Opportunities for Improving the Information Intensive Product Development Process

by

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Abstract:

Product development is an inherently information intensive process. The quantities of
information and the complexity of the development efforts both contribute to this state.
To address this and other product development issues, the National Science Foundation
and six sponsoring companies partnered to begin the MIT Center for Innovation in
Product Development (CIPD). The incentive for this research was to evaluate the needs
of the industry sponsors and critique the research strategy of the Information-Based
Development (IBD) research thrust within CIPD. Twenty-six interviews were conducted
at seven companies with products ranging in scope from electrical connectors on up to
airplanes. The Voice of the Customer methodology was applied in assessing the
information needs in product development. The following questions provided a
framework for each interview. “Where do you see information-related problems or
inefficiencies? How do they impact product quality and time to market? Which are the
most critical?” Customer statements were grouped in an affinity diagram according to
the KJ method as outlined by Jiro Kawakita. Current IBD research projects were then
mapped into this diagram to highlight the unmet needs. Through this process, four areas
of opportunity for improvement were identified: the awareness of available information
for access, the complete capture of information, the ease of use of information in decision
making, and the design of an information infrastructure which is appropriate for all stages
in the development process.

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Title: Associate Professor of Management Science
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1. Information and Product Development

1.1 Introduction

Product development is an inherently information intensive process. It is a multi-disciplinary effort requiring the coordinated efforts of groups of individuals to make thousands of decisions. In addition, the products being developed are technically challenging. They are often composed of hundreds or thousands of parts and are frequently customized. New products may even incorporate recently developed technologies. Each of these factors contributes to the information intensive environment.

In order to better understand and address these issues, a research thrust devoted to Information-Based Development was established within the MIT Center for Innovation in Product Development (CIPD). The research efforts in the CIPD are sponsored by the National Science Foundation and six partner companies, which include Xerox, Polaroid, Ford, General Motors, and ITT Industries. The objectives of this thesis are to assess the information-related needs of the industry sponsors and to critique the research strategy of the Information-Based Development Thrust.

In order to gain a better understanding of the information needs in product development, Voice of the Customer (VOC) interviews were conducted at each of the partner companies and also with Boeing. These seven companies produce a diverse set of products ranging from night vision goggles to color copiers and sport utility vehicles. ITT even does some work on the international space station. The VOC interviews focused on a common theme of information needs in these various product development efforts. The following questions provided a framework for each interview. “Where do you see information-related problems or inefficiencies? How do they impact product quality and time to market? Which are the most critical?” Then, interview responses were grouped into a framework according to the KJ method as outlined by Jiro Kawikata. Professors and students in the Information-Based Development thrust were also interviewed, and current research projects were mapped into the KJ diagram to highlight unmet needs. Through this process, opportunities for improvement were identified.

1.2 Why Product Development is Information-Intensive

1.2.1 Missing Information

In one sense, there is actually an absence of information when a product is being developed. Initially, there is too little information and, correspondingly, too much uncertainty. Pieces of the overall picture are missing and their resolution only becomes clearer as applicable information is generated from product development activities. Although a lack of information would not seem to imply a high degree of information intensity, it is exactly for this reason that the product development process is information-intensive. Rather than having the necessary information readily available, it is unknown and therefore requires time to be generated, retrieved and evaluated. Often the
information that must be found is dispersed. Thus, the absence of information requires requisite efforts in these areas.

As soon as the missing information begins to appear, it is a challenge to manage it all. Much of development information tends to be dynamic and lose its relevance quickly. It is this type of information that gets used to make the hundreds of thousands of decisions which advance the product. However, some amount of fundamental information must be absorbed and maintained in order to bring resolution to the design. In this case, a high level of retention and recall are important over the lifetime of the project.

1.2.2 Complex Design Problems

There are many dimensions of complexity in product development. The scale and scope of development efforts both contribute to the degree of complexity. The scale of a development project has to do with the number of people and the production volume. Project scope has to do with the number of parts in the product, the level of customization, and the application of new technologies.

The large quantities of information associated with product development provide one dimension of complexity. Large production volumes and customization require a great deal of correct and coordinated information. As well, complex products require the generation and maintenance of a lot of detailed information. If a product is composed of

<table>
<thead>
<tr>
<th></th>
<th>Rollerblade</th>
<th>HP Deskjet 500</th>
<th>Chrysler Concorde</th>
<th>Boeing 777</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Production Volume</td>
<td>100,000 units/year</td>
<td>1.5 million units/year</td>
<td>250,000 units/year</td>
<td>50 units/year</td>
</tr>
<tr>
<td>Sales Lifetime</td>
<td>3 years</td>
<td>3 years</td>
<td>6 years</td>
<td>30 years</td>
</tr>
<tr>
<td>Sales Price</td>
<td>$200</td>
<td>$365</td>
<td>$19,000</td>
<td>$130 million</td>
</tr>
<tr>
<td>Number of Unique Parts</td>
<td>35 parts</td>
<td>200 parts</td>
<td>10,000 parts</td>
<td>130,000 parts</td>
</tr>
<tr>
<td>Development Time</td>
<td>2 years</td>
<td>1.5 years</td>
<td>3.5 years</td>
<td>4.5 years</td>
</tr>
<tr>
<td>Internal Development Team (peak size)</td>
<td>5 people</td>
<td>100 people</td>
<td>850 people</td>
<td>6,800 people</td>
</tr>
<tr>
<td>External Development Team (peak size)</td>
<td>10 people</td>
<td>100 people</td>
<td>1,400 people</td>
<td>10,000 people</td>
</tr>
<tr>
<td>Development Cost</td>
<td>$750,000</td>
<td>$50 million</td>
<td>$1 billion</td>
<td>$3 billion</td>
</tr>
<tr>
<td>Production Cost</td>
<td>$1 million</td>
<td>$25 million</td>
<td>$600 million</td>
<td>$3 billion</td>
</tr>
</tbody>
</table>

Table 1-1 Attributes of four products and the corresponding development efforts. All numbers are approximate and based on publicly available information and company sources. From Ulrich and Eppinger, Product Design and Development, McGraw Hill, Inc., 1995.
thousands of parts, there will be multiple thousands of specifications and drawings associated with those parts. For example, a Ford automobile is composed of approximately 2500-3000 significant parts (when the engine counts as one part) and there is at least one design drawing per part and about twelve more drawings for manufacturing and tooling. This brings the total number of drawings up to around 40,000 (Shank, 98). The amount of information increases rapidly with the scale of the project. “Digitally defining the Boeing 777 required four terabytes of storage memory” (Gillette, 98). Table 1-1 lists several quantities of attributes of development projects of various scales. For comparison to one of the partner company products, a Xerox large production copier has an annual production of 7900 units, a sales lifetime of about 4½ years, and a price of $63,000. The copier contains 1500 unique parts and took 3 years and $60 million to develop. The development team included 120 engineers and technicians, 20 procurement people, and 15 manufacturing engineers (Elter, 98).

Product development may also involve the application of new technologies and new processes. Unfamiliar territories add another dimension of complexity, because there are many more uncertain variables to be determined in the design.

1.2.3 Coordination and Timing among Many People

Product development involves a coordinated effort among many people in many places, within an organization and across organizations. Many of the critical decisions require the multi-disciplinary expertise of a group of people. The goal is to get the right information to the right place at the right time. “It is like conducting a huge orchestra; everyone must join in at the right time” (Matulka, 98). The tangled image in Figure 1-1 shows the complexity in conducting cross-functional communication.

![Cross-functional communication tangle](image)

Figure 1-1 Cross-functional communication tangle. From McGrath, Setting the Pace in Product Development, Butterworth-Heinemann, 1996.
This organizational feat becomes more challenging as the number of people working on the product increases, because the number of communication paths increases geometrically with the number of people. The number of person to person communication paths increases according to \(N \times (N-1)\). \(N\) people can communicate with \(N-1\) others, everyone else but themselves. With a group of sixty, the number of paths is equal to \(60 \times 59 = 3,540\). This is shown graphically in the Figure 1-2. Now consider that approximately seventeen thousand individuals contributed to the development of the Boeing 777 during a four and one-half year time frame (Ulrich and Eppinger, 95). Even though this is an extreme example, the coordination and timing issues are still significant in smaller scale development efforts.

![Graph showing the number of communication paths versus the number of people.](image)

Figure 1-2 Number of communication paths versus number of people. From McGrath, Setting the Pace in Product Development, Butterworth-Heinemann, 1996.

### 1.2.4 Competitive Environment

Product developers are facing increasingly rigorous constraints. Customers have become more sophisticated in their demands, product development cycle times are shorter, and competition remains fierce. Information transactions are likewise subject to these constraints. In this high-pressure environment things change rapidly and it is difficult to absorb all of the information. However, some information is critical and must be maintained. For example, customer requirement statements must be used to derive a set of specifications. Then the specifications should be kept in the forefront and used to ensure quality at all stages of development. When there was more slack in the time frame, information would eventually get around to everyone, by word of mouth or otherwise. Now that the slack is being taken up, the information bottlenecks need to be eliminated. Key steps in the information critical path will need to be made explicit to ensure an information-rich design.
1.2.5 Product Development in the Information Age

In the 80’s the industrial focus was on lean manufacturing processes. There were serious efforts aimed at reducing inventory and optimizing throughput. By the 90’s the focus had shifted. Although manufacturing is still an important issue, product development was said to be the “new competitive battleground.” Customers had become more sophisticated in their demands. Companies were realizing that large percentages of their sales came from their newest lines of products and that being the first to market provided a real competitive advantage. At the same time, real advances had been made in applying information technologies. Initially the technology had been used primarily to replace the old procedures. Instead of entering financial information on paper, it was entered into a spreadsheet. Likewise, libraries of blueprints were no longer archived in storage rooms with filing cabinets. Instead there were databases of CAD drawings. In addition, the initial CAD systems were not geometrically smart. The positions of the line segments were known, but scaling and volumetric information was not known (Shank, 98). In essence, the power of the technology was not being used to expand the capabilities of previous methods and tools, it was just being used to replace them. Since then these tools have been greatly advanced and corporations are now interested in finding ways to exploit the technologies. The current terminology is “Knowledge Management”.

