AGILE PATHFINDERS IN THE AIRCRAFT AND AUTOMOBILE INDUSTRIES - A PROGRESS REPORT[1]

by
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Abstract

This paper describes the research plan, methods, and early progress of two coordinated Agile Pathfinders focused on the aircraft and automobile industries respectively. The projects began in June 1994 and are staffed by students, faculty, and research staff at MIT and Lehigh University.

The project is focusing on processes that have these characteristics:

• strong interactions among customers and subcontractors
• strong intertwining of engineering and business factors
• complex processes in need of greater speed, more efficient and flexible actions, and better computer tools

The methods being used are process mapping to identify crucial transactions between people and companies, linking transactions to clusters of specific engineering data called *features*, identifying transactions occurring early in product development that have large downstream effects, and speeding up the processes by providing computer tools and database access that connect people and their transactions to effects such as cost, time, assembly errors, inadequate production capacity, and so on.

The dominant form of manufacturing today is complex customer-supplier networks that we call "webs." The paper offers a working hypothesis that such a network of companies can improve its performance if participants take pro-active steps during early product design to pro-actively design and manage this web as an integrated system. We believe that "proactive design and integration of the web" is a concept that could be developed with useful procedures, metrics, and supporting software in a way that is similar to design for assembly. Such a concept is consistent with the goals of agile manufacturing and a prime focus of our project.

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[1]Work sponsored by the US Air Force Wright Patterson AFB under contracts F33615-94-C-4428 and F33615-94-C-4429. Inquiries about this program should be directed to Mr Carlo Cadet, Program Manager, MIT Room E40 223, 77 Mass. Ave., Cambridge MA 02139

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An important project goal is to show how to apply our methods in different industries. Our field studies suggest that companies in both the auto and aircraft industries have similar problems and could benefit from similar approaches.

I. Introduction

A. Project Goals and Objectives

The MIT/Lehigh Fast/Flexible Manufacturing project aims to increase the ability of companies to deliver complex products within a "web" of partner companies. A prime component of this capability is the ability to define and deliver specific customer requirements accurately and quickly. The project is developing new research methods and practical approaches that will improve corporate performance and add to academic knowledge. Researchers and students from MIT and Lehigh University in the fields of mechanical and industrial engineering, accounting, economics, and management are working with three companies to develop this knowledge. The companies are Vought Aircraft Company, a subsidiary of Northrop Grumman, Ford Motor Company and its subcontractor Budd Company, and General Motors Saginaw Steering Division.

Student research on site at the companies has focused on documenting important design and manufacturing activities and determining how they can be improved. Improved methods will combine both managerial and technical aspects and will range from better structuring of activities to new computer tools and databases. The new methods will be tried out in "pilot activities" at the partner companies.

This paper presents an overview of the project. Other papers in this conference give details about several engineering, management, and economic aspects of our work.

Agility has been expressed as having four underlying principles [Goldman, Nagel, and Preiss]

• delivering value to the customer
• being ready for change
• valuing human knowledge and skills
• forming virtual partnerships

Of these, the first three can be found within the operating philosophies of companies generally thought to be "lean" as described in The Machine that Changed the World. [Womack, Jones, and Roos] The fourth principle is different. In fact, Agile and Lean take quite different attitudes toward partnerships, and here is where an important research and practical challenge may lie. Companies like Toyota stress how long it takes to develop effective partnerships for procurement of complex automotive assemblies. Relationships of 20+ years are typical. In the world of agility, where such partnerships are predicted to be of dramatically shorter duration, extra attention will have to be paid to launching and maintaining supplier relations. For this and other reasons, our project focuses on such relationships.

Customer-supplier partnerships dominate the landscape of organizational forms for product realization of complex manufactured items.[2] Companies seek partners because the product's complexity generally precludes any one company having all the marketing, design, or manufacturing skills to make them. Partnerships are not new, but increasing competition has put new pressures on them. Also, some striking apparent organizational successes (e.g., Chrysler Corporation) that rely heavily on supplier-partners have influenced some to believe that vertical disintegration provides a path to greater corporate profitability. While such partnership networks offer significant advantages, they are quite complex and need to become more "agile." Improvement opportunities exist in terms of managing time, cost, risk, and quality. Our industrial partners are keenly aware of these opportunities.

We have found that customer-supplier relationships are surprisingly complex: suppliers of main assemblies have suppliers for subassemblies who have suppliers for parts, and all of these

[2]For example, [Schneider and Tzafestas] note that European auto manufacturers face a more dispersed set of suppliers than the Japanese do. They describe an ESPRIT program designed to systematize electronic interchange of design, procurement, and logistic data supporting the life cycle of cars in order to make automobile development more efficient.

have suppliers for fabrication machines, plus suppliers of tools and fixtures to help make and assemble the parts, subassemblies and final assemblies. We have given the name "web"[3] to this set of companies and their relationships. A generic map of a web devoted to designing and delivering complex mechanical assemblies is shown in Figure 1, while a specific one describing some automotive parts is shown in Figure 2. We are in the process of investigating the degree to which companies in the auto and aircraft industries are aware of their webs' complexities and determining the importance they give to documenting and controlling them.[4]

Our hypothesis is that to be agile requires that companies be able to manage this web, not merely survive in it. In particular, we feel that the best way to manage product realization in the web environment is to modify the product realization process so that the existence of the web is taken into account early and is paid careful attention as realization proceeds. We call these steps "pro-active web design" and "pro-active web management." Our project aims to provide tools and methods for pro-actively including web management in product/process design. The tools we have developed or are using are transactions analysis, activity/cost chains, organization maps, key characteristics, and contact chains. These are described briefly below and in detail in other papers at this conference.

