Fast and Flexible Communication of Engineering Information in the Aerospace Industry

Contract # F33615-94-C-4429

Fourth Quarterly Report for MIT
Period covering April - June 1995

Sponsored by:

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Wright Laboratories
Manufacturing and Technology Directorate
Information Technology Division

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Objectives and Goals

The objective of this project is to improve the design and production of complex mechanical assemblies that are produced in agile partnerships, with a focus on improving first time capability. Complex assemblies illustrate most of the problems of partnership manufacturing since they include many components with tight relationships to each other. Company partnerships between customers and suppliers are very common and will continue to be the dominant mode of manufacturing for the foreseeable future. New tools and methods will be needed to carry out both the design and manufacture of these items and the management of design and manufacturing processes ongoing simultaneously at many companies.

The project is being carried out in close collaboration with a sister project that is focusing on the automobile industry. These industries share the characteristics listed above. Many opportunities exist for each industry to learn from the other in spite of differences in production rate and manufacturing processes.

Background

The project's approach consists of the following six steps:

1. Map selected elements of the product development process using Transactions Analysis
2. Benchmark these elements individually and as a system within and across the target industries, identifying useful metrics
3. Formulate "best practice" hypotheses based on transactions mapping and benchmarking, capturing best practices in new tools or methods
4. Create pilot projects to test, demonstrate, and customize these best practices by using the tools and testing their usefulness
5. Assess pilot outcomes using the metrics developed, and develop migratable practices within and beyond the target industries
6. Synthesize, document, and publish the findings

In conjunction with a sister project focusing on the automobile industry, we are working with several partner companies in the auto and aircraft industries:

Vought (Division of Northrop-Grumman), Boeing
Ford, Budd Company, General Motors Saginaw Division

Project activities have been selected to provide insight into a broad range of product development phases in order to grasp the whole process and determine how to affect it as a whole. One way of summarizing the projects and their relationship to the product development process is illustrated in Figure 1.

