matrices presented in this document to develop more effective plans for vehicle development design structure improvement.

4.1 Comparison of Present and Future Process Flows

The flow charts and the Design Structure matrix for the present and for the future process flow were evaluated against each other for discrepancies. Figures 4-1.1a and b show the entire present design structure and future design structure. Both analysis tools confirmed that while the future process flow allows for more feedback in the upstream tasks, the four basic parts of the process--concept, theme, part, and tooling development--remain intact. The most significant difference between the two processes is Task 31 in the future process, the "On-Screen Computer Part Fit." This task uses the

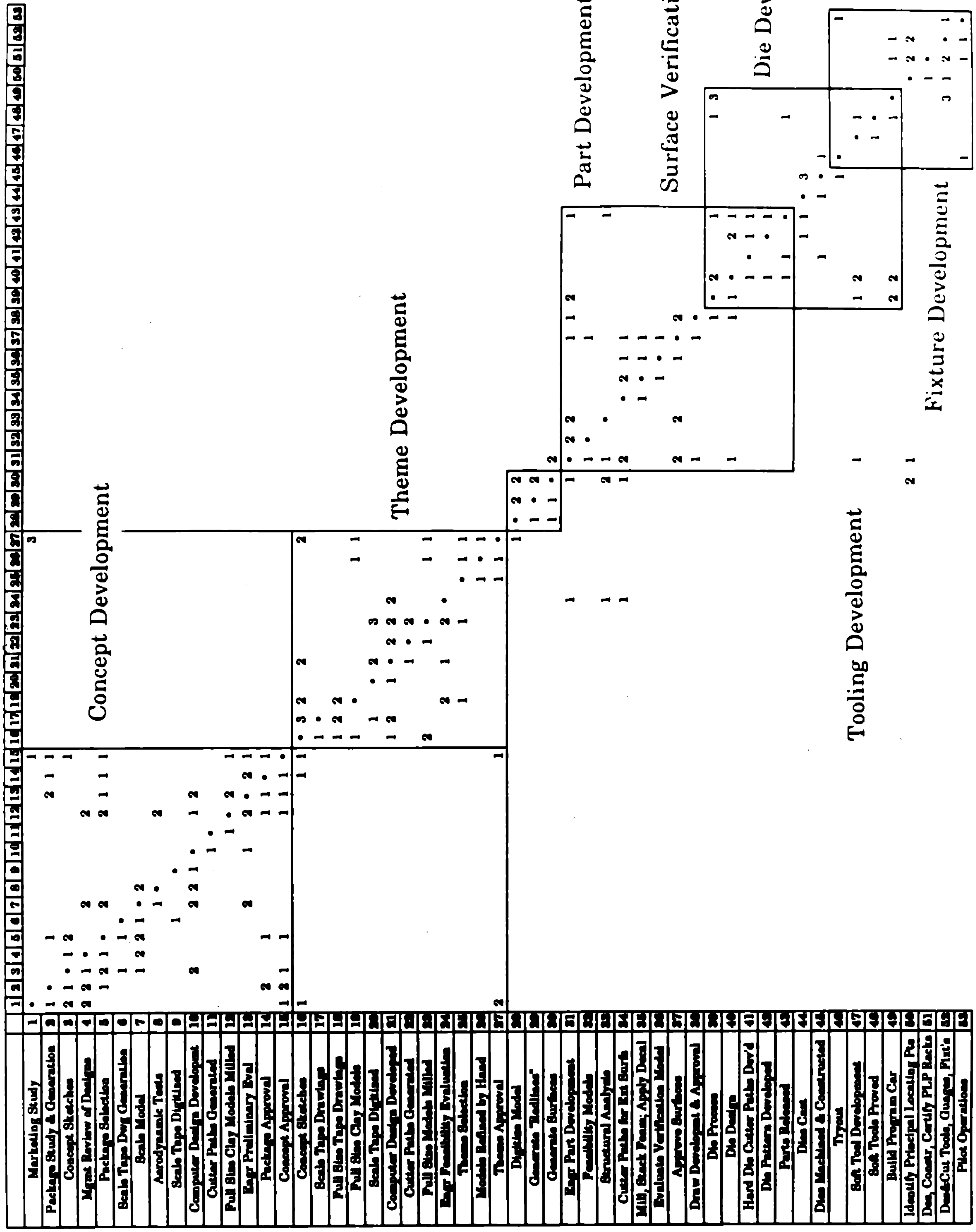
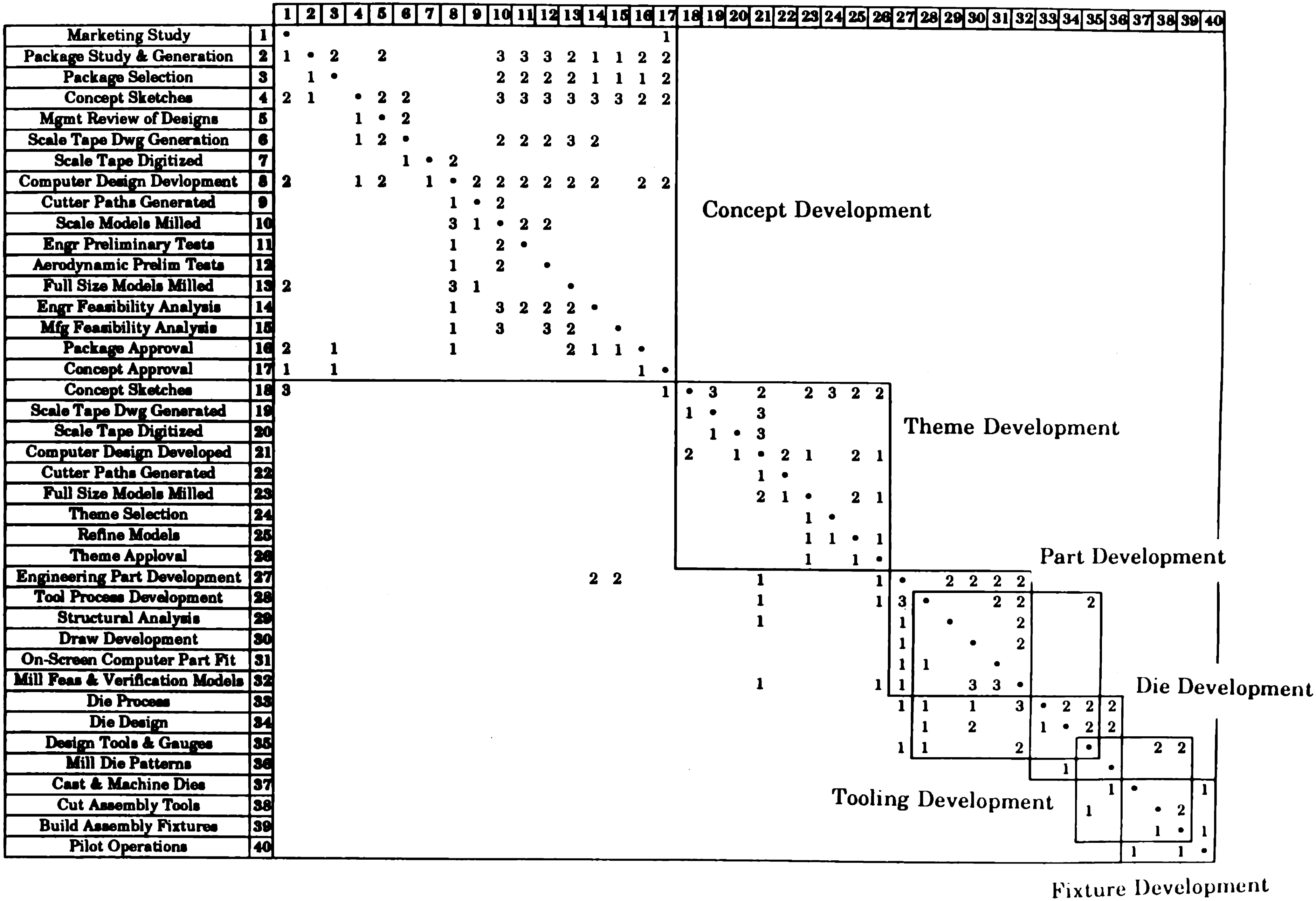