B. Project Plan

The project is organized around field studies with three partner companies and is modeled on the MIT Leaders for Manufacturing Program (LFM). The successful elements of LFM are close involvement of industrial partners, student internships lasting several months on site at the partner companies, and combined engineering-management research programs plus combined management-engineering supervision of student research.

As originally proposed, the project aimed to combine two existing techniques and determine if together they could reveal important process improvement opportunities and provide a structured way to implement those improvements. The two techniques are transactions analysis and feature-based design. Transactions analysis is an interview-based technique that reveals how organizations operate by identifying in great detail the entire set of transactions that make up the work of an organization. Interviews are conducted with the people who actually carry out the work. Feature based design is a technique that is the subject of current research. Its objective is to improve conventional geometric design data, such as computer-aided design models, by attaching design intent in the form of constraints, relationships to other features, and non-geometric information such as cost, preferred machine or supplier, importance, and so on. Our field work, described below, revealed that our partners already are using a similar concept called Key Characteristics (KCs). For this reason, we now utilize the terminology KC but the intent is the same.

The project plan comprises four main steps:

1. Field studies to document actual transaction maps of important design or manufacturing processes in order to establish an as-is baseline in terms of activities, time, cost, and problems.

2. Extraction of generic problems common to both industries from these field studies, and expression of these problems in terms of KCs and other representations that are described below.

3. Definition of improved processes or methods that could be applied at the field sites, and demonstration of these methods in the form of pilot projects.

4. Definition of computer tools that could improve the efficiency of transactions, the definition of KCs, or the design and management of the web, and demonstration of prototype software implementing these tools.

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[3]In [Goldman, Nagel, Preiss] a "web" is a set of companies that have prepared in advance to form opportunistic partnerships on short notice and of possibly short duration. Our definition is less ambitious.

[4]We were introduced to the idea of web mapping by Dr. I. S. Fan and Dr. G. Williams of Cranfield University, UK, who in June, 1994 showed us their research on documenting the "extended development chain" for the A340 wing by British Aerospace and dozens of suppliers. Cranfield's term corresponding to "web" is "Extended Enterprise." [Cooper, et al]

Integral to these steps is the development of a set of metrics, in terms of cost, time, first time capability, or other suitable bases of comparison, so that the effect of the pilot projects and computer tools can be estimated.

II. Approach to Understanding and Improving Product Realization in a Web Environment

A. Basic Assumptions and Approach

Our approach begins with the idea that product design, development and manufacture occur in a series of "transactions," that is, activities in which words, computerized information, data on paper, and objects like parts and fixtures are exchanged between people and companies. The top level mission of the process is to determine a customer's requirements and convert them into a product that delivers those requirements. This must be done on time, within budget, and with the required quality. The actual transactions may be quite different from the officially espoused design process and may defy the official organization chart. We assume that the existing set of transactions is a valid reflection of real conditions such as company policies, government regulations, the complexity of the product and its production methods, and so on. Understanding the actual transactions is the first step in improving the agility of the people and companies.

Transactions comprise information transfer. Because transactions occur in a web environment, information transfer is subject to hazards such as loss, incompleteness, and misinterpretation. Specific action must be taken to mitigate these hazards. Often we find transactions in place that are an attempt to recover from these hazards. Elaborate "corrective action" processes are one example. We call these "reactive" to distinguish them from "pro-active."

To boost the pro-active transactions and reduce the reactive ones, we need to formulate design information of high fidelity (that is, it accurately captures customer requirements) and maintain that fidelity as the information is converted into successively more detailed engineering specifications and sent out over the web. Note that each participant in the web is a customer of other members of the web, so requirements capture is an ongoing activity. The second main aspect of our approach is that information fidelity can be maintained better if it is structured in ways that support and improve the necessary transactions and help eliminate the transactions that are unnecessary. The emerging industrial technique of "key characteristics," described below, is being used to capture this information.

For example, if a designer needs to choose between several production sources by comparing cost and delivery time, he needs to know the relationships between possible tolerances he might specify and the cost and time capabilities of alternate methods or suppliers. If a supplier is to provide a fixture for joining three parts, he needs to have geometric models of the parts indicating where they will join, how the main dimensional requirements of the final assembly are linked through the various parts, and where the fixture is permitted to attach to them. If a final assembler finds that the parts do not fit, he needs to be able to trace back, through the web, the various parts, dimensions, tolerances, fixtures, and their suppliers in order to find the root cause and design an effective solution.

To accomplish the move from reactive to pro-active, and to capture information in ways that support pro-active transactions, we need tools that identify clusters of transactions, methods of visualizing and managing the web, systematic ways of defining information that is passed out onto the web, and methods of maintaining control over the coherence of that information until the dispersed processes and their outputs converge again as the product is made and assembled.

B. Tools Being Used or Developed

The tools we have developed or are using are transactions analysis, activity/cost chains, organization maps, key characteristics, and contact chains. Some of these are new while others are extensions of existing research techniques or adaptations of methods being used in industry already. Along with many of these tools we are developing pictorial ways of capturing the information. We call these "maps." Each map shows one view of the physical, organizational, informational, or engineering information being shared by web participants. These maps are proving useful in understanding the web environment. Figures 1 through 6, explained briefly below, are examples. No single map seems able to show the whole situation.