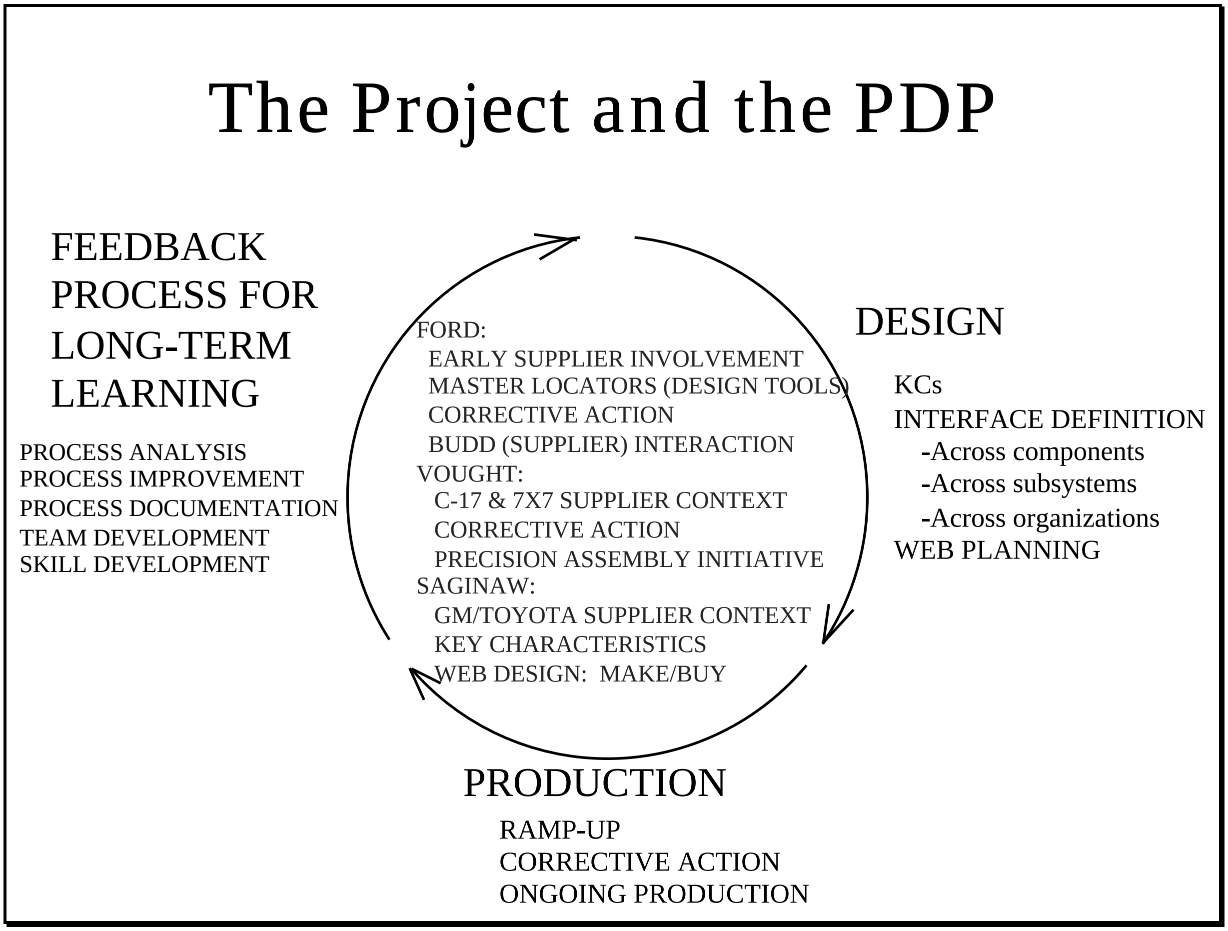


Figure 1. Relationship of the Fast/Flexible Program to Product Development Phases. Product development is broken into three main phases, with the project's general focus areas listed under each one. Inside the circle are example sites and the main activities undertaken at each one.

We have formulated and carried out the Fast/Flexible projects as indicated in Figure 1, dividing product development and manufacture into three main phases: design, production, and long term learning. The projects aim to improve the speed and flexibility of selected elements of this integrated process by applying several tools: maps of the supply chain, design structure matrices, contact and tolerance chains, transactions analysis, key characteristics, and activity-based costing. Field work, including intensive use of these tools, focused in the first year on the corrective action phase of production. The second year will consist of pilot projects to test and demonstrate the tools, followed by implementation plans to migrate the tools and methods to other companies and industries.

The projects have chosen to focus on assemblies for several reasons. First, assemblies amplify the problems of coordinating a web of suppliers, whereas purchasing a single component would involve at most a single chain of suppliers. Second, assemblies reveal problems of coordinating shared and distributed design and production in ways that are physically tangible: the parts don't fit. Third, assemblies are inherently integrative, requiring cooperation and interactions of many people and organizations. Finally, assemblies and the assembly process can act as forces of change in organizations, because all of the above characteristics of assemblies reveal shortcomings that can be improved. In virtually every site in our project, the people pushing most strongly for new design, procurement, and production methods are those responsible for performing assembly.

In framing our work, we have tried to pay attention to three main categories of activities at the partner companies:

- technical
  - engineering design and analysis tools, especially for understanding assemblies
  - manufacturing engineering analysis tools
  - data gathering and analysis methods
  - CAD modeling requirements
- organizational
  - integrated product teams and processes
  - corrective action teams and processes
  - customer-supplier relations during product design and corrective action
- managerial
  - training, skill sets, incentives for teams
  - short and long term hiring trends

The balance in the first year has been to the technical side, which we plan to redress during the second year.

The main lesson learned, as expected, is that the design phase is critical in making product launch successful. A crucial feature is that, in virtually every industry, product development is not an activity of one company but is in fact a joint activity of many firms that form a "supply web." It has been known for a long time that companies have "suppliers." We have focused our work on the fact that product development is a shared activity that is distributed over this web, that many of the problems encountered during product development are due to this fact, and that companies can improve their speed and flexibility by planning and actively managing this web.