1.3 Information Underlies Design

1.3.1 Theoretical Background

This research is based on the theory that information provides a scaffold for the design throughout the design process. Early on, design was recognized to be an information-based effort, which extended beyond the limited capability of the individual. “His chances of success are small because the number of factors which must fall simultaneously into place is so enormous” (Alexander, 64). Information can be used to extend the creative capacity of the individual.

The next several sections follow from the design process and describe its information foundations. Here I am using the word design to include a range of creative, inventive activities within the product development process. The design phase consists of both system-level and detailed design. The design work generally takes place after a concept has been selected and leads up to a testing and refinement phase and later to production ramp-up.

1.3.2 Defining the Requirements

The first step in the design process requires definition of a vague set of requirements. Defining a problem is a large part of solving the problem. Therefore, the problem boundary must be clarified. Similarly, in product development, the customer requirements must be assessed. In some cases the boundary of the problem is not fixed. For example if the problem is presented as the need for a new kettle design, then the designer already knows the general form of the solution. Instead, if the fundamental
requirement is to find a method for heating water, then the problem boundary has changed. In this case, a possible design would be a hot water tap (Alexander, 64).

1.3.3 The Ideal Design

One metaphor for an optimal design involves choosing an arrangement of iron filings which will be subjected to a magnetic field. If the design is optimal, the alignment pattern will not change when the force field is turned on. In our case, the product is the arrangement of the filings and the customer provides the magnetic field. It is not realistic to assume that the fundamental requirements can be defined with mathematical accuracy as in the case of the magnetic field. However, it is the job of the designer to decipher the boundary of the problem which is being addressed, or to assess the needs of the customer. This can be a difficult process when the problem is vague. And, in a complex design problem there is a “potentially infinite set of requirements” (Alexander, 64). In spite of this challenging task, if the product developer is a good designer, “the form he invents will penetrate the problem so deeply that it not only solves it but illuminates it” (Alexander, 64). The goal of the designer is similar to that of adaptive organism in a selective environment. “Given a desired state of affairs and an existing state of affairs, the task of an adaptive organism is to find the difference between these two states and then to find the correlating process that will erase the difference” (Simon, 69). In product development, the goal is to meet the customers’ needs.

In the magnetic field example, the design can be evaluated based on changes in the alignment of the filings. Similarly, the goodness of fit in product designs can be easily determined; when something goes wrong, the customer will generally notice. “Cognitively we experience the sensation of fit by recognizing where things don’t fit” (Simon, 69). In the product development case, it is important that customers not have to experience the lack of fit, because they may not recommend the product to others and they probably would not purchase the product again.

1.3.4 Design is a Search

“The theory of design is that general theory of search” (Simon, 69). With so many undetermined variables, the design process must sift through many possible outcomes. In a complex and novel design problem, a great deal of trial and error is likely to be required. “At the same time, the trial and error is not completely random or blind: it is, in fact, rather highly selective. The new expressions that are obtained by transforming given ones are examined to see whether they represent progress toward the goal. Indications of progress spur further search in the same direction. Lack of progress signals abandonment of a line of search. Problem solving requires selective trial and error” (Simon, 69). Therefore it is useful to keep track of partial information about the paths which are being searched.

1.4 Roadmap
With the theoretical background in mind, the next section, Chapter 2, of the thesis will discuss the customer research and definition of the "problem boundary." Following this, the State of the Art industry methods and tools will be discussed. By understanding how the current practices are addressing various parts of the larger problem, it will become clearer where there are opportunities for improvement. In Chapter 4, the results of the voice of the customer interviews will be presented in a framework. This framework will be used to clarify and articulate industry needs related to information and knowledge management. In Chapter 5, the research projects in the Information Based Development research thrust will be mapped into the framework. Then, in Chapter 6, the framework is used to identify gaps between industry practices, current research and industry needs. Particular gaps are identified which offer the greatest opportunities for improving of the information-based product development process.

2. Voice of the Customer Research

2.1 Voice of the Customer

The purpose of this Voice of the Customer evaluation is to ensure that the research strategy for the Information-Based Development thrust of the Center for Innovation in Product Development is addressing the needs its industry partners as they are the Center’s customers. The industry partners include Xerox, ITT, Ford, General Motors, and Polaroid. In addition, Boeing has participated in research with the Center. Interviews were conducted at each of the companies.

In this VOC research, CIPD is striving to make sure that all of the customers’ needs are met. The customers are a diverse set of companies offering a variety of products. ITT’s Defense and Electronics division produces night vision goggles for military use whereas Xerox produces color copiers. While the products may differ, the development process methods and tools are similar. The role of information, in particular, underlies all development processes.

As well, there may be many customers within the partner companies. That is the buyers of the technology may be different from the users. For instance, the active participants from industry have taken an interest in CIPD’s research. At some point they will communicate the new methods and tools to the development teams at their respective companies who will be implementing them. All of these groups, the active participants and the members of the development teams (designers, engineers, marketing staff, and financial analysts), need to be satisfied with the results of Thrust II’s research.

2.1.1 Scope of the Research

The primary focus of this research was in identifying the information-intensive areas of the product development process and assessing which were the most challenging. It was also important to get a sense of the quantities of information involved. For the final evaluation of Thrust II’s research, it was necessary to know where there were gaps
between what was being done in industry and what was already being addressed by the research. Industry interviews included questions about the state of the art methods and tools. All of the Thrust II professors and most of the students were also interviewed to find out which customer requirements their projects addressed.

2.1.2 Gathering Customer Data

This could be done in a number of ways. Interviews, focus groups, and observation of product use are all valid methods. For our purposes, interviews made the most sense. Twenty-six interviews were conducted at six companies (Xerox, ITT, Ford, GM, Polaroid and Boeing). As well, efforts were made to ensure that all of the important types of customers were interviewed. The interviewees worked in a variety of areas including product design, manufacturing, warranty claims, supply management, problem management, general management, and IT. Everyone’s opinions on this matter were valuable. One secretary had a great deal to tell me about the company’s internal communication mechanisms.

Many of the people interviewed were lead users of information methods, tools and technologies. These interviewees were responsible for the selection, implementation, or upkeep of the systems in one way or another. And, for that reason, they were able to identify problems which they saw as well as point out a few problems that other users had complained about. In the extreme cases, they would point to reasons why whole segments of the company population were not using the current method or tool. Several people were either directly or indirectly working in the areas of improving the PD process and information management. A complete list of the interviewees can be found following the Bibliography and Sources at the end of the thesis.

Because information is an intangible issue, many interviewees had not previously thought about opportunities for improvement. Interviews were often biased by the status quo. It is easier to complain about what is wrong than to envision entirely new systems which would meet needs where the more difficult approach been taken for granted. Therefore, it was necessary to try to evoke responses they would not have otherwise articulated. These unarticulated needs, or latent needs, would be recognized later on by customers using a product which met and exceeded their expectations. The interviews included a common set of initial questions, but they each followed a different route depending on the person’s responses and area of expertise. Many creative ideas came out of this that may not have otherwise. Perhaps a few latent needs were identified from continued questioning in an area that the interviewee had not previously considered.

2.1.3 Interview Technique

The questions were open-ended so that the interviewee was encouraged to expand more on each issue. Initial questions were fairly general and followed up with specific, concrete questions which related to the interviewee’s experiences. Questions were sequenced from general to specific in an attempt to conduct the interviews in a non-biased format (Kidder and Judd, 86). Prior to the interview, the background and purpose
of the research were described. The following questions provided a framework for each interview.

**Interview Questions**

**Quantity of Information**

- How many people are working on the product?
- Is there more than one location?
- How many parts, suppliers, specifications, and drawings are there?

**State of Art**

- What is being done at your company in the area of information and product development?
- How does information about the product and process get communicated?
- What works and doesn’t work?

**Information Needs**

- Where do you see information-related problems or inefficiencies?
- How do they impact product quality and time to market?
- Which are the most critical?

**2.2 Data Analysis**

**2.2.1 Organization of Data**

In traditional customer needs assessments, the responses are organized into a hierarchy. “The primary needs are the most general needs, while the secondary and tertiary needs express needs in more detail.” (Ulrich and Eppinger, 95) Because most of the responses in this area described what the problems were and not which were the most severe, I looked at a framework for breaking down the problems categorically rather than heuristically.

**2.2.2 The KJ Method**

In organizing all of the interview data, a technique called the KJ method was used. This is the first step in organizing customer requirements as outlined in *A New American Total Quality Management* (Shiba, Graham, and Walden, 93). In this process, individual’s quotes were grouped by category in an affinity diagram or tree structure. Where a customer statement applied to more than one category, the comment was duplicated so that information would not be lost. Structuring the problem in this way provided a mechanism for discovering relations between the requirements. This structure was also useful in making the gaps visible. The largest groupings were fairly general categories
which later provided a framework for evaluating the research strategy of the Information-Based Development Thrust. This framework was shown to customers several times as a way of clarifying and communicating a vague set of needs and as guideline for checking that any customer needs had not been missed.