Transactions analyses are interview-based studies of how organizations operate.[5] Performing transactions analyses at our three partner sites led us to recognize the inherent complexities of engineering partnerships and showed us the need to develop tools to make the complexities visible and deal with them. Transactions analyses reveal where intensive transactions activity occurs and also permit one to see how activities at one point in the process are linked to activities elsewhere. Actual transactions do not correspond to official organization charts or approved information transfers, and the degree to which they differ is a good indication of how the participants must skew the official process in order to make progress. Figure 3 shows a Design Structure Matrix, which is one way of documenting transactions.

Activity/cost chains are an extension of activity-based costing.[6] They are the result of using direct cost measurement techniques during the transactions analyses. In many cases, transactions can be associated with costs, so that cascades of transactions can be linked in order to sum up their component costs. Activity/cost analyses show how much it costs to do some basic activity such as to make a design change, adjust a fixture, or tighten a tolerance. An actual cost chain analysis is in Figure 4. Knowing these costs can help justify improvements in design and business processes. However, most companies do not know their actual costs to the required accuracy and usually compile costs in functionally defined cost centers rather than associating them with processes, especially when those processes cross functional boundaries and enter the web. A paper in this conference by Prof Manash Ray, Mr Martin Anderson, and Mr Trey Johnston describes this method in detail and gives examples.

Organization maps show explicitly who does what in the web of suppliers.[7] [8] These maps turn out to be quite complicated, since assemblies and related tooling seem to be divided up into very small elements and each element is contracted out to a different supplier (at least in the car industry). If companies were to make these maps during early product design, they would be able to plan out who should be in the partnerships and begin thinking about who should do what. Supplier selection criteria could be formulated based on where suppliers lie in the map and what their part is in delivering the final customer requirement. However, it appears that the web grows over time without top level awareness or management. Figure 5 an example organization map of a portion of automotive component design.

Key Characteristics (KCs) are currently in use at each of our three partner companies and at many others.[9] KCs are aspects of the product that require close attention. They are intended to capture customer requirements and express them systematically as design and production metrics. Hundreds of specifications, dimensions, and tolerances typically appear on drawings. The assignment of a KC to a dimension or surface finish, for example, indicates that this particular aspect is the important one to deliver. Different companies have utilized this idea in different ways. GM distinguishes key product characteristics (KPCs), that the customer is aware of, and key control characteristics (KCCs), that the manufacturer must control in order to deliver the KPCs. Another paper in the conference by Prof. Anna Thornton and Mr. Don Lee of MIT discusses KCs and their potential.

Contact chains link the key characteristics of assemblies of parts and fixtures to each other so as to describe how fitup is supposed to be achieved.[10] KCs, for example, highlight visible fits like those around car doors, since fitup dimensions and tolerances are documented by the chains and fitup is a KC for customer satisfaction. Figure 6 shows the contact chains responsible for assuring fitup of the access door of an aircraft engine. A metric we have proposed is to count how many company or organizational boundaries are crossed by a single contact chain. Our assumption is that smaller is better. If companies define these contact chains early in design, they can assign

[5] Mr Martin Anderson directs the Transactions Analysis research on the project.
[6] Prof Manash Ray directs the activity / cost chain research on the project.
[7] The work of [Cooper et al] is presented as an organization map.
[8] Prof Charles Fine directs the web -related research on the project.
[9] Prof Anna Thornton directs the KC research on the project.
[10] Prof David Gossard directs the contact chain research on the project.

responsibility explicitly to the different suppliers for their roles in supporting the chains. However, it appears that while individual engineers commonly calculate these chains for local assembly fitup analyses, the contact chain concept has not been utilized as a way of unifying the work of several cooperating companies. No current computer aided design (CAD) tools include contact chain representation capability, although the potential to add this capability exists. CAD is commonly used to define parts, less often for assemblies, and hardly at all for assembly fixtures. Another paper in the conference by Mssrs Minho Chang, Timothy Cunningham, Don Lee, and Narendra Soman describes design and management of the web in terms of KCs and contact chains.

Agility Metrics are intended to help companies determine if they are operating in an agile way.[11] [Goldman, Nagel and Preiss] present a list of 100 questions that provide general guidance in this area but a more precise set of metrics is needed. Tools and methods will be devloped that relate directly to the web activities we find among our industry partners. These will be aimed at returning quantitative results from measures that are easy to understand and easy to calculate.

We present next a description of our partner companies and the results of field studies our students carried out at these companies last summer. These field studies led us to define many of the tools listed above and the field observations described in Section III.

C. Field Studies

Nine graduate students carried out summer research activities at three industrial partners' sites. Their tasks were to identify important processes and carry out transactions analyses of them and to determine effective sets of key characteristics to capture the information being transmitted. The students will return to the sites during Januarys and summers throughout the project.

1. GENERAL MOTORS SAGINAW STEERING DIVISION

This large operation makes a wide variety of precision and heavy duty assemblies for a large number of automotive customers. Production rates vary from custom to mass. Different domestic and foreign customers provide design requirements in the full range from vague wishes to fully dimensioned drawings and process plans. The organization must therefore maintain a variety of customer response processes ranging from performing a complete design to merely executing a finished design. While the organization has a great deal of experience dealing with traditional product and process technologies, it is beginning to be challenged to design radically different products and to use its existing plant and design staff far more efficiently than in the past. The students have gathered cost, time, process and product data that will permit them to map the traditional engineering response to the entire range of customers as well as to account for the costs of the transactions in these processes.