Web management consists of several activities discussed below: attention to technical coordination with specific agreed-upon definitions of engineering data, specifications, and reference points such as assembly datums and measuring points; establishment of organizational arrangements that manage the distributed responsibility for delivering the technical specifications; and definition of incentives and relationships that permit the web to operate successfully, especially when problems arise.

The other lesson, not expected, is that long term learning (and in some cases short term learning as well) is not pursued systematically in many companies. Companies do not record data about design or production processes; or if they do, the data are used locally and discarded when the project is over. Development teams are disbanded and lessons learned are not recorded or carried on to the next project. In some cases, higher management thinks that these beneficial activities are happening but many times they are wrong.

Current work also suggests that integrated product teams are not as effective as they could be. Some teams seem to drift or orbit around their objective rather than home in directly. We are witnessing this right now at one of our sites, where IPTs are new. We can see that a focus on assembly from the top down would help this team focus, and our students on site are working along these lines.

Current Status

As - Is Site Documentation

The first year of the project has been devoted to understanding several industrial sites and designing pilot projects to carry out there. These sites are Vought Aircraft Company (Division of Northrop-Grumman), Delphi Systems Saginaw Division of General Motors, Ford Motor Co. Truck and Sport Utility Vehicles design offices in Dearborn MI and manufacturing facilities in Louisville KY and St. Louis MO together with Ford's sheet metal supplier Budd Co., their design office in Troy MI and manufacturing facility in Shelbyville KY. The activities documented in both projects are

1. Vought: This is the situation of a supplier of airframe components to the C-17 program and Boeing's commercial aircraft products; the main focus is on assembly operations and corrective action; the immediate goal is to determine the effect of supplier relations and design package data on the amounts and kinds of problems encountered during assembly plus Vought's methods of resolving those problems internally and with its customers and suppliers; the long term goal is to recommend improved procedures for structuring part and assembly information so that fewer errors will occur and they will be solved more quickly and conclusively. The main tools being used are transactions analysis, Key Characteristics, and Contact Chains.

2. Delphi: This is the situation of a supplier of steering gear components and systems to a wide variety of auto makers, each of which has different requirements and degree of knowledge about the components themselves; the goal is to map the entire business process, find iterations and incomplete information, and recommend a better and faster process for handling incoming bid requests. Tighter connection between questions arising in early design and information about costs, available capacity, and process capabilities is needed. The methods of transactions analysis, activity-cost chains, and key characteristics are the tools being used.

3. Ford/Budd: This is the relationship between a customer and a supplier of complex sheet metal assemblies, analogous in many ways to the Vought situation, with the same goals: to determine the effect of supplier relations and design package data on the amounts and kinds of problems encountered during assembly and to recommend improved procedures for structuring part and assembly information so

that fewer errors will occur and they will be solved more quickly and conclusively. The methods of transactions analysis, contact chains, and Key Characteristics are the main tools being used.

Cross-Industry Benchmarking

The auto and aircraft industries are similar in many ways, although there are important differences. Comparisons are particularly relevant between Vought and Ford/Budd. Some qualitative benchmarking has been done and more is anticipated regarding four major issues in product development:

a) when do suppliers become involved, what things do they supply, (design services, parts, subassemblies, tools and fixtures), what decisions are made when they are present, what role do they have, how do the decisions affect them

b) what specific technical methods, symbols, CAD tools, and systematizing methods are used during design to manage the system nature of assemblies and the supply chain's involvement in their production

c) what happens when problems arise on the plant floor, usually during product launch in the car industry and more or less all the time in the aircraft industry, how are those problems solved, what steps during design (could) mitigate those problems or permit them to be solved faster

d) what, if any, long term learning occurs that permits the activities in a), b) and c) to be done better, faster, or with fewer errors during the next development cycle.

Due to the similarities of the products from a technical and supply chain point of view, it is not surprising that similar methods are being adopted in both industries, although at different rates. In several of these areas, however, the car industry seems to be ahead. Its methods appear more mature (see discussion of Capability Maturity Matrix below) and it has logged more time working on these issues.