2.2.3 Next Steps

In order to reap the benefits of this customer analysis, it is necessary to communicate the findings to the CIPD “product designers.” The next steps in this process include evaluating the relative importance of the needs and sharing the important findings with people in CIPD and in industry who need to understand the customer needs which relate to their area of work. Those customers which would be good participants in our ongoing development efforts will also be identified for follow up work on this topic.

3. The State of the Art

3.1 Product Development as a Process

3.1.1 The Process Viewpoint

Product development has recently begun to be viewed as a process and, like other processes, this one has a structured approach. The phases in product development include the following: concept development, planning, design, test and evaluation, production ramp-up, and product release. These phases often overlap to some degree and efforts are coordinated to make the process run smoothly. This view of a continuous process differs from that of a set of discrete tasks. It more accurately represents the necessary completion of certain events and the advancement of underlying knowledge that corresponds with those events. As the design gets better defined, the current state of information becomes more certain and complete. By viewing this as a process, comparisons can be made to manufacturing systems or a factory. “The goal of the information factory should be to accelerate throughput while minimizing waste” (Tilove, 98).

3.1.2 Managing the Information Factory

While almost all companies recognize that improving product development offers a competitive advantage, not very many recognize the important role that information plays in this. The “Knowledge Management” trend is only beginning to gain speed. Actually, most companies are partially working on this already, usually in the area of Information Technology (IT). Some larger companies are devoting part of their workforce entirely to the issue. But only a few, are looking more broadly at the greater scope of the problem and investigating related issues like organizational structure, geographic locations of projects, and information sharing. It is important to note that the information mechanisms within an organization are more than just the company’s computer system.
They include any structured approach that facilitates information access, exchange, or use.

Companies each have their own name for the knowledge management effort. Sometimes it is referred to as Product Data Management and other times it falls into the IT category. For example, at GM it is called “Math-based” development, because of the roots in computer-aided design and engineering. However, this name understates the full effort since the technology is rapidly expanding beyond the geometry focused CAD and CAE technologies. "A framework is emerging for managing all data associated with a product throughout its life cycle" (Deitz, 97). By using the technology to integrate all of the types of information which are generated, the process can be made more efficient. When referring to the new technical capabilities, Dan Deitz said in an article of Mechanical Engineering that “This is about automating individual tasks to form a process.”

The state of the art practices in knowledge management include a variety of methods and tools. And, in many instances, the best practice involves cases where the methods and tools are well matched with technologies which automate the methods and tools. In the manufacturing analogy, the methods and tools outline the series of tasks that must be performed, while the people and technologies are the machinery which perform the tasks. These topics will be discussed in the following sections, beginning with the state of the art development methods and tools.

3.2 Industry Methods and Tools

3.2.1 Methods Provide Structure for the Information

Methodologies are valuable, because they provide a structure for keeping track of information in the product development process. The approach may outline certain steps by which unknown information about the product may be found, organized, or evaluated. Methods also act as check-lists which ensure that the required information is complete. For example, a list of specifications provides a check that the product meets the customer’s needs, regulatory standards, and any other objectives. The following techniques are common in the literature and used fairly frequently in industry. The planning and managing procedures are aimed at more reliably predicting project completion dates. The guidelines for identifying customer needs and up to those for reflecting on the process are all aimed at achieving very high quality, informed product designs.

3.2.2 Planning and Managing

Planning involves defining the tasks, scheduling, budgeting, and determining staffing requirements. Managing involves the continuous maintenance and upkeep of all of these things. Since the information related to these issues provides a direction for the development team, it is important that the information mechanisms be effective in terms of asking the right questions up front and providing a common understanding within the development team. A few of the methods that are used in planning and managing include
Gantt and PERT charts, task lists, NPV analysis, and risk analysis. Detailed Gantt charts are often posted in meeting rooms as a visual way to make team members aware of the project status and upcoming deadlines.

In the beginning of the planning phase task lists are generated. These provide necessary information about the scope of the project and the deliverables of the team. Knowing the extent of the effort is a prerequisite for appropriately scheduling and staffing the development team. It is important to make the schedule credible. “Early schedules are only 45% accurate,” and for this reason “no one believes in them” (McGrath, 96). One way of improving the accuracy of scheduling is to use information about past development cycle times of similar products. The planning stage is also a good time to solicit ideas for accelerating the development process.

3.2.3 Customer Needs and Product Specifications

Customer data are gathered in a similar manner as that which was described in Chapter 2. Companies conduct interviews and focus group sessions with their customers. This process occurs during the concept development phase as well as in the detailed design phase. During the styling design, for example, Ford uses electronic renderings as well as models to get input from potential customers. In addition, many companies ask customers to participate as beta testers of their products. In this case, prototypes or products from the early production batches are usually given to customers in exchange for high quality feedback. At Hewlett-Packard, customers who beta test printers are asked to fill out a system set-up survey, report any malfunctioning of the system, and occasionally submit print samples.

Once customer data have been obtained, they are interpreted and organized into useful formats. Interpreting the data involves scrubbing, or stripping away the extraneous information, to establish the underlying need. Customer needs lists are created and then used to determine product specifications. This requires knowing more about the variables of the product that will affect the need. For example, there may be several specifications related to a customer need for safety.

In addition to establishing product specifications, the interviewing process can be used to determine a customer’s utility function, or valuation, of a particular attribute of the product. This method is used to determine the relative importance the customer places on various attributes of the product. Utility assessments, along with competitor benchmarks, provide a mechanism for evaluating tradeoffs among design parameters. Ford uses a technique called “Value Analysis” in which functions of the vehicle are assigned comparative ‘value’ numbers. Ford vehicle X may have a particular attribute (like safety) value of 6.7 whereas competitor Y’s value may be 4.3 and competitor Z’s may be 8.1. If this is the case, the development team would look more closely at how competitor Z is able to provide more customer value (Roggenkamp, 98).
3.2.4 Ensuring an Informed Design

Ensuring an informed design may be one of the toughest jobs for people working on knowledge management. “In developing a complex product, there may be 10 million decisions.” Most of these can be handled by an individual if he has access to “handbooks, computerized records, and other repositories of experience.” However, “the most critical decisions (1000 to 10,000 for a large, complex product),” generally “do not lie entirely within the experience of any individual.” These require the “collective experience” of a group of individuals (Clausing, 94). With this in mind it is discouraging to find out that in most companies “less than 5% of the information available to decision makers is actually used” (Boyd, 94). The following examples of information mechanisms exist in part to force designers to gather the data necessary to make informed decisions.

Quality Function Deployment

A whole set of “informed design” methodologies falls under the category of Quality Function Deployment. The goal of QFD is to maintain a customer focus throughout the development process, from the customer to the factory floor. One type of structured framework that is used to maintain organized customer data is the House of Quality. In this framework, the relationships between the customer’s needs and the design parameters are shown graphically. Where there is a strong dependence between the parameter and the need, stronger markers are used to represent this. An underlying tenet of QFD involves the use of “visual, connected” information mechanisms. Posting a large-scale printout of the House of Quality on the wall of a meeting room would be an illustration of this. In doing this, the relevant information is easily accessible and provides a centerpiece for discussion. Concurrent engineering efforts are improved by using clear, visually connected materials, because they help develop a common understanding about the goals and decisions of the group (Clausing, 94).

In addition to QFD, there is Enhanced Quality Function Deployment, or EQFD. This approach differs from QFD in that it includes additional techniques which are better suited for the design of “conceptually dynamic products.” These are products where the system-level concept must be selected before the subsystem parts can be designed. In the water heating example, the system-level concept was either a kettle or a hot water tap. This had to be decided before subsystems, like the handle of the kettle, could be designed. Pugh concept selection is an EQFD technique which addresses this issue. In Pugh selection, several concepts are compared against a reference datum and the criteria for comparison is based on the customers’ needs (Clausing, 94). Hewlett-Packard used this approach in the redesign of a tubing assembly for a refillable ink system in an inkjet printer. Another focus of EQFD is on robust design and Taguchi methods for quality design. Both ITT and Xerox’s development efforts include robust design. ITT even has an annual symposium to promote the use of Taguchi methods in the design and optimization of its products.
Concurrent Engineering and Design for X

Development teams are increasingly aware of the benefits of including non-engineering functions earlier in the process. As a result, teams will invite manufacturers and suppliers to participate in the relevant decision making processes early in the process. Often the development team is cross-functional in its membership. Concurrent engineering aids in the "Design for X," or DFX. This push is aimed at making designers aware of multiple constraints on the design. For example, design for manufacturing (DFM), design for assembly (DFA), and design for recyclability all impose limitations on the design space. Incorporating these ideas early in the design process saves a lot in terms of rework and fire-fighting later on.

Critical Parameters

Critical Parameters offer a methodology for capturing and prioritizing information about the key functional elements in the product. Since this idea was used at Xerox, consider the following example of a critical parameter to be the torque on one of the motors in a new copier. At one point there were 28 problems which related to this one critical parameter. There was little understanding about how the problems were related to one another, and when one engineer would work to improve a problem, they found that another problem would be worsened. Without the CP, the common dependency of the problems on the motor torque would not have been as easily recognized (Fall, 97).

Prototyping

Prototyping is a valuable mechanism for testing the technical feasibility or visual styling (or a combination of both) of the design. They can be used at many points in the design process and concentrate on only one part of the design or on the integration of all of the parts in the design. Prototypes generate useful information because they aid in detecting unanticipated issues. Prototypes also facilitate meaningful discussion about the design. In recent years, companies have relied less on the building of physical prototypes and more on analytical methods. But there are still certain tests which require physical prototypes. In the automotive industry, ride and handling, durability, thermal, squeak and rattle, and vibration are tests which require physical models. Rapid prototyping technologies are improving the ability to speed up the time required to build physical prototypes. GM uses a rapid prototyping based on a material depositing technique. They said that it was becoming as easy to build models as it was to hit ‘print’ when you finish word processing a document (Richter, 98).