Figure 4-1.1a Design Structure Matrix for Present Process Flow



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Marketing Study	1	•																1																							
Package Study & Generation	2	1	•	2		2					3	3	3	2	1	1	2	2																							
Package Selection	3		1	•							2	2	2	2	1	1	1	2																							
Concept Sketches	4	2	1		•	2	2				3	3	3	3	3	3	2	2																							
Mgmt Review of Designs	5				1	•	2																																		
Scale Tape Dwg Generation	6				1	2	•				2	2	2	3	2																										
Scale Tape Digitized	7						1	•	2																																
Computer Design Devlopment	8	2			1	2		1	•	2	2	2	2	2	2		2	2																							
Cutter Paths Generated	9								1	•	2																														
Scale Models Milled	10								3	1	•	2	2																												
Engr Preliminary Tests	11								1		2	•																													
Aerodynamic Prelim Tests	12								1		2		•																												
Full Size Models Milled	13	2							3	1				•																											
Engr Feasibility Analysis	14								1		3	2	2	2	•																										
Mfg Feasibility Analysis	15								1		3		3	2		•																									
Package Approval	16	2		1					1					2	1	1	•																								
Concept Approval	17	1		1													1	•																							
Concept Sketches	18	3																1	•	3		2		2	3	2	2														
Scale Tape Dwg Generated	19																		1	•		3																			
Scale Tape Digitized	20																			1	•	3																			
Computer Design Developed	21																		2		1	•	2	1		2	1														
Cutter Paths Generated	22																					1	•																		
Full Size Models Milled	23																					2	1	•		2	1														
Theme Selection	24																							1	•																
Refine Models	25																							1	1	•	1														
Theme Applova l	26																							1		1	•														
Engineering Part Development	27														2	2						1					1	•		2	2	2	2								
Tool Process Development	28																					1					1	3	•			2	2			2					
Structural Analysis	29																					1						1		•			2								
Draw Development	30																											1			•		2								
On-Screen Computer Part Fit	31																											1	1			•									
Mill Feas & Verification Models	32																					1					1	1			3	3	•								
Die Process	33																											1	1		1		3	•	2	2	2				
Die Design	34																												1		2			1	•	2	2				
Design Tools & Gauges	35																											1	1				2			•			2	2	
Mill Die Patterns	36																																		1		•				
Cast & Machine Dies	37																																				1	•			1
Cut Assembly Tools	38																																			1			•	2	
Build Assembly Fixtures	39																																						1	•	1
Pilot Operations	40																																					1		1	•