We can see some differences between the car and plane industries in terms of industry structure, supplier relations, technology sharing, methods of deciding how/what to outsource, and so on. In several of these areas, too, the car industry seems to have a healthier situation in the sense that more technology sharing and earlier supplier involvement are evident. The aircraft industry could learn several general and specific practices from the auto industry in these areas.

On the aircraft side, a prime focus of our project has been sheet metal assemblies. We have observed two important characteristics:

1. heavy involvement of a supply chain in the actual production of the assemblies, but relatively little involvement of the suppliers during product development

2. a lack of awareness by the product developers of the system nature of assemblies and the opportunity to use assembly as an integrator of the "integrated product team" approach

Because of synergies and communication between our two projects, we have had many opportunities to compare these characteristics between aircraft and automobile companies. It appears to us that some car companies are ahead in overcoming the difficulties cited in characteristics 1 and 2 above compared to aircraft companies. Suppliers are involved earlier, and very specific kinds of information are exchanged that make production of assemblies and diagnosis of assembly problems easier. Some recognition of assembly as an IPT integrator can be found in car companies, but using assembly in this way is not a standard practice and is of course not appropriate in every case. However, people responsible for final assembly are often the originators of new design practices that result in better integration.

Both industries are pursuing a sort of downsizing but for somewhat different reasons. In both cases this has led to the departure of knowledgeable people. Suppliers are therefore becoming more and more important. Recent work by the MIT Lean Aircraft Initiative [Klein] indicates that suppliers participate in relatively few aircraft industry IPTs (29%), and IPTs charged with generating airframe products in particular count only 29% of their membership from suppliers.

At the same time, our Vought site is engaged in an innovative effort to develop and implement a new way of assembling parts that depends on drastically fewer dedicated tools. A huge effort to create cross-trained and multi-skilled people will be required to implement such a system and survive in the new environment of less military work and a more competitive commercial environment. Yet Klein also reports that few teams get ongoing training in IPT skills and only 29% of teams report having Human Resources representatives on them. Anecdotal observation at Vought confirms this finding.