2. VOUGHT AIRCRAFT CORP, A SUBSIDIARY OF NORTHROP GRUMMAN

Vought is a full service first tier supplier of aircraft assemblies to both commercial and government programs. Vought is responding vigorously to changes in both of these markets and has a history of analyzing and improving its internal processes. Like Saginaw, its customers present it with the full range of requirements from detailed prints to concepts requiring complete engineering and process development. Some of its programs are very long lived; in addition, these programs are subject to continual large and small engineering changes reflecting attempts to solve engineering problems of quite long standing. Many of these problems probably stem from the fact that the designs predate modern computerized design methods. We have characterized the problems as primarily rooted in dimensions and tolerances of parts and their associated fabrication and assembly tools and fixtures, with errors in the range of 0.5 mm to 3 mm being pursued with vigor.

Three facts must be faced: first, these older programs will continue for the foreseeable future and their problems will continue until they are solved; second, it has not been proven that modern computer methods are yet capable of eliminating these problems; third, solving these problems for old products by creating new designs, tooling, and fixtures is prohibitively costly. Vought is in the midst of developing new design procedures in partnership with a commercial customer. An important goal for Vought is to standardize and streamline the design of parts, assemblies, and

[11] Prof Mikell Groover directs the agility metrics research on the project.

fixtures so that less effort is required in problem solving and more parts fit together the first time. The students have documented transactions describing the original design and launch of three older assemblies as well as the problem-solving transactions that have been developed in response to the dimensional issues encountered. They will have access to the most recent programs in future visits.

3. FORD MOTOR COMPANY AND BUDD COMPANY

These two companies are partners in production of sheet metal parts for automobiles. Ford designs parts and subassemblies which are made by Budd or Budd's suppliers. Important fabrication and assembly tools and fixtures are made by still other suppliers. Ford recently launched a new model of its successful Explorer vehicle, with significant changes in the front-end sheet metal body parts. The launch process typically requires a large team of engineers about seven months, but Ford's goal is to reduce this time in half. A focal activity in any new vehicle launch is the discovery and removal of fitup errors between the parts. These errors, like those in aircraft, fall in the range of 0.5 mm to 3 mm. The sources of the errors are many and are similar to those encountered in the aircraft industry: inherent variability of material properties, inaccuracy of fabrication and assembly fixtures, errors in the original design process of parts and tools, and omissions or errors in transmitting design specifications or information among the various suppliers of parts and tools.

In order for Ford and Budd to shorten the launch period significantly, they will have to improve the original definition of parts and fixtures (the part designs are already 100% on computers) and increase the completeness and validity of information packages that are exchanged between designers of parts, fabrication tools, assembly tools, and measuring equipment. A basic component of this challenge is to increase information traceability to the point where the root causes of problems can be found. The students have documented the design processes that generated the original parts as well as the problem-solving activities that have been occurring during the launch process.

III. What we have learned

This set of sites presents us with a rich variety of situations, but a number of common themes have emerged. The theme that appears to have the most potential for giving visibility to improvement opportunities is the web of customers, suppliers, parts, assemblies, tools, and fixtures. This web is the dominant feature of all our partners' activities and the source of most of the transactions we have documented. In any "Agile Future" such webs will play central roles, so improving their performance has high priority.

Our observations at this early stage in our research may be expressed as the following list of situations, operating patterns, and problems:

• <u>the operating pattern of the web</u>: based on a customer's need, a company defines a need for an assembly or fixture, for example, and seeks to obtain it from a supplier, who in turn obtains parts or fixtures from other companies; at the end of a long and geographically dispersed process, the parts are supposed to come together at the first company to fill the original need

• <u>pervasiveness of the web environment:</u> parts, assemblies, tools, fixtures, and equipment are procured from suppliers who often have other suppliers in turn; this appears to be true in spite of recent efforts by companies to reduce the number of suppliers they rely on

• <u>dispersal of the design and production process</u>: many of the choices made during product development by one member of the web must be carried out by another whose capabilities, equipment, methods, costs, and additional suppliers are not known when the original choices are made

• <u>growth of hierarchical supplier relationships</u>: assemblers like Ford used to directly control all of their suppliers; increasingly, assemblers follow the Japanese pattern and deal with a first tier only, and this tier deals with the next tier, and so on; this increases the dispersion of web activities

• <u>loss, omission, obscurity, or misinterpretation of information</u>: information is lost on the web; drawings provided to suppliers lack crucial details, or it is incorrectly assumed that the supplier will fill in the details, or a requirement is mis-stated, or a tolerance datum goes unrecognized, etc.; there is a lack of clear representations for the most important relationships

• lack of first-time capability: the product does not deliver the requirements on the first try, or the production process has too low a yield at first, or attempts to correct problems do not work the first time, and so on; the root cause of a problem is rarely found, or rarely found on the first try, because the information needed to determine it is dispersed over this web and therefore is almost impossible to reassemble coherently

• lack of visibility into the cost or performance consequences of a design or production choice: materials, tolerances, suppliers, production methods and design implementations must all be chosen during product development, but the information required to do so to achieve a good balance of time, cost, quality, and risk is not available

• local solutions: because the web is not well mapped, when problems occur, the solutions proposed and implemented take into consideration only the impacts on easily observable related web elements; more distant web elements may be severely negatively impacted by these "solutions" in ways that are invisible to the engineers who are solving their immediate, local problems; when the consequent new problems appear, often much later and far away from the original problem, they, in turn, may be solved with only a local perspective

• complexity of the products: it takes a huge amount of knowledge to describe and execute the processes required to make complex products, and it appears that this knowledge resides unsystematically in the heads of the people carrying them out rather than in an organized database of any kind; a lot of transactions activity goes into repeatedly locating, organizing, and interpreting this information

• long design cycles: it takes a long time to design complex products (four years for a car, five years for a commercial aircraft, ten or more years for a military aircraft) - during this time people move to different jobs, requirements change, and information gets lost.