Figure 4-1.1b Design Structure Matrix for Future Process Flow

computer designs of the parts to check the three dimensional fit of the parts; that is, to ensure that the parts can be assembled and that the assembly yields the desired final shape and structural characteristics. Another important difference is the elimination of surface verification (section (3.2.3.1) due to increased computer aided design (CAD). The figure below illustrates this difference. Even the absence of a weak coupling of theme approval to the marketing study in the future process flow can be anticipated, although it is not shown.

		1	2	2a	3	4
Concept Development	1	•				
Theme Development	2	X	•			
Computerize Surfaces	2a		X	•		
Part Development	3			X	•	X
Die and Tooling Development	4			X	X	•

Present Design Structure

		1	2	3	4
Concept Development	1	•			
Theme Development	2	X	•		
Part Development	3		X	•	X
Die and Tooling Development	4		X	X	•

Future Design Structure

Figure 4.1-2 Comparison of Present and Future Design Structures

Both matrices show overlap of feedback loops in the later stages, the future process showing more extensive overlap than the present one and both show two main loops in the first half of the process. These major loops differ slightly. The future process requires 17, instead of 15, tasks to be completed before concept approval despite the fact that theme approval occurs at an earlier step. Put another way, more activity and analysis takes place upstream in the future process flow compared to the present flow. The amount of feedback during this time in the process also differs between the two scenarios: the future process flow calls for far more feedback than the present process.

The shift toward a more intensive upfront analysis does not indicate that the future process is worse or better than the present one. The increased number of feedback loops may not necessarily slow the process down, if managed well. Conversely, a fewer number of steps does not necessarily indicate a more streamlined process. Again, it is *how* these tasks interrelate that determines the efficiency of the process.

4.2 Analysis of and Observations on the Present Flow

While the future process flow showed some improvements over the present flow, more changes could be suggested from analyzing what the company was currently doing rather than what it intended to do. Consequently, analysis focussed more closely on the information on the present process flow. In analyzing the matrix for the entire process (figure 4-1.1a), each milestone in the process could be identified via a block of tasks. Put together in the entire matrix, the tasks within each block that depended upon input from other blocks could now easily be seen. From this diagram, the inputs for entire blocks could be determined. For example, the first step of theme development, Task 16 (concept sketches) depended upon input from Task 1 (marketing study), Task 14 (package approval), and Task 15 (concept approval), as shown by the "1"s in row 16, columns 1, 14, and 15.

The process flow obtained from the Design Structure Matrix using only the primary dependencies was compared to the process flow obtained during interviews. The networks developed are shown in figure 4-2.1. This comparison showed the differences between the ideal process flow and the actual process flow (the "should-be" versus the "currently-followed"). Any discrepancy, it was hoped, would suggest an alternative process flow. Analysis of the blocks of each of the milestones, figures 3-2.8, 3-2.9, and 3-2.10, also proved fruitful. By examining these blocks and using knowledge of the system, redundant or otherwise unnecessary steps were identified. Elimination of these tasks was formed into recommendations for change to the process.

In both, Design Office activities encompassing all the styling studios and surface digitizing efforts, are isolated from the Engineering and Manufacturing efforts; in fact, very little if any, information generated from the studios is fed directly into the engineering and manufacturing tasks.

Upon comparison, the network developed from the matrix (hereafter referred to as the "network") illustrates far more feedback than the flow chart. With closer inspection, however, the two are different in structure. The network, based on primary dependencies, shows the earliest relative time at which the process *can* be completed. The flow chart merely illustrates what the interviewees *perceive* the process to be. Thus, by looking only at the flow chart, valuable insights into the real workings of the process are difficult at best. The network and matrix, in showing the dependence of Task 31 upon Task 24, ask what the value is added by the theme development and approval, and why the tasks performed by the Design Office seem repetitive. The matrix also shows that Task 31, part development, is critical to the process flow, and that the input it really needs is the production surface, Task 30. According to the flow chart, however, part development cannot begin without theme approval.

These observations can be seen directly from the Design Structure matrix. The matrix also shows that all tasks, except the first (Task 16) and last (Task 27), in theme development have no dependence upon concept development information. The first and last tasks in theme development, concept sketch generation and theme approval respectively, need an approved package and marketing study results. Since the marketing study is the first task to be accomplished, only Tasks 14 and 15 prevent Task 16 from starting sooner. Consequently, Tasks 14 and 15 prevent the <u>theme development</u> from starting sooner. This conclusion led to the following recommendations.

4.3 The Recommendations

The matrix and flow chart show that coordination among the tasks between the styling, design engineering and manufacturing engineering functions need improvement. As mentioned in the University of Michigan paper [11], simultaneous design integrates the three aforementioned functions to yield high quality, manufacturable designs. The analysis tools also showed that not every task was needed to build a world-class vehicle. The recommendations can be divided into changes to the milestone ordering, which suggest a platform-centered organization[5], and changes to the individual task orderings, which suggest remaining with a functional organization.