3.2.5 Testing and Evaluation

Testing and evaluation occur at many stages throughout the development process. Initially, design ideas are tested to assess their technical feasibility. Later on, products from the initial manufacturing production runs go through a series of qualification tests like shipping and handling, extreme temperature, and even drop tests. The results of these experiments are communicated back to the development team. Important findings
are compared with the specifications and used to make decisions about the design. These numbers also help managers in gauging the development status. At Xerox, copying test results were posted in one of the main hallways where people would see them.

Issues tracking and problem management were two additional efforts at Xerox. Shortcomings in different aspects of the product were added to a list of problems in a database along with the name of the person who was responsible for the issue and a timeframe for solving the problem. If the issue had not been resolved within the timeframe, the person responsible would be notified by email.

3.2.6 Reflecting on the Process

At the end of the development process, companies are finding it worthwhile to reflect on the project and to record the “lessons learned.” By spending some time documenting what was learned, companies can leverage what they know to improve or speed up future development efforts. Large savings can be achieved, especially when future products are variations of the same platform. ITT has worked to capture the “Best Practices” throughout its organization and to make these widely available across its business units. In other companies, such as Ford, the lessons from the current design are recorded in “design guides” or as lists of design rules which can be used by future developers.

3.3 Industry Technologies

3.3.1 Electronic Transfer of Data

Electronic transfer of data has become a favored practice in industry, and a variety of technologies are used by product developers. These can be divided into two groups: synchronous and asynchronous (Sosa, 98). Synchronous refers to modes that allow for direct interaction among people. They take the place of face to face meetings and conversations. Typically, these technologies are higher bandwidth, real-time communication mechanisms. This category includes audio, video, and CAD conferencing. Telephone conversations, application sharing, and on-line chat media also fall into this group. In the asynchronous data transfer modes, there is a disjoint between the time of transfer and the time of response. The asynchronous modes include voice mail, email, regular mail, pagers, faxes, centralized databases, and internet/intranet based tools. All of these tools are used in industry. The degree to which each particular technology is used depends on the application and on the customs of the organization. Often, human interaction is required as a precursor or follow-up measure to electronic sharing of information.

3.3.2 CAD, CAM, CAE

Analytical tools such as Computer Aided Design, Manufacturing, and Engineering have been used in development efforts for many years. The extent to which they have replaced physical testing and prototyping has increased recently as the technologies have provided more in depth capabilities. Solid modelers can tell you more than just about the geometry
of the part in a drawing. Finite element analysis can be used to analyze the stress distribution of a part under a variety of loading conditions. The airflow around a part and the temperature change resulting from use of the part may also be simulated. And, these simulations may be done on the order of days or hours instead of taking weeks with physical models. At the same time, these tools decrease prototyping expenditures in companies. “In the last few years, prototyping costs have been cut by 35-40%” (Blumberg, 98).

Analytical tools are not only saving companies time and money from decreasing the number of tests and prototypes, they are also providing mechanisms for developing very high quality products. One of the stories at Ford was about a car accident in which two Ford cars hit head on at an impact speed of 150 mph (both drivers were going 75 mph). It turned out that drivers suffered only minor injuries. Pictures of the Ford automobiles showed that the wheels had been pushed back almost to the front of the front doors. Crash simulations had allowed them to predict this type of damage more accurately than ever before and under a greater number scenarios than previously would have been feasible (Shank, Roggenkamp, 98).

However, there are still some limitations with the use of these tools. One of the greatest is the issue of compatibility of the software programs. There may be several types of CAD programs within a company let alone the number of different programs used by suppliers. At one point as many as seventeen different CAD systems were being used at GM throughout the company. Now there are only two systems, but there are still compatibility issues (Pickett, 98). One of the problems is that each system is specialized for a particular function. Ideally, the surface drawings for an automobile could be done with one program and the technical part drawings could be done with another, and they could both be integrated in the end.

Visualization of Geometry

Several companies are making large investments in the visualization of the digital drawings. One of the partner companies was in the process of building a conference room with a large screen and a system for projecting maneuverable images of design drawings. Another partner company had invested $2 million in a Silicon Graphics CAVE system. The CAVE was basically a small room with computer screens projected onto three of the walls. A tracking system monitored the movements of a bat (instead of mouse) which the person would use to select menus and so on. In the automotive companies, three-dimensional virtual vehicles are occasionally used to get customer feedback. The customer can turn it, walk around it etc.

Decision Support

Technologies are increasingly providing the capability for manipulating and evaluating many alternative design concepts. They offer decision support because they are capable of not only telling you when there is a problem, but how it relates to other aspects of the design and how it can be improved. At Ford, all of the part drawings are digitally
assembled to create what is referred to as the “digital buck.” Then this can be used to do simulations of driving over bumps, for example. The tool will highlight areas where parts are too close and will bump into each other under rough driving conditions. Design advisors are another tool which offers decision support. These software programs provide high-level assistance in specific design problems. The design advisor could include manufacturing rules which relate to the particular design. An opposite approach are optimization programs which come up with designs based on the constraints and inputs of the problem. Another area which aids in decision making includes collaborative technologies. This type of software supports network-centered product development in which many people can work (digitally) on a project at one time. When one engineer makes a change related to her part of the project, the software will automatically update any other affected parts.

3.3.3 Beyond geometry, Integration and Enterprise data

The product data management effort is expanding to include more than just the traditional CAD, CAM, and CAE information. The goal is to manage all of the data related to products and to address complex organizational problems. Traditionally, dispersed databases have been set up as repositories for certain types of information, like a parts categorization or warranty records. In some cases efforts are being made to link these

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Figure 3-1 Ford NAAO Product Information Flow diagram. (Based on a schematic from Ford Systems for Product Information Flow 1992, courtesy of Ford.)
databases and offer a middle area for data access. A schematic of Ford’s North American Automotive Operations (NAAO) product information flow is shown in Figure 3-1. This is a system of ten databases, most of which are used in the later part of the development process and into production for the management of customer orders, procurement, and inventory.

New tools like the Web, Java, and object-oriented programming are offering solutions to the data-incompatibility problem which had previously hindered this integration effort. The Web makes it possible to access information from many dispersed areas and is not restricted by the size and complexity of the information. The next section will discuss this in more detail. Java offers a platform independent way of accessing information through the intranet. Lastly, object oriented programming “simplifies the process of creating a unified computer network” (Deitz, 97). As data-compatibility improves, companies will be better able to incorporate information about the product and the process.

3.3.4 Company Intranets

Almost all companies are using intranets to communicate data between team members and across functions and business units. This common repository of information serves as a communication hub and great efforts are being made to make useful information available. In one development project at Ford, two-thirds of the people were in the working in the U.S. while one-third were in Europe. The group was able to share test results daily by posting them on a company web site. Additionally, a lot of forethought is being put into making the web sites easily understandable with consistent templates and automatic links back to the top of a web page. Maintaining the information is almost as important as providing the information in the first place, and companies are setting up systems in which information sites are registered and people are alerted to keep the site up to date. The goal in many companies is to make the intranet a part of people’s daily work.

Types of Information on Company Web Sites

As well as information relevant to development projects, company web sites often contain administrative, company-relevant information, educational materials, and mechanisms for external feedback such as from customers and suppliers. Administrative information includes org charts, employee contact information, benefits information, forms and process sheets, etc. Educational manuals and training material are also often put on the web where employees can refer to it on their own schedules and at their own pace.

A significant amount of information on company web sites is specific to particular development efforts. The types of references available to developers can include up to date financial and market predictions, best practices, design rules, manufacturing guidelines, past performance of processes and tools, parts catalogs, specifications, customer requirements, regulations and standards, engineering calculation tools, patents,
materials specs, part weights, costs, and test procedures. At Ford a survey was given to employees to find out what types of information they needed in order to do their jobs. The results of this survey were used to determine a limited number of categories of information on their web site. A subset of these categories (the top ten items) include the following:

- Vehicle Design Specifications
- System Level Design Specifications
- Attribute Value Analysis
- Competitive Performance Benchmarking
- Investment Benchmarking
- Design Guidelines
- Best Practices and Lessons Learned
- Design Verification of Product Specifications – Completed Reports
- Failure Mode and Effects Analysis – Completed Reports
- Quality Function Deployment – Completed Reports

3.4 Non-Technical Issues

3.4.1 Best Communication Practices

Companies which are successful at developing high quality products and achieving rapid development cycles have some characteristics in common. They tend to encourage communication “between functions, between suppliers and buyers, between product developers and customers, and between their own company and other companies” (PDM Roundtable, 97). There is also a high degree of integration in the product development efforts in these companies. Non-engineering functions are included early in the process and participate in making decisions. Development teams are co-located and managers are given enough authority to do their jobs. Employees are knowledgeable and fully utilize the information tools and technologies available to them.

The importance of encouraging communication can not be overemphasized. A lack of cross-functional communication leads to choppy efforts in which responsibility for the product is continuously being “thrown over the wall” from one functional group to the next. About 40% of hand-offs like these are “garbled or confused,” and “42% of the work had to be repeated because of an upstream change such as late customer input, specifications in error, or something being overlooked.” This means that “two out of every five working days were wasted” and that development productivity would increase 72% if repeat rework could be avoided (McGrath, 96). Since communication plays such a large role in this issue, it is worthwhile to consider approaches to bridge the cross-functional communication gaps.