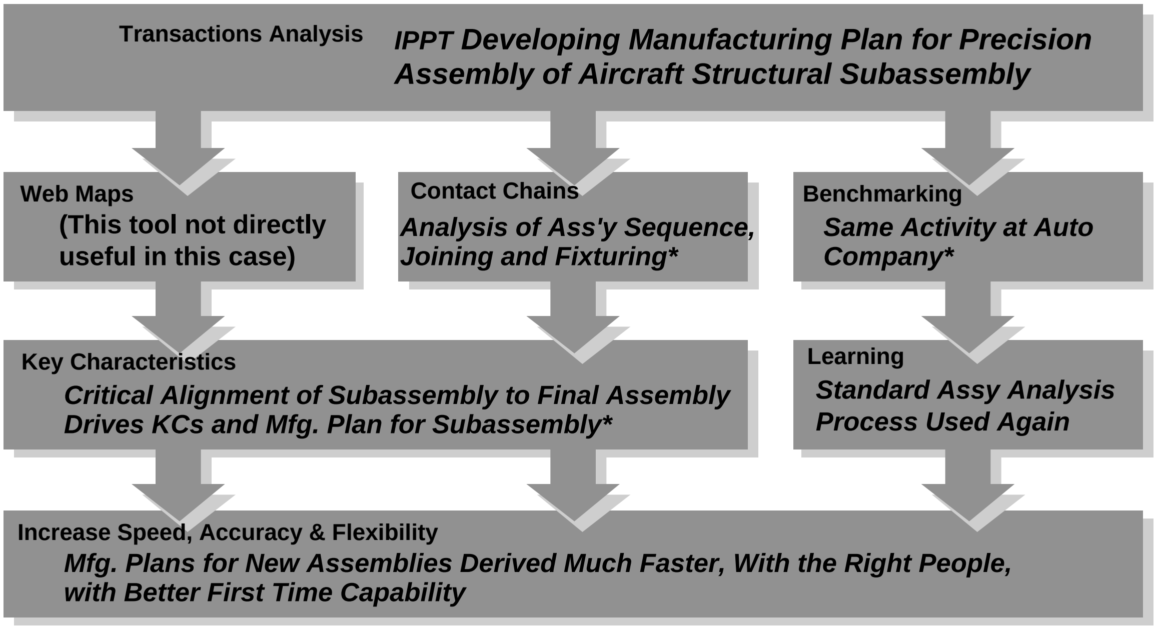
Tools Being Developed

The tools being developed or adapted for use are Transactions Analysis (a kind of process mapping), Web Diagrams (for capturing the business and technical relationships between customers and suppliers), Key Characteristics (a way of identifying and structuring the critical requirements of a product, assembly, subassembly, or part in terms of deliverables to a customer), Contact Chains (for capturing the physical relationships between parts in an assembly), the Design Structure Matrix (for capturing inter-related information flows in a process and to highlight iterations and concentrated transactions), and Activity-Cost Chains (to determine the total costs of sets of related activities in a process).

We have already learned that our tools are useful and effective. They have helped us to understand our sites' operations and have helped the sites to identify or solve specific problems related to product development or manufacturing. Transactions analysis directed us to the conclusion that careful attention to the supply web is critical to successful design and manufacture. Contact chains permitted us to identify difficult assemblies and decide where to focus design activities that would avoid ongoing corrective action. Difficult points in the contact chain correlated well with clusters of transactions discovered during transactions analysis. Key characteristics proved effective in identifying top level deliverables for individual parts and assemblies, leading to more rational design of those items. KCs will be a driving force in our pilot project at Vought, shaping the recommendations regarding process flow and new methods for reducing dependence on hard fixtures.

An example of the way these tools interact to produce our projects' desired results is shown in Figure 2.

Tool Links



*MIT Contributions Here

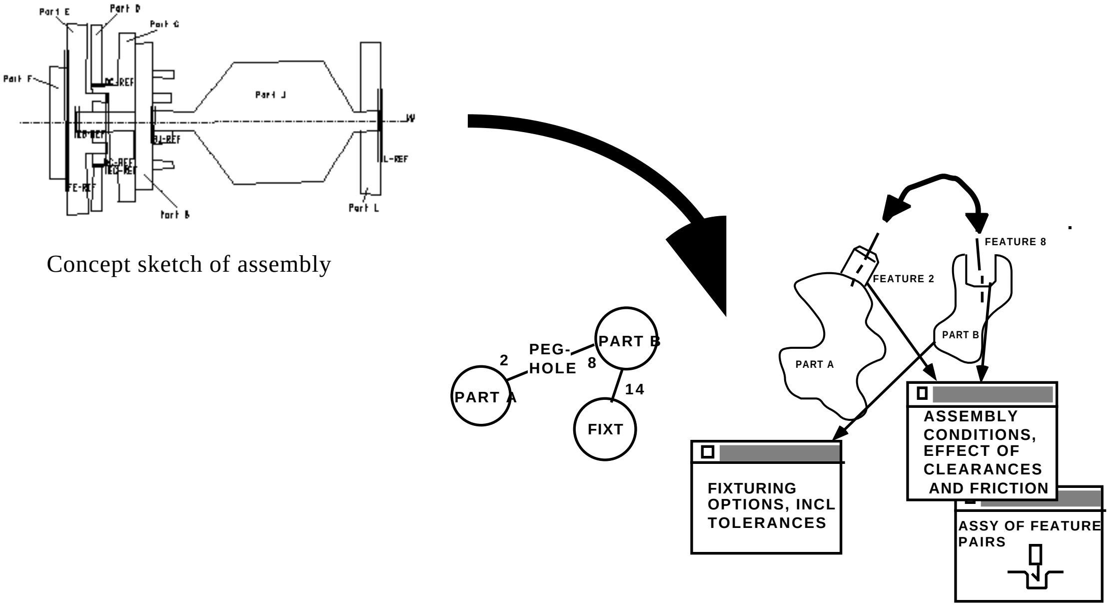
Figure 2. Examples of How the Tools Developed in the Projects Work Together to Deliver the Final Results. This flow mirrors the plan for the Vought pilot study described below.