• inadequacy of current design methods: even though a digital definition of parts and assemblies greatly reduces the errors that occur in vendor-supplied parts, errors still persist; it is necessary to move to the next steps, namely to bring tooling and equipment under digital definition and to coordinate their design with the design of parts and assemblies

• inadequacy of present manufacturing and assembly methods: large amounts of money are spent on tools and fixtures but errors occur during assembly anyway; this appears to be true whether there is a digital definition of the product or not; both speed and flexibility are impaired by large amounts of inflexible tooling, fixtures, and machines; the potential exists for designing or using these items more flexibly

• external constraints: in both military and civilian environments, external constraints occasionally mandate that certain suppliers be used; this removes a degree of freedom from web management

• need for more attention early in the process: the activities that occur (or do not occur) at the beginning of the design process have a disproportionate influence on the later stages, where we observe many problem-solving transactions that could be eliminated; many of the missing transactions would involve better understanding the customer's needs and specifications as well as matching the supplier's capabilities to those needs

• lack of adequate cost models: many opportunities for improvement are already known to the companies but it is difficult to justify their apparent cost because the cost penalties associated with the present processes are dispersed over the web of suppliers and are therefore almost invisible

This list of problems has been obvserved primarily in the mechanical aspects of products. In primarily electronic areas, the opportunities for coordinating webs of suppliers are greater. Information has been standardized to a greater degree, CAD systems have an easier time exchanging data, interfaces can be defined with less ambiguity, and product design can be cleanly modularized more easily. Modules can often be designed by specialist firms with good confidence that the final assembly will work. Companies like Hewlett-Packard, Apple Computer, and Sony are among many who can confidently put together virtual manufacturing networks for products like workstations. Web problems observed at our sites could thus be one more indication of the degree to which mechanical industries lag behind electronic industries. It is possible that this lag is the result of fundamental differences between electronic and mechanical products. On this basis, more attention to the web in mechanical industries may be necessary and hopefully rewarding.

IV. Future Work

A. Pilot Projects

Four pilot projects are currently being defined that will test our hypotheses and seek to improve the problems we identified:

1. Pro-active management of the web: Existing academic literature on managing product realization processes says little about proactive management of the supplier network of organizations. It says equally little about their infrastructure of people, tools, protocols, processes, information, systems, and support that is integral to the development and delivery of complex manufactured products. Our research to date suggests that many of the problems encountered that increase cost and time in product realization processes could have been avoided or reduced with a more proactive approach to web management.

This pilot will look across all of our research sites to focus on the development of two tools: (1) a "web map" tool that will illustrate the entire system of suppliers and critical information about these web members and their inter-relationships (see e.g., Figure 1) and (2) a web management computational tool that provides analysis about trade-offs among cost, quality (tolerances), time, and risk across the web members for the identified key characteristics in the design.

2. Enrichment of product design data to reduce the need for corrective action: This pilot will compare corrective action methods at Vought and Ford/Budd as the basis for identifying missing design information that causes some kinds of corrective action; recommendations will be made concerning use of contact chains and KCs to capture the missing information, more effective corrective action procedures, and metrics for determining if corrective action has been improved.

3. Development of product realization process improvements and information architecture tools to help streamline and make more accurate all steps in the "concept through production" cycle: Based on research conducted at Sagniaw, we will develop the architecture for management tools designed to help many multi-product companies reduce the barriers among functional groups in the "web" of organizations creating products. Starting with the pivotal "customer requirements definition" process, and moving through design, development, and production, we will seek procedural techniques, management tools, and information management techniques to increase speed and flexibility of the process. We will pay particular concern to information management techniques that link distant organizational units and seemingly "incompatible" data bases.

4. Development of predictive tools for tolerance accumulation in sheet metal assemblies: Methods will be developed to help designers assign KCs and contact chain references and predict mathematically what fitup problems can be expected; recommendations will be made concerning the best use of this tool in the overall management of the web as well as recommended enhancements to conventional CAD and the underlying data models of parts, assemblies, and fixtures.

B. Long Term Benefits

We believe there exists an opportunity to develop tools to map the web, develop baselines and metrics, and pro-actively manage better the trade-offs that must be made during the PRP. Also, we believe that, while corrective action will never be eliminated, it can be significantly reduced. A major thrust of our work will be devoted to seeing if the entire web for procuring complex assemblies can be held together with the concept of the contact chain. Such chains could be defined early in design and used as the reference point for assigning responsibilities to suppliers, assessing their ability to deliver, and checking the coherence of the design at later stages (is the chain still intact, have unnecessary or uncontrolled links been added, which is the weakest, have unnecessary or inadequate suppliers been added, can time/cost/quality/tolerance tradeoffs be managed systematically from the chain view, etc.). If this idea survives scrutiny it might be a model for how to hold other kinds of design issues together as they are realized by a web.

Finally, we hope that this work will be useful as an effort to "flesh out" the details of the concepts of agile manufacturing. Those concepts were established without a deep empirical or case study foundation. Our in-depth field studies have the potential to confirm and sharpen some of the insights on improving agility in manufacturing organizations--particularly those related to the speed of executing the required set of transactions and the management of supplier network partnerships.