One way of encouraging communication is to locate people who are working on related projects nearby one other. A study conducted by Thomas J. Allen, showed that the frequency of technical communication depends on the separation distance between people in the development team. Figure 3-2 shows probability of communication versus
separation distance. Communication frequency drops off rapidly when people are located more than two or three meters away from each other. In addition, team members should be introduced to each other early on in the development process; people who know each other or have met are much more likely to communicate later on.

![Graph showing probability of communication versus separation distance.](image)

Figure 3-2 Probability of communication versus separation distance. From Allen, Managing the Flow of Technology, MIT Press, 1977.

### 3.4.2 Organizational Structure

Organizational structure has a strong influence on the ease of the product development. In functionally aligned organizations, it is more difficult to coordinate joint efforts among people. Each function works on more than one product at a time. There are many handoffs and no one is directly responsible. The tradeoff is that the organization is able to maintain and draw upon expertise in each of the functions. At the other extreme are organizations where teams of people (with a variety of expertise) are devoted specifically to the development of a particular product. In this case, communication and coordination effort and the time to market are all minimized as shown in the Figure 3-3. Matrixed organizations offer a compromise between focused teams and functionally-aligned organizations. In a matrixed organization, employees are organized by project and by function. They often report to a manager of their project and also to a supervisor in their functional area. Matrixed organizations and focused development teams both support concurrent engineering, but focused teams provide the best structure for communication, coordination, and decision making. Also shown in the graph are Core teams and autonomous teams. Core teams are a specific type of team with about ten members (including people in engineering, manufacturing, marketing and customer service) who are dedicated solely to the project (McGrath, 96). Autonomous teams are entrepreneurial in nature and are also specifically devoted to a project.
GM has Vehicle Line Executive teams which consist of about twenty-five members from many functions. A unique practice is that VLE team leaders are requested to stay for two or three cycles (once as an assistant and twice as a leader) of vehicle designs. Having the same person in charge for more than one development cycle provides consistency and leverages past experience in the development process.


4.1 Initial Frameworks Considered

4.1.1 Interview Quotes and Interpretation

Interviewees were asked the following questions: Where do you see information-related problems or inefficiencies? How do they impact product quality and time to market? Examples of responses include the following:

“'We are mass-producing customization.”' -Paul Shank, Ford

“Sometimes you need to act without information.” -Lou Fantozzi, Xerox

“During a four-year development cycle, there are many changes in the market and in company organization.” -Dianne Bommarito, GM

The first quote emphasizes the information quantities and complexities in product development. Coordinating and timing of correct information is critical in managing the
customization of large volumes of production. The second response suggests that there is something wrong with the information infrastructure in the organization. The information may be unavailable or not be easily accessible or people may be unaware that the information exists. Perhaps the information does not get transferred to the people who need it. There may also just be too much information to deal with in a timely manner. The third statement stresses the dynamic environment for which the information systems need to be robust. Since both the design assumptions and the organization are continuously changing, the information mechanisms need to be consistent so that important information can be maintained and updated throughout the development cycle.

Interview responses were organized into categories according to the KJ method. The broadest categories were used to develop a framework for evaluating the needs of the industry partners. Initially, an information life cycle framework was considered. The steps in this cycle included generation, collection, transformation, communication, utilization, and archival of information. Another consideration was the “Corporate Communication Cycle” which followed the flow of information from the customer, to the market researcher, product planner, design engineer, manufacturing engineer, production worker, and finally to distribution (Clausing, 94). However, a different categorization of the information needs fell out of the categorization of interviewee responses. This information-based development framework will be discussed in section 4.2. But, one other initial framework which provides insight into this topic is the information maturity framework.

4.1.2 Information Maturity Framework

A common complaint is that there’s a lot of data, but not much information. In the diagram below, the reasoning behind the lack of information becomes clearer.

![Information Maturity Framework Diagram]

-Ken Kuna, Ford

Figure 4-1 Information Maturity Framework.

The top series of nouns step through the progression of stages in moving from an occurrence to results. The bottom series of verbs denote the actions which must occur in order to advance through the stages. For data to be produced, there must be an observation. Then, the data must be analyzed, or manipulated into a meaningful form like a percentage, to provide information. This percentage, for example, can be related or compared with other known results in order to provide knowledge. And, once the
product developer is convinced that this new knowledge is correct, he will apply it. So, if there is a lot of data, but not information, then the bottleneck is in analyzing data.

4.2 Information-Based Development Framework

Accessing, capturing, transferring, and retaining information are all common tasks necessary for using information. The Information-Based Development, or IBD, framework below shows these common tasks surrounding an information infrastructure.

![IBD Framework](image)

Figure 4-2 IBD Framework.

In this scenario, information can be accessed and then transferred, transferred and then retained, or accessed and used directly etc. The efficiency with which these tasks can be carried out depends on the particular information infrastructure that a company has. The framework categories are further described in the following list of definitions.

- **Access** - to find and retrieve information which has already been captured.
- **Capture** - the representation of an observation.
- **Transfer** – to share or communicate information
- **Preserve** – the maintenance, archival, or learning of information for future use.
- **Use** - to analyze, relate, accept, or apply information.
- **Infrastructure** – the formal and informal methods, tools, and technologies which facilitate the above tasks.

Note that the definition of information here is different from that in the Information Maturity Framework. For the remainder of this thesis, information will be referred to more generally to include data, ‘information’, knowledge, and wisdom.
Use of information is important. Interim use involves analyzing, transforming, integrating, relating, and accepting information. This work continually adds value to the underlying data. However, end use of information is where the full value is attained. Making informed decisions and further defining the product are two examples of end use which provide valuable results. The infrastructure provides mechanisms for accessing, capturing, transferring, and retaining information. One or more of these tasks may need to be done in the process of interim information use. Each of these needs categories will be covered in more detail in the next sections.

4.2.1 Access

Accessing the right information involves locating, retrieving, and sifting through any excess information. The product developer's ability to get to the right information will depend on how easily accessible it is. If information is not accessible at all, it may be because it is unavailable at that time, people are not aware that it exists, people do not know where it can be found, or the necessary infrastructure is not in place. These categories are shown in the first column of the KJ diagram, Figure 4-3, below. In the second column, the information is accessible, but may not be accessible in a timely manner, from many locations, and it may be difficult to locate and identify the right information. The ease of access will depend on the infrastructure. Although not specifically listed, the link to the infrastructure is implied for each of the tasks. Also, several types of information which are typically inaccessible or difficult to access are listed in the diagram below.

The availability of information reflects some fundamental limitations as well as any deficiency in the infrastructure. Some information is just not available. The test results are not complete, no one had ever researched the issue, or there are only a few experts in the field and they are impossible to reach within the time frame. It follows that another limitation arises from the difficulty in reaching people. Developers are time limited and cannot always be on call. The captioned statement that “We need intercoms in every office” reflects this limitation given people’s busy schedules and the current infrastructure. Lack of awareness is also a barrier to finding information and there are often huge inefficiencies associated with this. One interviewee said that the company needed an “Available Resources” list, because they would “frequently devote large resources toward development only to discover that the work had already been done at another location” (Slocum, '97).

In many cases the infrastructure does not provide adequate mechanisms for access. For example, one estimate was that “20% of useful information is stored in shared systems while 80% is in unstructured systems – on desktops in Word or Excel files,” (Cote, 98). Therefore, it may be impossible for someone to locate particular information without knowing who created it. When information cannot be found, the ability to relate information (and advance to knowledge in the information maturity framework) is impaired. One interviewee complained that “If a group worked on a crash analysis, it would be hard for them to find out if their results correlated to testing. The infrastructure is not there to do so” (Tilove, 98).
Sometimes the information is accessible, but the process is not as easy or efficient as it could be. It may be difficult to access files at all times and in all places. For instance, it may not be possible to refer to notes when discussions occur spontaneously, away from people’s desks. In addition, it is time consuming to gather dispersed information. A lot of effort at GM is spent on locating all of the CAD drawings of parts for a digital assembly. And, once the drawings are found, more work must be done to get them into the right format. Moreover, the work to convert the drawings into a compatible format is not being done by the people who originally created the drawings (Pickett, 98). Much of this work could potentially be avoided by arranging for the CAD drawings to be in a compatible format and delivered by the people responsible for them.

Another difficulty stems from the massive amounts of information which are found in searches. It is difficult to recognize the right information amidst the numerous and possibly redundant findings. The statement highlighted in the diagram captures this
sentiment well. “The database should show the consensus best practice and not list alternatives which confuse people” (Kuna, 98).

4.2.2 Capture

Capturing information involves the representing and documenting of events and observations - it is the initial harnessing of loose information. Capturing differs from access because it is the initial finding and recording of an event. Access assumes that the information has already been represented and exists somewhere. Capturing differs from preserving, because it is the initial representation and placement of information into the larger framework. Preservation involves maintaining the captivity of information. Two examples of information capture are the documenting of an expert’s learnings or the identification of critical dimensions for a part.

Capture requires a lot of insight; it is much easier to work from a known set of information than to recognize where pieces are missing and create new information. Figure 4-4 presents categories of the challenges in capturing information. The challenges include the limited availability in observing some events, the lack of or high cost of representation, and the need for methodologies and infrastructure for capture. And, if the information has already been captured, then the challenge is to make sure that it is captured well, that it is presented accurately, completely, and not in excess.

As before, there are certain fundamental limitations in capturing information. There may be events that are difficult to observe and product scenarios which cannot be tested reliably. In these situations, certain questions cannot be answered given the current technologies. More often, the impediment is the lack of methodology or form of representation. For example, knowledge capture is an area which lacks representation. The captioned quote in the diagram states that “Information is in people’s heads” (Kuna, 98). This alludes to the difficulties in representing what people know. It is difficult to fully capture the wisdom that an employee has gained over many years of experience. At Xerox, “70 senior employees are retiring in the next few years” and it was estimated that they would “take over a 1000 years of experience with them” (Sherman, 97). In other cases, the information may be more easily represented, but there is no consistent terminology or methodology in the infrastructure to guide in this process.