We have also found that a web map for a complex assembly and the corresponding contact chain can be superimposed to indicate clearly the roles of customers and suppliers in delivering the KCs, tolerances, and quality requirements of the assembly. This means that web communications, interfaces, and management could be set up using the combination of these tools.

Software Tools

As noted below, some commercial off-the-shelf software will be utilized in the Vought pilot project. In addition, demonstration software is being developed to address a major problem in CAD of complex assemblies. The problem is that few or none of the tools being developed or adopted here for describing and managing design and procurement of assemblies are supported by current commercial CAD. That is, a designer cannot presently lay out the design of an assembly top-down, starting with the definition of the KCs and the surfaces, axes, or datums that they constrain. Instead, the designer must begin by defining specific geometry, constraining it with various parameters and relationships. This is appropriate for individual parts but skips over the crucial layout stage when the relationships between parts should be established.

The demonstration tool being developed is based on the concept of feature-based design for assembly [De Fazio et al] in which parts are defined in terms of arbitrary geometry plus definite geometric and non-geometric characteristics that define how the parts assemble to each other. Previous attempts to create such a design tool required the designer to define the parts first, then "assemble" them by indicating which mating features were to be joined. The new tool reverses this process, permitting the joining regions to be defined first on sketches of non-committal geometry that can be refined later. Figure 3 illustrates some aspects of this tool in its present evolving form.



Concept sketch of assembly

Construction of assembly using parts with incomplete geometries and well defined assembly features

Figure 3. Use of concept sketches and feature based design to represent and construct assembly relationships and store related information simultaneously

The demonstration tool is being written in the environment of the commercial CAD tool ProEngineer, which supports some of the desired capabilities now. It is also being written to take advantage of existing assembly analysis software [Baldwin et al] developed by Dr. Whitney and his colleagues in the late 1980s. ProEngineer also supports commercial tolerance analysis via VSA. The result will ultimately be a tool that can unify a large number of assembly-critical design tasks that our previous work on this project has identified as necessary to improved design and manufacture of complex assemblies.

Pilot Projects

Pilot projects are under way at several of the sites. These pilots are designed to benchmark specific product development processes, apply the tools listed above, and use them to suggest improvements to the sites' processes. Specific metrics are being proposed, each appropriate to the process chosen for pilot activity. A migration plan will be written to help make the tools applicable in other companies and applications.

At Vought the pilot is aligned to Vought's new initiative in precision assembly. We are applying all our tools (except web mapping since the parts are made in-house) to defining the manufacturing plan, assessing the internal learning opportunities, making cost saving predictions, and generally shadowing the Vought activity with the chance to compare results later. The Vought initiative is planned in several stages lasting for the next 5 years. The first stage will take about 2 years, longer than our present contract permits us to follow. Vought has chosen a relatively simple assembly to start on, planning to move to more complex ones later.

Although the planning of our pilot is incomplete, it will have the following elements:

a) technical modeling of the contact chain and main tolerances of a wing-like skin subassembly

b) process mapping of the as-is method of assembling this unit using current hard tooling, including time and cost estimates as well as first time capability

c) generation of process alternatives, including tolerance analysis, definition of mating features, time and cost estimates, and estimated changes in first time capability

d) illustration of systematic definition of Key Characteristics of this unit flowed down from higher level assembly and customer requirements

e) comparison of the pilot's method of arriving at process, cost, KC, and time estimates with the method used by Vought, as well as comparison of the recommendations themselves

Figure 2 above captures the anticipated flow of the pilot project, illustrating how the tools will contribute to it.

Metrics Being Developed

Time and cost are traditional metrics for judging a manufacturing process that meets its technical requirements. In addition, we are looking at a top level metric that could be roughly called "process maturity." We found it first in connection with the CMU Software Engineering Institute's capability-maturity matrix, but it is well described by Roger Bohn [Bohn] as well. He has applied it to general technical areas beyond software, using similar terms and taking similar positions. CMU took its structure from work that dates to the late 1970s. [Crosby] It is illustrated schematically in Figure 4. This formulation emphasizes different ways that processes can be carried out, with the lowest level being ad hoc and experience-based. Higher levels are increasingly repeatable, systematic, documented, able to be taught to new participants, and receptive to continuous improvement.