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[5] For more information on platform organization, see Scott Roodvoets, <u>An Evaluation of the Influence of Platform Team Organization on Product Development Performance</u>, M.S. MIT Thesis, ©1991.

4.3.1 Changes to the Milestone Ordering

In an effort to increase co-ordination between concept and theme development, the elimination of the package and concept approval steps is recommended. This elimination is intended to combine the concept and theme development phases as suggested in figure 4-3.1 below).

		1	2a	3	4
Concept and Theme Development	1	•			
Computerize Surfaces	2a	X	•		
Part Development	3		X	•	X
Die and Tooling Development	4		X	X	•

Figure 4-3.1 Design Structure Matrix Showing Proposed Reordering of Milestones

By combining concept and theme development, less redundancy in the Design Office activities, such as clay modelling, and greater coordination between all functions (styling, design engineering, manufacturing engineering) involved in the upstream tasks is anticipated. To realize these benefits, development teams that would develop the package and theme simultaneously while addressing styling, engineering, and manufacturing issues early in the process could be implemented. Such teams could use a bill of materials early in the development process to aid in design and cost estimation, as well as to serve as an informational record for subsequent teams.

While critics may argue that engineers are unable to handle the many design changes that would be expected so early in the process and that designers' creativity would be threatened by engineering influence over the vehicle during the conceptual stage, this recommendation will provide the following benefits to counter these difficulties. First, the package and concept is developed *together*. While engineering and manufacturing concerns will play a bigger role in the decisions made at this time, designers would no longer be forced to design around an approved package; their input can have a greater influence on the design geometry. In addition, cost estimates will be more accurate since a large part of the tooling cost is due to the dies. Because final die design and holding fixture geometries depend upon released part designs, which in turn depend upon the approved production surfaces, die and fixture costs can be predicted more accurately since fewer engineering changes to the approved surfaces would occur.

Second, in developing the package and concept simultaneously, the teams may investigate several more alternative combinations than if one package was simply passed on for designers to style around. Teams comprised of people with varying backgrounds are better able to evaluate a new package and theme combination from several viewpoints, thus adding to the possible number of final choices for the product.

Third, although only one of several (five or six) team's work is chosen for final production, the collective ability of these teams to identify new and different manufacturing methods and engineering design concepts increases the knowledge of the organization and the creativity that can be elicited during the vehicle design phase of the process. Identifying new process and product technologies allows the continuous improvement in vehicle design and manufacture to take place. Furthermore, if the teams share their ideas among themselves during their package-and-theme development stage, the entire company will be better off since the quality of all the vehicles in the selection for volume production will be higher than if they did not share their knowledge.

Since this recommendation implies a vastly different organizational structure from the one that currently exists, the implementation of this suggested solution to the time-to-market problem requires much thought and consideration. The next chapter addresses implementation issues.

4.3.2 Changes to Task Ordering

Instead of manipulating the milestones, a less radical change to the process would involve the elimination and restructuring of tasks. The suggested recommendations for these changes are:

1. To eliminate the use of clay models during concept development and rely on computerized solid modelling and surfacing instead;

2. To eliminate manual changes to the clay model during theme development, thus eliminating the need for surface verification later;

3 To utilize faster digitizing and surface generating technology, should (2) become impossible due to matters beyond the company's control;

4. To devote more engineering resources to the up-stream tasks

The elimination of clay models during concept development can reduce the time required for concept development. The purpose of the clay model at this stage is to ensure that the general vehicle shape will be able to accommodate the features being considered: engine compartment large enough for the type of engine and fuel efficiency desired, for example. Using a database of past vehicles and some experience, the general shape can be checked on a computer screen. Clay models are intended to check the overall size of the vehicle as well. Again, with a database and some proficiency, the physical size of the new vehicle may be ascertained without having to mill a clay model.

Figure 4-3.2 below shows the Design Structure Matrix for concept development with and without clay models.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Marketing Study	1	•														1
Package Study & Generation	2	1	•			1								2	1	1
Concept Sketches	3	2	1	•	1	2										1
Mgmt Review of Designs	4	2	2	1	•			2					2			
Package Selection	5		1	2	1	•		2					2	1	1	1
Scale Tape Dwg Generation	6			1		1	•									
Scale Model	7			1	2	2	1	•	2							
Aerodynamic Tests	8							1	•				2			
Scale Tape Digitized	9						1			•						
Computer Design Developmt	10			2				2	2	1	•		1	2		
Cutter Paths Generated	11										1	•				
Full Size Clay Models Milled	12											1	•	2		1
Engr Preliminary Eval	13							2			1		2	•	2	1
Package Approval	14		2			1							1	1	•	1
Concept Approval	15	1	2	1		1							1	1	1	•

Clay Model Usage

		1	2	3	4	5	6	7	8	13	14	15
Marketing Study	1	•										1
Package Study & Generation	2	1	•			1				2	1	1
Concept Sketches on Computer	3	2	1	•	1	2						1
Mgmt Review of Designs	4	2	2	1	•			2				
Package Selection	5		1	2	1	•		2		1	1	1
Scale Tape Dwg Generation	6			1		1	•					
Scale Model	7			1	2	2	1	•	2			
Aerodynamic Tests	8							1	•			
Engr Preliminary Eval	13							2		•	2	1
Package Approval	14		2			1				1	•	1
Concept Approval	15	1	2	1		1				1	1	•

Computer Screen Check

Figure 4-3.2 Elimination of Clay Models in Concept Development

Not only does the elimination of these tasks reduce the total number of tasks required for concept development--simplifying the overall process, in this case (see figure 3-2.5)--but also the surfaces may be generated during this phase, allowing engineering and structural analysis work to begin. The earlier engineering and structural analysis are completed, the earlier the concept may be approved.