Certain types of information are inherently difficult to capture. A few of these include dynamic, dispersed, preliminary, and tacit information. For example, when the underlying events are dynamic, there is a need for a high-frequency capture mechanism which can keep up with current state of affairs. When events are dispersed organizationally or geographically, capture is also a more arduous task. In addition, preliminary and uncertain ideas are difficult to assess. Sometimes the issue may not have been researched or thought out. The valuation of the tradeoffs between the various project objectives is one case where preliminary information from marketing and engineering needs to be captured to make initial estimates. Tacit information is trickier to capture, because people don’t always realize what they know. Many practices are
taken for granted by companies. People know the practices, because “they have always been done that way.” Tacit information is especially important to capture when duplicating processes, such as a manufacturing line, for multiple company sites. In general, all of these types of information are at risk of being lost when the organization changes.

Figure 4-4 Information Capture KJ.

How valuable the capturing effort is depends a lot on the quality and accuracy of the representation. If the captured information doesn’t lead to the right interpretation by someone else later on, then the effort has been a wasted. At Ford, three pieces of warranty information are recorded at the dealers. This includes the customer’s wording of the problem, the actual repair, and the name of the repair person. In some statistical work, it was found that there were several complaints which related to the accelerator. With further research, they found that these complaints were all from women and that it was because the pedal was tougher to push for the average woman than for the average man. “This problem would not have been found from just looking at the repair data” (Caulfield, 98). In this case, the information was well represented and led to an accurate
conclusion. If only the repair data had been captured, an accurate conclusion may not have been reached.

How well information is captured also depends on the completeness and density. It is important to fully capture that information which is necessary to convey an understanding of an observation, but excess information should not be captured since it wastes people’s time. In the case where an event can be represented in many ways, it should be represented by the one that provides the best understanding. In the example from Xerox, 28 problems related to 1 parameter, the motor torque (Faull, 97). It was more efficient to represent the common denominator, or finest grain information. This one parameter provided more insight into the relationships between the various problems. When tweaking one problem area, it was possible to see how it would affect another. Capturing the context of information is also useful, especially when the information is intended to be reused. “The why needs to be recorded in the technical memory. It is important to know why a design was chosen in case the assumptions change” (Pickett, 98).

4.2.3 Transfer

Transfer is the sharing of information. This includes sending information from place to place and communicating information from person to person. The category includes but extends beyond electronic forms of information sharing. A diagram which lists the industry needs related to transfer is shown as Figure 4-5. In this diagram, information may not be transferred because of the incentives, the amount of effort required, or the uncertainty in knowing who needs the information. If the information is transferred, then it is necessary to evaluate how well it was transferred. Was there quality communication or sharing, was the ease of transfer reasonable, and was the transfer timely? It is also necessary to consider another potential barrier in this case. Was the transfer completed? Did the receiver check for the information, did he actively read and participate in the transfer, and were several transfers made when required?

There are several reasons why information is often not transferred. Unfortunately some of them have to do with the incentive system. Expertise is valued in a company and people may be less willing to share the information if it compromises their value in the company. In addition, if the design change process is too difficult, engineers will be less inclined to submit ideas early in the process. Aside from the disincentives, people may be reluctant to submit preliminary estimates or other uncertain information. “There is a reluctance for people to share incomplete information” (Blumberg, 98). And, a more formidable problem is that “Suppliers may not want to share their drawings if they are proprietary” (Pickett, 98).

Other transfer obstacles include the effort required to share information and the awareness of who needs to know. Preparation-intensive meetings, reports and presentations require large amounts of effort relative to the amount of information shared. When the effort level required is too high, it becomes easier for a person not to share the information, especially if the frequency of sharing information is high. And, once the
effort has been spent, it is inefficient if it does not get shared with all of the people who may need it.

![Diagram of information transfer]

Figure 4-5 Information Transfer KJ.

The quality with which information is transferred depends on the form of transfer. Higher bandwidth technologies tend to provide more of a complete communication medium, but are still not a perfect substitute for face to face communication. “Video conferencing, teleconferencing, and other virtual co-location technologies need to be supplemented with human interaction” (Gillette, 97). It is a challenge to make sharing of high quality, where people are learning from the information sharing, and to do so efficiently. The infrastructure needs to have mechanisms which promote interaction and creativity. “People used to gather around drawings and mockups. This doesn’t happen when individuals are hidden behind their computer screens” (Kuna, 98). The infrastructure also needs to make the transfer easy, even when the receiving parties are dispersed organizationally or geographically, speak different languages, and work in
different time zones. And, the transfers need to be coordinated. When communication does not occur in a timely manner, design decisions may be adversely affected and rework may be required later on in the process. "Manufacturing rules need to be known early in the design process; a lot of redesign work is done because people didn’t know that something couldn’t be manufactured" (Kuna, 98).

The completion step in the information sharing process presents an additional failure mode for transfer. Sometimes this failure to complete or receive information is unintentional. For example, people may not be aware that results are posted in the database. But, sometimes information is intentionally overlooked, put on hold, or ignored. The format matters a great deal. Interesting and concise messages are much more likely to be read than the opposite. "If I write a report, 10% of the people will read it. If I give a presentation, 80% of the people will come to it" (Roggenkamp, 98).

4.2.4 Preserve

Information preservation is the maintenance of information for future use. This includes learning, archiving, and tracking. Information that is not preserved is lost. The incentives and ease of maintaining data determine the degree to which it is preserved. If it is retained, then the challenges are to make sure that the information is learned fully, tracked completely, and stored in organized, shared systems. These issues are outlined in Figure 4-6.

The first step in preserving information is to store it in a somewhat permanent location. Electronic archival is easy and inexpensive. It requires no extra effort when work is already being done electronically. However, if the form of information is non-standard, it tends to be much more difficult to save it for retrieval later on. Voice mail, for example, is not easily archived for future recall and reuse. When information is not electronic, it may be even more difficult to get people to put it into an electronic form. This is one of the challenges behind the captioned quote. When employees leave, the company loses their expertise. The infrastructure needs to be designed with incentives to counter this trend. Additionally, much thought needs to be put into the documenting of information for future use. If this is done in a meaningful way, the information will be of value later on. "The why needs to be recorded in the technical memory. It is important to know why a design was chosen in case the assumptions change" (Pickett, 98).

Once information is recorded in a saveable format, the next step is to make sure that it gets put into an organized, user-friendly, shared system. One interviewee expressed a need for information to be put into common systems. An estimated "80% of useful information is stored in unstructured systems like Word or Excel on individual’s desktops" (Cote, 98). This is an issue not only because the information cannot be used later on, but because there are serious legal implications as well. "When discovery claims are filed, lawyers ask you to turn over all info related to that project. If they suspect you are in violation they can freeze workstations for a month, and copy everything on them" (Cote, 98). It is almost impossible to know where all of the information related to a particular project is when 80% of it is not in a common system.
The next level is to ensure that systems support the leveraging of legacy data and knowledge re-use. Archived information needs to be updated regularly and dispensed of when it is no longer applicable. The challenge is to keep the information complete but not in excess. Another issue is that the context for which information will need to be retrieved is often different from that which it was initially stored. Information about parts may get stored in a database which was originally set up for ordering parts and is therefore organized by part number. This system is great for the person managing the supply chain, but not at all user-friendly for the design engineer who wants to find out which part was used in the previous design.

### 4.2.5 Use

Analyzing, relating, accepting, and applying are all forms of information use. How usable information depends on the quality, quantity, timeliness, presentation, and complexity. How frequently information gets used depends on the incentives and ease of use, and also on the capabilities of the infrastructure. Again, use is important. An example of interim use of information could involve integrating a set of information and evaluating the results. These actions make the information of more value; it becomes knowledge or wisdom. In this state, the information is ready for end use or application. Using available information should be emphasized. “We find that analytically based decisions achieve better outcomes, faster, and with more reliability than just intuitive
judgments made by most managers and developers” (Smith, Reinertson, 98). A KJ of these issues is presented below as Figure 4-8.

Quality decisions can only be made if the underlying information is of high quality, if it is accurate and up-to-date, complete, and the degree of uncertainty and reliability are known. Product developers need ways to judge if the information is reliable. One interviewee requested that “a name and a face” be attached to the information in a database” (Kuna, 98). There is also a need to have information sooner and in some cases it may be worth using uncertain info to make early judgments which can be later revised. The need for information generally drops off over time. The developer may need to have an answer by certain time. If it is not available, she will go ahead and make a decision. Knowing the information later on provides only a little value; it either confirms the original judgment or it provides grounds for rework. However, the information becomes more certain over time as more testing and in depth analysis is completed. This tradeoff is shown in Figure 4-7. The challenge is to find the optimal tradeoff or, if possible, to

![Figure 4-7 Certainty-Timeliness Tradeoff.](image)

shift the certainty curve to the left (by improving the efficiency of information sharing or the speeding up analytical and physical tests) so that information is certain by the time it is needed. This can be difficult since many analytical tools require a lot of up-front work, but once they are complete can quickly provide results for many different scenarios. Note that this tradeoff applies to dynamic project information. There is still some fundamental information about the product and process which does not lose value over time. This is the type of information which should be maintained since there may be a need for it at some future date.