Processes Categories **Levels**	**Management** *Software project planning, management, etc.*	**Organizational** *Senior management review, etc.*	**Engineering** *Requirements analysis, design, code, test, etc.*
5 Optimizing		Technology Change Management	
		Process Change Management	Defect Prevention
4 Managed	Quantitative Process Management		Software Quality Management
3 Defined	Integrated Software Management Intergroup Coordination	Organization Process Focus Organization Process Definition Training Program	Software Product Engineering Peer Reviews
2 Repeatable	Requirements Management Software Project Planning Software Project Tracking & Oversight Software Subcontract Management Software Quality Assurance Software Configuration Management		
1 Initial	Ad Hoc Processes		

Figure 4. Capability Maturity Matrix (CMU Software Engineering Institute Key Practices Document). Sample matrix based on software development practices. We intend to extend this framework and apply it to developing complex mechanical products

This kind of metric could be better than supposedly easily calculated and familiar "results" metrics such as cost, development time. Instead, the CMM is a way of judging and improving the processes that create the results. CMM has some depth and prescriptive value. That is, there are specific characteristics associated with being at each level, and a pilot project has the opportunity to translate some of these characteristics into specific recommendations.

It appears that our aircraft site is at the lowest levels in those areas where we have been working. Naturally, since these levels depend on skills more than on procedures, the departure of skilled people could cause problems in the future.

Work During the March - June 1995 Quarter

During this quarter, efforts were focused in three areas

1. preparing for the summer site work at Boeing, Vought, and Ford

2. strengthening the project by increasing capability in human relations and organizational issues

3. obtaining another student

Planning for the summer site activities involved frequent telephone contact with Vought to better understand their emerging Precision Assembly Project (PAP). This effort will focus first on the upper skin panel of the 767 horizontal stabilizer. A visit was made to Vought April 20-21 to visit the plant floor, discuss the project with its managers, obtain technical and financial information, and arrange contact persons for the summer. A presentation was made to senior management describing our past work and future plans.

Following this visit, staff and students studied the PAP project's objectives and the physical parts (in the form of sketches provided by Vought). Plans were formulated to carry on our own "shadow" PAP activity, to include process mapping, Key Characteristics definition and flowdown, contact chain analysis, tolerance analysis, cost analysis, manufacturing process simulation, and process recommendations. Copies of VSA and Witness software were obtained to support these activities. Plans were made to spend the summer in a series of programmed visits to Vought, Boeing, and Ford in order to obtain comparative information on planning, supplier relations, and variation control, all in relation to how each of these companies deals with assemblies.

The plan for this shadow project is still being formulated due to the emerging PAP plan itself.

In addition, a student associated with the MIT Leaders for Manufacturing Program (LFM) was recruited to spend 6 months at Boeing studying that company's methods of outsourcing complex assemblies to suppliers such as Vought.

To strengthen the project's capabilities in organizational issues, contact was made with Professors Rebecca Henderson and Janice Klein of the MIT Sloan School of Management. Both of these scholars deal with various aspects of organizational behavior in high technology industries such as pharmaceuticals and aircraft.

A new Master of Science student, Tariq Shaukat, was hired to do a thesis in the area of IPT dynamics and long term learning in product development at the Vought site. Mr. Shaukat is registered in the Technology and Public Policy Program at MIT.

The Principal Investigator, Dr. Whitney, is also co-supervisor, along with Prof. Fine, of two other LFM students associated with the companion Agile automobile project. Each student is working at a different division of General Motors. One is studying Japanese and US stamping die development and procurement processes, including customer-supplier relations. A major focus of his study will be transactions and contact chain analyses of each process. The other is studying GM's procurement strategies for complex systems including anti-skid brakes and active suspensions. Complex issues arise due to the interaction between these systems and the car's structure, as well as questions regarding retention of core design and system engineering competence inside GM: the more GM outsources these separate items, the less overall control it has over the combined system as well as the more subsystem design knowledge it surrenders. This study will utilize transactions analysis and Design Structure Matrices to describe the technical and strategic issues.

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