Eliminating manual changes to the clay models during theme development (Task 26) forces all changes to be made by changing the computer surface and remilling the clay model. Although more cumbersome than quickly changing the offending surfaces manually, regenerating and remilling the clay surface offers the advantage, again, to the downstream tasks (part development and structural analysis) by providing surfaces readily. In addition, the need to digitize the "production surface" from the clay model, or Task 2a in figure 3-2.2, is eliminated as shown in figure 4-3.3 below.

		1	2	2a	3	4
Concept Development	1	•				
Theme Development	2	X	•			
Computerize Surfaces	**2a**		X	•		
Part Development	3			X	•	X
Die and Tooling Development	4			X	X	•

		1	2	3	4
Concept Development	1	•			
Theme Development	2	X	•		
Part Development	3		X	•	X
Die and Tooling Development	4			X	•

Figure 4-3.3 Elimination of Manual Changes to Clay Models during Theme Development

The elimination of the need to digitize production surfaces is reflected in the future process flow, as mentioned earlier. Finally, the need for surface verification is unnecessary since the master set of data is the set of points stored on computer and not represented by clay. Thus, surface verification--the checking of assembled parts' conformance to the production surface--can, in theory, also be performed on computer.

For various reasons to be explored in Chapter 5, eliminating clay modelling entirely from the process flow may not be feasible. In this case, improving the time to translate physical clay surfaces into computerized points will help to shorten total process time. No steps would be added or deleted, however. New digitizing technologies are currently being pursued by some automakers.

Finally, an increased engineering commitment of resources to the earlier stages of development would enable the early analyses to be accomplished either more quickly or in greater depth. While the advantages of speed in engineering analysis are obvious to total vehicle development time, the advantages of more complete engineering analysis at the concept development and theme development stages may be illuminated via the design structure matrix in the following way. A more complete engineering analysis at the theme development stage (Task 24 in figure 4-1.1a, engineering feasibility analysis) contributes necessary information to engineering part development, Task 31. Task 31, in turn, is essential to beginning the part and tooling development phases (see figure 4-1.1a). Thus, the more complete engineering analysis by the time of theme approval may have secondary effects. Engineering analysis includes surface division, structural analysis, and crash worthiness as well as the listing of a bill of materials.

Implementation issues associated with these recommendations are discussed in the next chapter.

CHAPTER V

IMPLEMENTATION ISSUES

In making the changes suggested in Chapter IV come to fruition, several issues must be clearly thought out. The considerations addressed in this chapter are only the most immediate. Other issues such as compensation and incentive systems, evaluation systems, future vision for the company, and others are not addressed but must be understood and planned for.

In section 5.1, a simplified view of a platform organization is offered. this organization revolves around development teams and has some obvious strengths but subtle weaknesses. In section 5.2, a functionally organized company is assumed. The changes discussed pertain to changing the current process via task reordering or altering.

5.1 Implementing Changes to Milestone Reordering

The changes required to rearrange and regroup the milestones as suggested in the last chapter imply profound changes to the organization. These changes suggest a further step away from a functional organization and toward a "program" or "platform" organization, much like the Honda concept of development teams [10].

5.1.1 Changes Required by the Recommendation

The recommendation to eliminate the package and concept approval steps requires changes in the way in which vehicles are currently developed. These changes include increased recordkeeping activities, establishment of a bill of materials (BOM) early in the development, and implementation of teams to simultaneously design and engineer the vehicle. The thrust behind these changes is the increased integration of the design and styling functions with the engineering and manufacturing ones.

5.1.1.1 Recordkeeping

Accurate and detailed recordkeeping will result in a database of designs, engineering analyses, cost analyses, and reasons for approval or disapproval of a package-theme combination. This database can then provide valuable feedback to the development of the next vehicle, be it a new platform or a variation on an existing one. For example, the database of designs could provide inspiration to designers for the next vehicle. Past engineering and cost analyses can be used to compare vehicles, to maintain consistency in calculations, to serve as a basis for some estimated values, and to provide a list of critical parameters that must be known, set, or measured. Keeping track of the reasons why approval for a package-theme combination was granted or denied can help to guide development of future work by pointing out the considerations important to the final go/no go decision.

5.1.1.2 Bill of Materials

A Bill of Materials not only is a convenient way to keep a record of parts for engineering and manufacturing purposes, but also aids tremendously in determining costs. A BOM lists all the parts in the vehicle. This list can be grouped by subassembly, material content, or supplier, among other parameters, depending upon what the list is needed for. In this way, more thought can be given to exactly how the part will be made and obtained, how it will be incorporated into the manufacturing process, and how it will function in the finished vehicle. In addition, this improved understanding of the manufacture and assembly costs for each individual part and for the whole vehicle, improve the accuracy of the estimated vehicle cost. While the first BOM created will be difficult to list, subsequent bills can draw on previous lists and therefore become easier to develop. Further, it may be used in later materials requirements planning (MRP) systems during production.