The quantity of information needs to be reasonable for developers to be able to keep up with it and still be productive in their own work. It is inefficient to go through all of the messages and reports which are generated. One complaint was that “50-80% of email is not necessary and may take as much as one-half hour per day to sort through” (Wong, 97). The limited time frame forces people to look at only the highest priority material,
but the infrastructure needs a prioritization mechanism which can eliminate the inefficient time spent sorting. Sorting is not the only problem, large quantities of information are also more difficult to understand and manage. "When investigating 1500 problems, it was found that these related to about 80 Critical Parameters." Managing 80 issues is much simpler than 1500 (Faull, 97). A similar sentiment is captured by a quote in Figure 4-8. "Presenting exception-based data is more efficient. The system should only tell me when something is going wrong" (Bommarito, 98).

Figure 4-8 Information Use KJ.

How information is presented is often under valued. The presentation greatly influences the usability. There is a need for information to be presented so that it is quickly and correctly interpretable. This is especially true for complex or unfamiliar information and for information which is continually changing, like frequent up dates. "We need a snapshot of project progression relative to schedule" (Bommarito, 98). The presentation also needs to be appropriate for the user. CAD systems work well for the designer of part, but do not show an assembly for a manufacturer (Blumberg, 98). Another challenge is to find better ways of representing the interconnections and tradeoffs among design parameters. If non-intuitive results can be made apparent, developers are much more likely to accept and apply them.

4.2.6 Infrastructure

The information infrastructure includes the formal and informal methods, tools, and technologies which are available in a product development organization. The
infrastructure is in place to facilitate access, capture, transfer, retention, and use of information. Although the connotation of infrastructure is technical, it actually implies much more than the system of workstations and databases. The infrastructure includes informal customs and incentives as well as PDP methodologies. "Product development is complex because it involves people, processes, & technology" (Tilove, 98). Therefore, great technical challenges exist but so do many non-technical challenges. The infrastructure needs to meet all of these varied needs. Figure 4-9 presents a framework for assessing how well an infrastructure meets the needs of the organization. Is it in place, efficient, well-structured, robust, and does it get used?

Both formal and informal information mechanisms need to be in place and efficient. In many cases informal mechanisms usually require less effort than the formal alternatives and still provide a large part of the solution. For example, "A lot of information gets to new engineers by word of mouth. It is an informal process" (Kuna, 98). But, it is

Figure 4.9 Information Infrastructure KJ.
important to establish the right incentives and structure for the informal mechanisms to work. Where possible, people who need to communicate should be located near each other and encouraged to share information. Incentives should also be in place to encourage information use and informed decision-making processes. Formal methods are also needed in the management of critical information. Whatever the mechanisms, they should be chosen with the tradeoffs in mind since different methods and technologies are better for different applications.

The information infrastructure needs to be well thought out and structured for the environment in which it will be used. A large scale, mass-production, and customization business will be very demanding on the infrastructure. Issues like scalability and reliability will be critical in that business. Another consideration is that the system meet global standards. This is especially key, if the company has a design or manufacturing site in another country. The infrastructure should be structured so that best practices, design rules, test results, and other meaningful information are made available to this other site. If necessary, they should be translated into the language of the country. On another note, the infrastructure needs to be appropriate for the particular stage in the development process, including marketing analysis, designing parts, managing supply and warranty info etc. There is a need for estimation tools in the process. “There are no tools for rough analysis. We do not need complex programs that need to run on a Cray for two days. We want to use engineering workstations to make initial estimates.” (Pickett, 98).

There are many parameters for which the infrastructure must be robust. The organization may change as new people are hired and others move on to different projects. When this happens, it is important to prevent information loss and to maintain the infrastructure. “It is often a trick to find the owner of web site, because people change projects” (Cote, 98). In addition to organizational changes, the design assumptions may change. “During a four-year development cycle, there are many changes in the market and in company organization” (Bommarito, 98). A robust infrastructure will provide tools for the development team to react to these changes. Lastly, the infrastructure has to be robust for multiple users and contexts, and be able to handle many forms of information.

Even if the infrastructure includes very sophisticated technologies for multiple applications, it is only worthwhile if it gets used by everyone, all the time. Often companies have a hard time getting people to use new methods and tools or to fully learn the capabilities of the technologies. In this case, it may be worthwhile to provide training or change the infrastructure to accommodate the needs of the users. “The system would work if it were in people’s daily routines to look in the database” (Light, 97).
5. Needs Met by Information-Based Development Research

5.1 Goals of the Information-Based Development Research

The objectives of the Information-Based Development research effort are to better understand the information-intensive product development process and to create methods and tools which will help companies develop "high-quality products faster and with less effort than is possible today" (Eppinger, 97). In order to achieve these objectives, research is being done in concert with five sponsoring companies to develop and experiment with the new methods and tools. The belief behind this effort is the following: "Product development is a complex activity involving many individuals, multiple perspectives, numerous methods, and countless decisions. These are all linked in complex ways by information. We believe that we can assist a large portion of the product development process through our study of information-based development" (Eppinger, 97).

The research activities have been divided into four areas: Data/Network Visualization, Critical Information, Information Flow Modeling, and Integrated Product Modeling. In the next few sections, these four areas will be described and mapped into the IBD Needs Framework. The result of this mapping is to identify which needs are being addressed by current research and where there are opportunities for future research. A description of the four research areas is included in Appendix A.

5.2 Mapping into the IBD Needs Framework

5.2.1 Combined Research Efforts

The combined research efforts address several industry needs in the areas of information capture, transfer, use, and infrastructure as well as a few needs in the areas of access and preservation. In particular, a lot of work is being done on the capturing and use of large quantities of complex and dispersed information. A common theme among the research areas is that they are aimed at large scale projects where there is a need for prioritization and focus in dealing with massive amounts of data. They answer a need for keeping track of and making sense of the most critical of the information. In addition, there is also a lot of work being done in the areas of transfer and the information infrastructure. These efforts consider the facilitation of information sharing and the automation of the design evaluation and selection process. Currently, there are only a few projects in the areas of information access and preservation, but some of these issues are already being solved commercially or through internal efforts in companies. All of the information needs are listed in the IBD Framework in Figure 5-1. In this diagram, the needs which are currently being addressed by IBD Thrust research projects are shaded and identified by category.
Figure 5-1 Mapping of IBD Thrust Research to the Needs Framework

5.2.2 Data/Network Visualization

As the amount of information keeps growing, it is becoming increasingly difficult to find relevant information. A keyword search in a large database will result in a long list of possible documents to choose from. There is no way to know if you’ve found all of the applicable documents and no good way to identify the most relevant documents. In other words, it is difficult to assess search results in terms of completeness and relativity.

The Data/Network Visualization research area is aimed at representing search results of primarily textual information in an easily understandable, visual format. The current research is specific to patent searches. The results of patent searches are organized by citation, or reference, and presented graphically. The graph shows family relationships between a patent and other patents in a particular set. For example, a parent in the family tree would be cited in the patent being examined. The graphs may also be manipulated to highlight sections of the tree to show which patents are most closely related.
Figure 5-2 Mapping of Data/Network Visualization Research to the Needs Framework

This project addresses the needs for access of the right information and for an easily and correctly interpretable visual presentation of the resulting information. This research fulfills a need for design teams to establish new art and to learn about the state of the art. If development teams are aware of this information, they can avoid infringement and find useful ideas for the concept generation phase of the development process. The primary focus of this research is in helping people to find the right information. Representing search results graphically leverages people's visual processing skills and ability to find spatial relationships. This eliminates the need to sift through and partially read into a long list of documents when the content and connections are already organized. For these reasons, people can more quickly identify the “right information.”
5.2.3 Critical Information

The bulk of the research being done in the Critical Information area is related to “Key Characteristics” or KCs. KCs are “those features in a product that, for their expected process variation will have a significant impact on the customer requirements of a product” (Thornton, 97). The objective of this study is to develop a method for identifying, maintaining, and managing KCs for the end result of an improved product. The mapping of these objectives into the IBD framework is shown in Figure 5-3. KC methods address needs in the areas of information capture and preservation and they provide a formal mechanism in the infrastructure to aid in managing information. They are also fulfilling a lack of representation, which is necessary for the capture of a particular type of information. In this case, the risks are being identified and represented quantitatively. By limiting the capture to only the key information, the set of KCs provides a high priority set of information to be utilized throughout the design process. Knowing about the risks provides a good basis for making design decisions, especially related to the selection of suppliers and manufacturing processes.

![Diagram of Critical Information](image)

Figure 5-3 Mapping of Critical Information Research to the Needs Framework
Key characteristics do not just help in terms of providing a limiting factor where there would have otherwise been massive amounts of information, they also provide higher quality information about complex design tradeoffs. KCs improve information density. The amount of information to keep track of goes down, but the value goes up. This goes back to the 28 problems in a Xerox copier all relating to one critical feature, the torque of a particular motor. Knowing this relationship greatly simplified the problem solving process, because individual owners of the various problems were not all optimizing the torque subject to just their own constraints. And, because Key Characteristics are quantitative, there is a way to measure changes in product functionality.

In addition to providing a methodology for tracking KCs during a development project, one research project is aimed at capturing design intent, or the reasoning behind design decisions. By incorporating design reasoning, KC records can serve as a document of the development effort. This will provide a structure for information re-use.

5.2.4 Information Flow Modeling

The objectives of the Information Flow Modeling research area are to "provide roadmaps through the data describing products and design processes" and to "provide managers with an overview of flows and exchanges of information" (Eppinger, 97). The first objective aims to improve information flow among members of a development team, while the second seeks to help project managers better assess and respond to the current project status. This research primarily addresses two needs, facilitating and enhancing information transfer and providing clear methodologies for managing information. It also touches on some of the issues related to the capturing, maintaining, and utilization of information. The needs addressed by this research area are shown in Figure 5-4.