APPENDIX: ILLUSTRATIONS OF THE WEB

Each of the representations below is a "view" of the web, emphasizing different aspects. These views share a great deal of information and present it in different ways. Figure 6 is the closest to traditional CAD representations, but it fails to show the cost implications of Figure 4 or the organizational relationships of Figure 5. We expect that a set of computer tools that will aid the management of this web will enable participants to create each of these views (or others) and operate on the information in various ways. An important near-term goal of the projects is to define the architecture of data bases and information support for such tools.

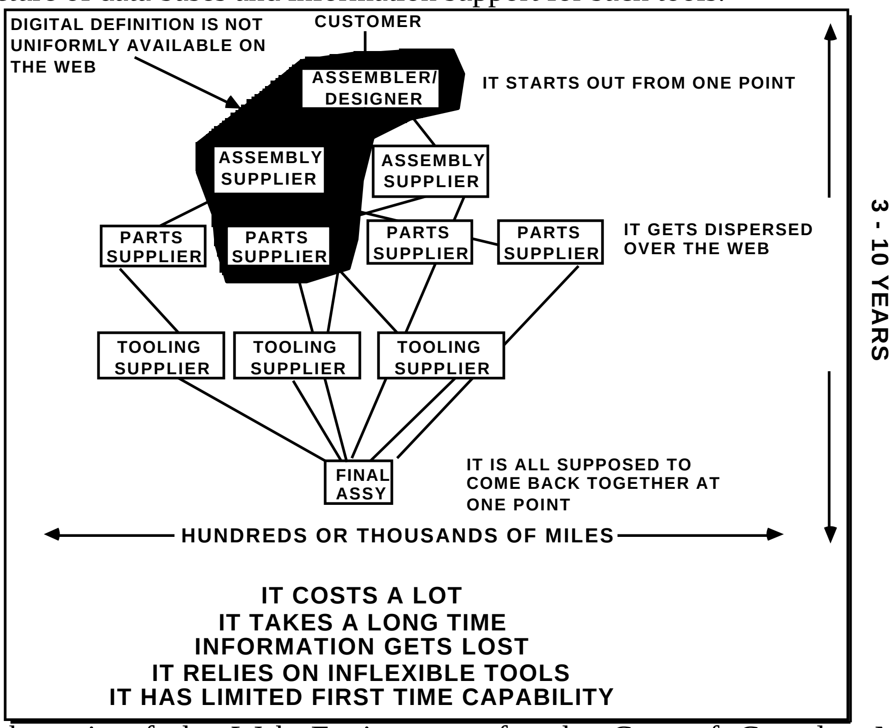

Figure 1. Schematic of the Web Environment for the Case of Complex Mechanical Assemblies. An assembly is designed or partially designed at the top to meet a set of customer requirements expressed as fitup specifications. The design is dispersed geographically and over time, during which new design activities occur, members are added to the chain, and information is lost. Only at the end can the original designer determine if the parts fit, that is, if the original customer requirement has been met. (Developed by D. Whitney from discussions with team members.)

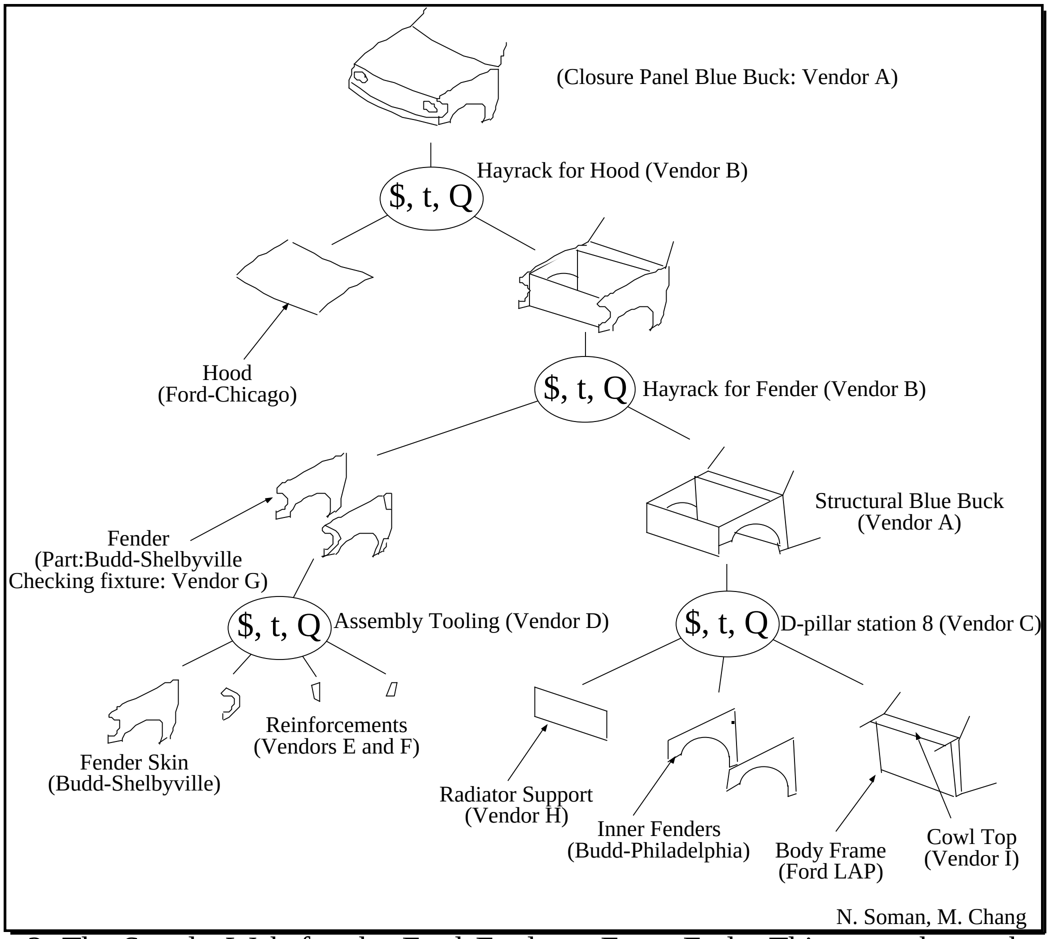

Figure 2. The Supply Web for the Ford Explorer Front End. This map shows the parts, fixtures, and their respective vendors and indicates that even for a small number of parts and fixtures there can be a large number of vendors. The bubbles with "$, t, Q" inside indicate major points where money and time are spent to obtain quality. Developed by Mssrs Narendra Soman and Minho Chang.