5.1.1.3 Design by Teams

Establishing a team to develop a package and theme combination improves the process flow in a number of different ways. First, communication between the various functions increases and improves as a result of placing people from those functions in close proximity to each other and requiring them to work together to achieve a joint goal. Rotation programs in which people are transferred to various departments during the development of a vehicle, computer networks to make communication easier and more readily accessible, and further training to enable team members to understand other disciplines would also enhance communication between the various functions. Second, the final product is better under the teamwork scenario since many problems can be uncovered and solved early in the process: the stylists learn what can and cannot be manufactured--and ultimately sold--and design and manufacturing engineers have more time to decide part construction and assembly issues. Third, the total amount of time required to develop the vehicle is reduced as a result of better communication between team members and less wasted time in designing vehicles that cannot be manufactured and parts that cannot be assembled. Finally, the rest of the organization is exposed to the new vehicle through team members, increasing the likelihood of its acceptance in the company. This acceptance is analogous to another automaker's "Company Buy-In" milestone (see figure 5-1.1).

The organization will necessarily take some time to become accustomed to these changes. Not surprisingly, some amount of resistance to change can be expected during a shift from old to new organizational methods. Defining

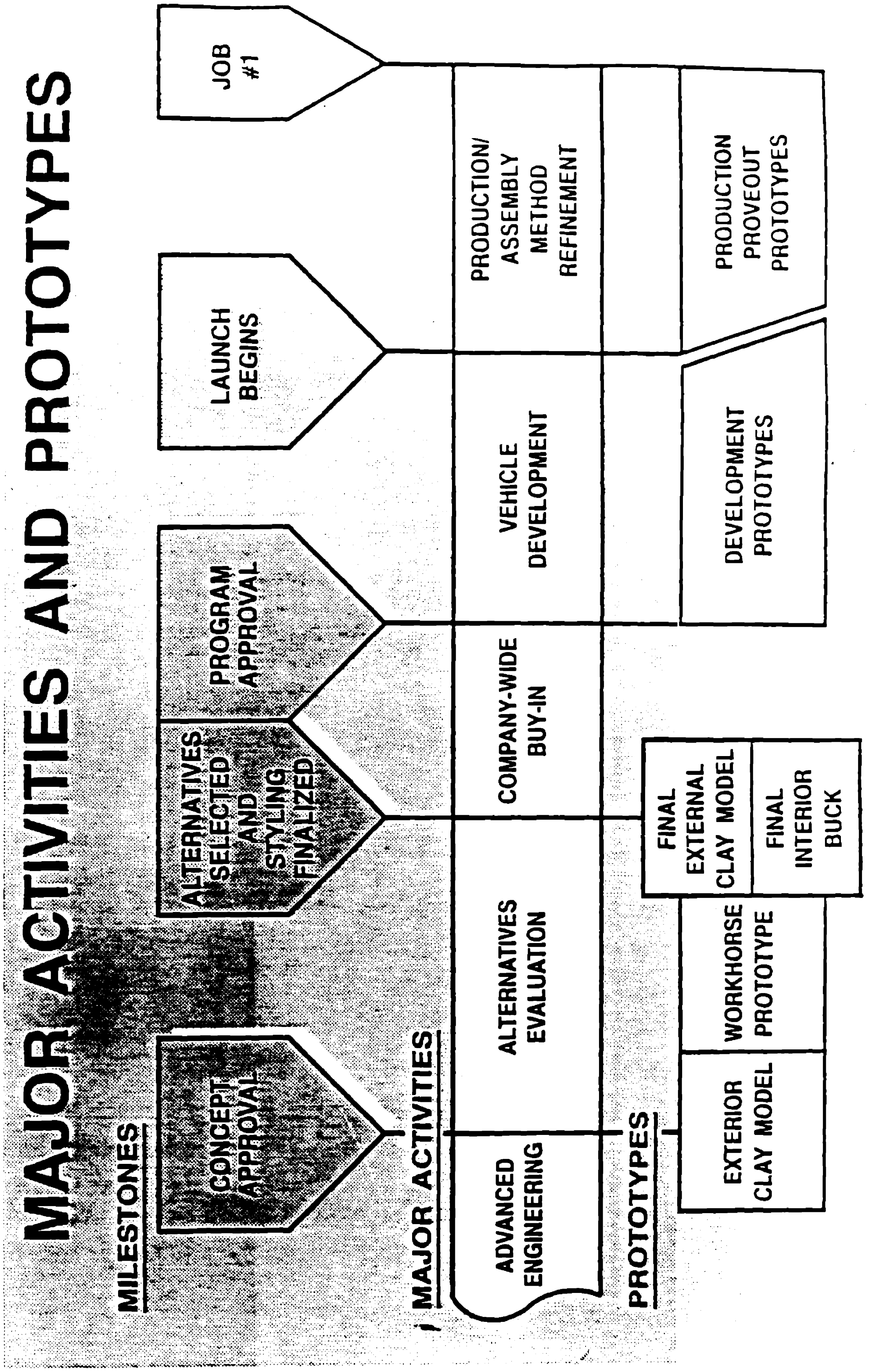

Figure 5-1.1 Process Flow for Another Automaker's Vehicle Development Process

the goals of the change and understanding where the resistance stems from are important to the successful implementation of a new process.