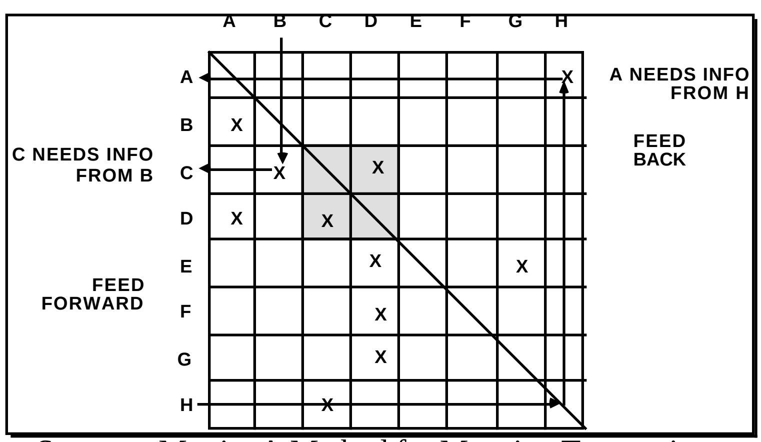

Figure 3. A Design Structure Matrix, A Method for Mapping Transactions

The Design Structure Matrix (DSM) is one of many ways to capture transactions information. [Steward, Eppinger et al] The transactions are listed in nominal sequence down the side and across the top. An X indicates that information is exchanged between two transactions. The DSM is able to capture in one diagram a large set of complex relationships and make them visible. It is especially good for identifying clusters of related activities as well as pointing out places where the process is likely to repeat a chain of activities. While Figure 3 uses Xs to capture relationships between activities, one can use numbers to represent the strength of the relationship, the time required, or the cost incurred. Following and totalling the costs yields "cost chain analyses" like that in Figure 4.

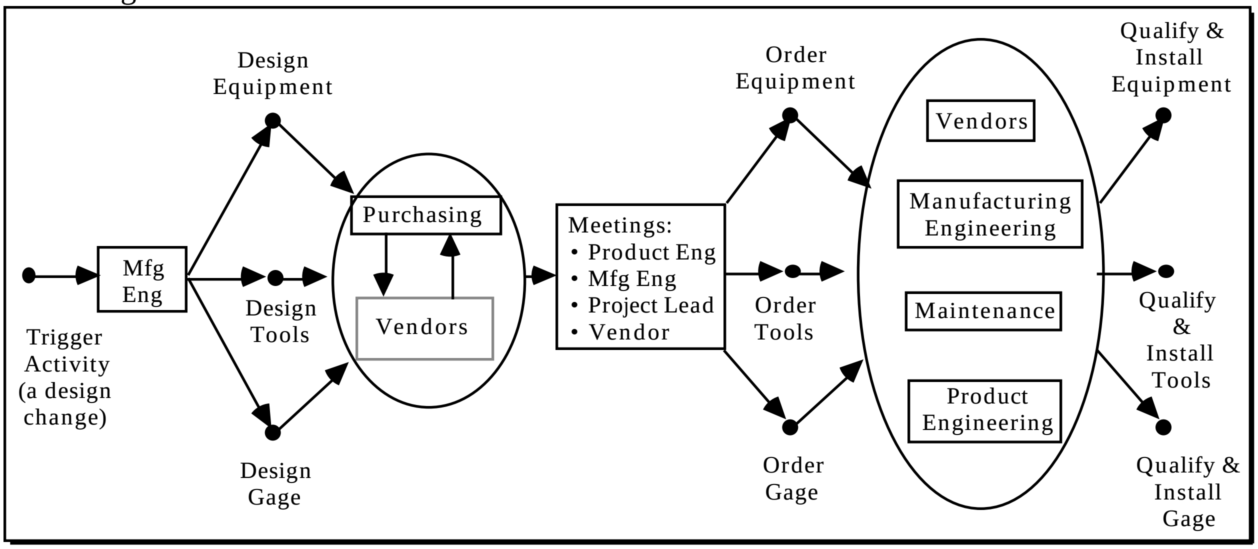

Figure 4. An Actual Cost Chain for a Single Design Change Requiring New Equipment. These activities cross functional and company boundaries and ripple across the web. Costs accumulate at each step. The total person costs in this example inside the design company only, not including equipment costs, amounted to many thousands of dollars. (Developed by Trey Johnston and Manash Ray)