5.1.2 New Organizational Methods: Complete Design Teams

Central to the implementation of the suggested solution is the idea of a team approach. Using several teams to accomplish what a large, functional organization currently does represents a significant break from current practice. Consequently, defining the job of the team is critical, since the team cannot refer to the traditional process for information or support. Furthermore, a phased introduction to teamwork is best to allow the organization to adapt to this new method of design.

5.1.2.1 Teams' Function and Management

As mentioned several times before, each team should be responsible for developing a product strategy. This means that the team must design a package and theme, develop a marketing strategy, estimate the costs of engineering and manufacturing the vehicle, and determine the tooling sources and stamping and assembly plants. Increased recordkeeping activities and development of a B.O.M., as described, above could help especially in the design and manufacturing engineering endeavors during each iteration of the process.

Accordingly, the teams should consist of people from all functional areas--styling, design engineering, manufacturing engineering, marketing, finance, and production--for full benefit of these different backgrounds. The team members must be able to contribute to every goal that the team is responsible for. For example, engineers and financial people should either agree on the marketing strategy or suggest alternatives, even though marketing is not their strength. In addition, the top management of the company *guides* the teams' activities but does not dictate them. This concept of team interaction closely resembles that of Honda's new product development teams [10], with the exception that all functions are represented on the teams, instead of just engineers.

In starting up teams, task assignment within the team may be beneficial to its organization. As Ancona and Caldwell's [2] work suggests, designating one person as the ambassador, another as the task coordinator, and so on, may alleviate some of the problems that could occur early in the development of the vehicle. Recruiting people for these teams must be considered in light of the teams overall function and its internal workings.

5.1.2.2 Teams' Operation

Since many different disciplines are involved in this new concept of team design, extra training in all the fields would be desirable for all team members. Intra-company transfers between each of the functional areas and team assignments would also enhance team performance by strengthening each team member's background in a given area and by strengthening ties between the teams and the functional areas. In a similar sense, ties with academic institutions may also be cultivated more.

How the teams relate to one another and to the rest of the organization is also critical to their successful performance. According to Ancona [3], successful teams communicate often with the organization in which they work. In this context, the "outside organization" is the rest of the company: top management, plant personnel, engineering personnel, manufacturing staffs, financial staffs, and internal marketing analysts, to name a few. Without this contact, each team works in its own vacuum and probably will not be able to integrate its ideas well into the larger organization later. In addition, Ancona and Caldwell [2] identify four activities which in team members engage to maintain contact between team members and between the team and the organization. Along these lines, each team should designate, at the outset, members who will take on these responsibilities of maintaining contact with the organization, with other teams and within the team.

5.1.3 Criticisms of the Suggested Solution

As with any major change to an organization, resistance can be expected. Anticipating this resistance and understanding its basis--that is, understanding the real weaknesses in the proposal--is imperative to overcoming it [5, 9].

5.1.3.1 Culture

In the current culture, a system of "experts" has been developed over decades in which people join a functional area and learn that field. The relay of information from one area to the next is accomplished by the system; that is, the path that information follows through the process has been developed via tradition over the years. The implementation of the recommendation, including the introduction of design teams, consequently interrupts this system by eliminating one of the most important and early milestones. In addition, a loss of expertise may be feared as the organization moves toward a platform structure and people become displaced from their area of knowledge.

Again, a phased introduction to team package-and-theme design (the formation of one team, then two more, and so on) introduces the organization "gently" to this new concept by allowing plenty of time to adjust to this new method. In addition, learning how the team functions in the organizational environment, what team members need to know in order to improve overall team performance, and how they learn this information, should be done over time to ensure the early success crucial to the later widespread implementation of the system. The formation of several "functional intracompany conferences" may also help to develop and spread area specific expertise among the teams. Nevertheless, achieving this structure throughout the entire company as quickly as possible is important to gaining the full advantages of this organization. The implementation will require a huge effort that cannot be undertaken without the support of senior management.

5.1.3.2 Logistics

The culture discussed above revolves around the process timing schedule. Implicit in the recommendation is a significant change to this schedule. Hence, a new timing scheme--which must be strictly adhered to--must be developed for the team development. Initial uneasiness with this new timing can easily be foreseen, and therefore efforts to prevent reversion to the current process timing should be strong.

The deployment of manpower, also, has traditionally been influenced by the timing schedule. Again, the solution derived from this analysis, implies significantly different staffing requirements. Despite their current presence in the "up-stream" activities of designing of a vehicle, design engineering and manufacturing engineering personnel are needed in greater numbers in order for the teams to conduct engineering analyses, develop a bill of materials, and provide cost estimation data. Such a deployment, while considered impossible at present, is necessary for the functioning of the teams and could also be accommodated under a phased introduction.

5.2 Implementing Changes to Task Reordering

Task reordering does not imply as drastic a change to the present process as milestone reordering. Nevertheless, the recommendations suggested in Chapter 4 do require some important changes.