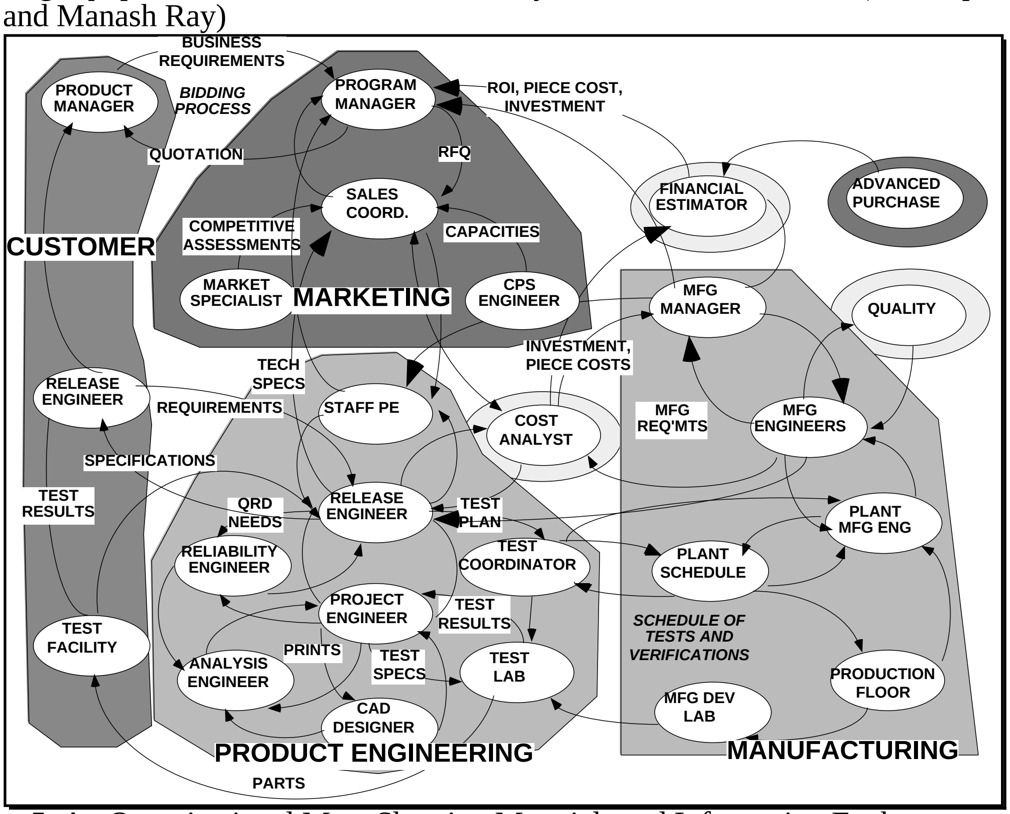

Figure 5. An Organizational Map, Showing Materials and Information Exchanges

This simplified organizational map shows the flows of information and material between organizations at an automotive components plant during product development. The physical nature of the items being exchanged is captured in the contact chain map such as Figure 6 while the informational relationships are captured in process maps like Figure 3. (Developed by Peter Greif, Paul Gutwald, Trey Johnston, Don Lee, David Marquette, and Martin Anderson.)

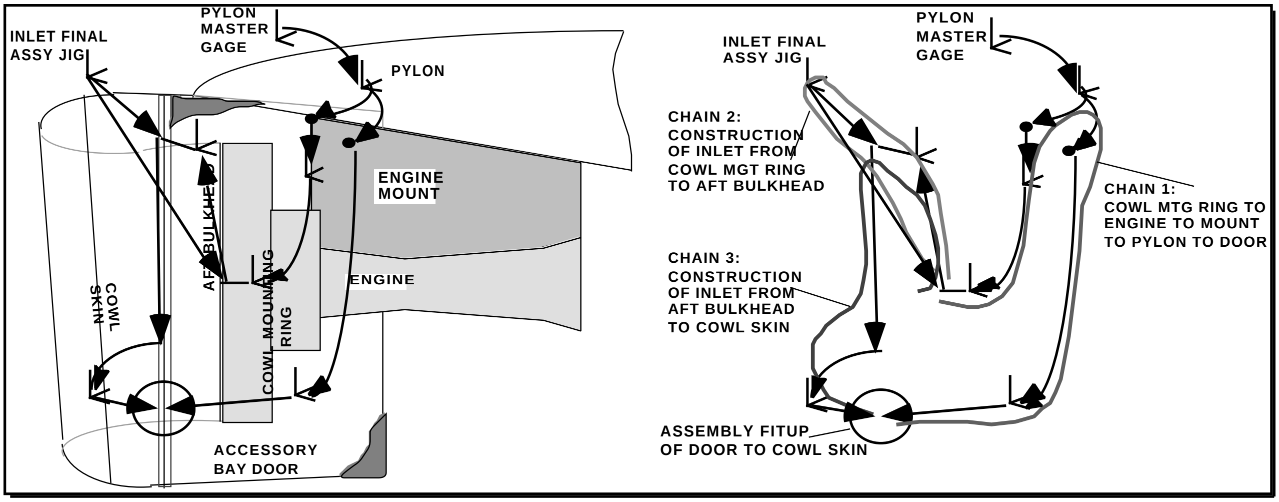

Figure 6. Contact Chain for Aircraft Engine Inlet. The contact chains link a series of parts together. Each node in the chain is the mating of two parts. During assembly, parts obtain positional references from fixtures, so several of the contact chains illustrated here contain fixtures. Points where chains meet are places where important part fits occur. In this case the important fit is between the engine accessory bay door and the inlet cowl skin. The assembly tolerance stems from the initial customer requirement that engines be replaceable in a few minutes. Inlet cowls and engines must be interchangeable, while doors are permanently attached to wings. A close fit between the cowl and the door is required for aerodynamic reasons. (Developed by Timothy Cunningham and Daniel Whitney)

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