5.2.1 Use of Computers

Widespread and frequent use of computers is not currently a characteristic of many automakers during the early stages of vehicle development. Clay models have been used extensively during concept and theme development (and in later stages as well) over the years; completely eliminating them from vehicle development will be difficult. Resistance to using computer-generated images of vehicles is expressed as a dissatisfaction with the resolution of final images. Another argument against using computers for aesthetic and surface evaluation is that only full size models convey the right sense of proportion, balance, and reflections; good evaluations on a smaller model or on a screen are not envisioned to be possible.

One counter argument in favor of computer usage is the proficiency that results from practice. In other words, the more the computer systems are used, the easier the correlation between computer screen and physical, full size model is made. This proficiency takes a long time to achieve; hence, the sooner this organizational "talent" is cultivated, the better off the company will be in the long run.

5.2.2 Labor Relations and Allocation of Human Resources

More difficult to overcome than resistance to computer usage will be the reallocation of labor, especially if labor is unwilling to be reallocated. Strict job classifications hinder any flexibility the workforce may have, especially in clay modelling, digitizing, and surface generation where skills are related. In addition, insufficient engineering talent available to be deployed to upstream tasks may prevent suggested recommendation (4) from being implemented. Finally, a management mindset must be changed; artistic and engineering talent should be freely shared with or distributed throughout the rest of the company to fully realize the benefits of these recommendations. Re-allocation of engineering and styling talent, therefore, should be made on the basis of the engineer or artist, and the reasons for such decisions should be stated clearly by upper management to avoid fighting for talent within the corporation. In this way, the strategy for the changes is articulated to the organization.

CHAPTER VI

DISCUSSION of the DESIGN STRUCTURE MATRIX

In time-based competition, the most successful automakers have shown the vehicle development process to be a source of competitive advantage. Efficiency in the development process translates into faster times from concept to marketplace. Thus, a more efficient development process could mean increased success.

Several tools to analyze a process are available. Most of these focus on the tasks in a process, however, rather than on the dependencies between tasks. The tool used in this document, in contrast, focussed on task interrelationships. Using the Design Structure Matrix to analyze one automaker's development process and to suggest options for efficiency-motivated changes was demonstrated and was found to be helpful. Still, improvements may be made to the tool itself.

6.1 The Design Structure Matrix

The Design Structure Matrix provided and supported valuable insights into the actual vehicle development process. Nevertheless, we experienced some problems in using it and have some improvements that may be made.

6.1.1 Criticisms

At worst, the Design Structure Matrix was difficult to understand for those completely unfamiliar with it. Daunted by its apparent complexity, they were reluctant to take the first steps in learning more. Most, however, did find it to be a valuable way to analyze a process. At first glance, the matrix highlights inflows, outflows, and feedback loops; at a deeper level, matrix manipulation and insight reveal important information about the process which can guide an effective restructuring of it. Nevertheless, the matrix quickly becomes complicated as the number of tasks in the process increases. While computer software cannot help to simplify this complexity, it helps in tearing and partitioning by eliminating much of the cumbersome work involved.

In addition, determining the critical path from the Design Structure Matrix is not as straightforward as a network or critical path analysis. This is perhaps the case because timing data is not represented on the original binary matrix. The only way to ascertain the importance of a particular task is by the number of marks in its column (see section 2.3 for the full discussion of Design Structure Matrices).

6.1.2 Variations to the Matrix

The improvement used in this analysis is a variation on the work of Eppinger et. al. [8] and provides a way to classify the importance of the dependence between tasks. The scale may be modified, but the idea of classification leads to other improvements, such as using timing data as a means of classification in the matrix itself.

To show the amount of time for each step, Eppinger [15] suggests that the row height and column width correspond to the relative amount of time required for the task. Consequently, tasks that require the most time take up the most room in the matrix and blocks that require the most time are the largest in area.

A further variation to include timing data in the matrix is to use numbers to represent the relative amount of time necessary to complete the task with the input received. This would differentiate the relative importance of each input beyond assigning primary, secondary, and tertiary values; it would allude to the actual amount of time necessary for the completion of the task, or block of tasks.

6.1.3 Suggestions for Further Research

The beauty of the Design Structure Matrix is in its adaptability to any process. Thus, applying the matrix to other processes would not only increase the database of processes, but would also provide the opportunity to gain more insights into this analysis tool and to make more variations on it. The endless variations on its structure give the matrix its robustness, further increasing its applicability to today's manufacturing environment.

6.2 Conclusions

The two broad suggestions for improvement made in Chapter IV are only two of the infinite possibilities. While introducing a platform organization to the company may reap huge rewards in the future, the tremendous short term upheaval could prove disastrous, especially if it involves several reorganizations in a relatively short period of time. On the other hand, a functional organization, which has been used for years, would not require such a large corporate overhaul but may not achieve as much efficiency either. These options represent the extremes of the trade-off between functional coordination (the first option) and engineering strength (the second option). While it may seem to be easiest for the organization to swing to either extreme, elements of both should be included in the organizational structure. For now, maintaining the current trend toward a platform organization may be the best as long as functional engineering expertise is maintained. Regardless of the "ideal" organizational structure for the company, the path to achieve this goal must be carefully thought out and clearly articulated throughout the corporation.

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