Project managers need information throughout the development process. They need to capture information early on in order to do project planning and they need to continuously capture information to assess project progress. In addition, they need to maintain product information throughout the process. The information flow research addresses a need for capturing task information in large-scale projects and using it to better plan and manage projects. One of the modeling tools being used is the Design Structure Matrix (DSM). DSM assists in organizing and scheduling tasks based on "information clusters," or tasks which will frequently require information to be exchanged. By making the information exchanges explicit, organizations can be structured better and tasks can be scheduled better to align with "patterns of information flows in those areas where the flows interact highly" (Eppinger, 97). Improved structuring means that the communication lines and feedback loops are shortened.

Part of the Design Structure Matrix research is aimed at improving the timing of information flows and takes into consideration the uncertainty of preliminary information. In the science of information flow, projects are being done to determine what information is exchanged between design team members and to evaluate the preferred methods of transfer in different types of information exchange. These projects map into the framework in the categories of quality and timeliness of transfer and use.
The continuous capture and maintenance of information is an important challenge. Project managers need ongoing, updated information to know if they are keeping the project on track according to schedule, budget, and high standards of quality, and if they are not, they will need to know how to respond to the current situation. A manager also needs to keep track of high priority information and to be aware of design tradeoffs. They need to make sure information is found or that work is done to generate information which is required to make informed decisions. All of these needs deal with information flows and are addressed by this research.

### 5.2.5 Integrated Product Modeling

The Integrated Product Modeling effort has the objective of providing tools for the "rigorous, integrated, analytical modeling of product systems" (Wallace, 97). This objective has taken the form of a prototype software implementation of a modeling and optimization tool called Distributed Object-based Modeling and Evaluation, or DOME. The DOME project creates a part of an information infrastructure and integrates many current pieces of infrastructures. It is tool which maintains all of the information about a
product throughout the development process. And, it provides a mechanism for search, evaluation and optimization at the system level given all of the subsystem parameters. The work on this project addresses a need for making large quantities of complex information usable. A variety of inputs (different components or materials) can be evaluated in a search. The model is also robust to changes in the underlying assumptions. Whenever a variable changes, the model automatically updates and provides and shows how all of the other parameters were affected. The mapping of this research into the needs framework is shown in Figure 5-5.

![Integrated Product Modeling Diagram]

Figure 5-5 Mapping of Integrated Product Modeling Research to the Needs Framework

Since DOME provides a hub for all of the product information, it forces all of the necessary information to be captured. This fulfills the need for complete capture of information. Further, the right information is captured along with the appropriate quantitative theoretic models or value functions. Individual experts can work on various parts of the overall model, like the heat transfer part or the cost evaluation part. Then the combined efforts are represented in the model and put on a common ground so that decisions can be made which optimize around all aspects of the product.
The user interface of the DOME software can be manipulated to look into various parts of the design problem. The input parameters, connections between parameters and the criteria for evaluation are all shown. When a parameter is changed and the design results differ, it allows a person to go in and examine the "reasoning" behind the new result. This fulfills a need for developers to be able to visualize complex connections and decision rationale. In this way, DOME provides insight where both the amount of information and the numerous interconnections would have otherwise made it impossible to interpret and understand the greater, system level problem.

Because DOME provides an infrastructure in which to design products, it becomes a part of people's daily work. As a result, a lot of thought on this project has been put into creating a system which is easy to use for multiple people with different areas of expertise. It is a collaborative technology which allows people to contribute and also to understand the greater scope of the design effort.

6. Gaps and Opportunities

6.1 Gaps

The gaps are those areas where there are needs which are not being addressed by the research in the Information-Based Development thrust or by commercial or industrial efforts. The gaps are visibly apparent in the IBD Framework in Figure 6-1. They are the topics which are not shaded, boxed, or circled. The shaded needs are being addressed by IBD research as discussed in Chapter 5. The boxed needs are likely to be solved commercially and the circled needs are beginning to be addressed by companies. The gaps are the items which are left out of all of these efforts.

A few of the gaps will be addressed as commercial products are developed which meet those needs. One such area is the missing infrastructure for universal handling of multiple forms of information. For example, a product called Entuity, is already tying together the handling of a few different types of information. This software allows people to save voice mail messages and faxes in a filing system similar to an email filing system. Messages and faxes can be incorporated, forwarded, and saved. Several needs (access, maintenance, and use) are improved by providing the ability to keep track of correspondence. And, the flexibility to forward a fax or to print it privately at the printer on your desk helps people to do their work more effectively. In the future commercial products will provide even more flexibility by encompassing additional forms of information (video, voice recognition etc.) and by providing the capabilities to do more with the information (search through it, crop and save particular sections, convert between formats etc.). Standards which meet international as well as national requirements will be demanded or the technologies will become flexible in interfacing. These technologies will also be portable, possibly wearable, or accessible from many places.
Figure 6-1 Gaps which are or will be addressed in industry or commercially.

Those needs which are beginning to be addressed by efforts in industry are circled in Figure 6-1. These include providing the incentives and culture for sharing and archiving information. Several areas which are also specific to each company include the information infrastructure and the decisions about that infrastructure. These needs are met when the company implements an infrastructure that is designed for the particular type of business. Companies are beginning to build infrastructures which are robust to organizational changes and long development cycle times. With this investment in mind, it is likely that efforts which ensure that the infrastructure gets used as a part of people's daily work will follow. It is also a good idea for companies to create an "Information Culture." Employees must be aware of the necessity for data to be presented concisely and in an interesting format. It is also important that employees be considerate to fellow employees by not swamping them with irrelevant information.
6.2 Opportunities

6.2.1 Opportunities Identified in the Needs Analysis

This process has identified several gaps. Not all of them are critical though. Our current efforts are, however, targeting the right problems. The use and management of large quantities of detailed, complex, interconnected information are two of the tough problems. Improving these will truly allow development teams to create higher quality products with less effort than is currently possible. Further study could be done in these areas, but there are still opportunities where other needs are not being met. Four areas which are not being addressed include the awareness of available information for access, the complete capture of information, the ease of use of information in decision making, and the design of an infrastructure which is appropriate for the time constraints and stages in the product development process. These opportunities are shown circled in Figure 6-2.

Figure 6-2 Opportunities identified through the needs analysis.
6.2.2 Description of the Greater Problem

Product development is complex because it deals with “People, processes, and technology” (Matulka, 98). The difficulty arises in weaving these three things together to get the optimal fabric for development. The structure of the process needs to take advantage of the strong points of each resource. It needs to capitalize on people’s creativity and on the technology for all it is capable of, a common working ground with powerful analytical tools and a repository for all the information. The analytical tools can be used to do all of the number crunching if people supply the creative ideas for analysis. The objective is to coordinate the people and the technology via the process. This is a different objective than it was a decade ago, because there are many more technologies available today.

The process is no longer limited by the upper bounds of human memory and learning capabilities. People do not need to keep track of all of the details and calculate the tradeoffs among hundreds of variables, because the technology is there to do this. In terms of the IBD Framework, this means that there will be many more options for the use of information than were previously feasible. The capabilities are available to use information in better ways. Developers may test out many more design options and achieve more accurate results than before. Quantity and complexity are not as limiting as they used to be. So, now the challenge is to figure out how to best apply the tools and to get all of the information necessary so that the tools can be fully utilized. This will cause a shift in effort into the areas of capture and access of information.

6.2.3 Getting all of the Right Information and Using It

Getting all the right info and using it is the key. However, information can be gotten in many ways. It may be already known, received as a deliverable from someone else’s tasks, accessed through a search, or captured in an active study or discussion. If it is already known, then there is no more work to be done in retrieval. If it will be received from someone else, then this is a transfer, and there is a lot of research being done to improve the quality and timeliness of transfers. However, if the information needs to be accessed, then things are a little more difficult, and some up-front work could be done to make this easier for people.

Awareness of Available Information for Access

One of the major obstacles in using the available information is that no one is aware that it exists. Unless data is current and has recently come across someone’s desk or been emailed to them, they will not be likely to know about it. If the data is from the near past, then it may be in a person’s reach to recall who the owner of the data was and then track that person down to ask about it. In general though, awareness of available information is lacking.
Employees do not have enough time to go out of their way to become aware of all of the different types of information which are available to them. There needs to be a mechanism for easily identifying whether or not they can find what they are interested in. Currently there is no way to do this, and so it is not even worth checking. If there were a known mechanism which was visually interpretable people could quickly be made aware of the information that is out there. People need “snapshots” of the information landscape. Ideally this tool would point people in the direction of the information whether it be in a database or with another person.

Companies could leverage the re-usability of information to achieve huge efficiencies. Several of the needs statements requested things like an “Available Resources” list for the whole company and an alert when it was possible to “use part of an existing manufacturing line.” Rework could be decreased over many projects as well as within one project, if there were methods for making people aware of opportunities for re-use.

**Complete Capture of Information**

If information is not already accessible, then it must be captured (or generated and captured). It requires a great deal of forethought and insight on the developer’s part to know where information is missing and which missing information would play an important role in the quality of the product. A lot of this ‘missing information’ is actually “in people’s heads.” As the technology allows the complexity of development efforts to grow, knowledge capture will be necessary. Although, the human network is an important part of the information infrastructure, it can not be extended efficiently enough or to the scale required to maintain and process the amount of information that is known.

**Creative Generation of Information**

In addition to what is known, there are many opportunities for incorporating new ideas. Despite the move toward a more technical mechanical process, the success of products still goes back to people’s creativity – the process is inherently inventive. Finding ways to foster creativity within the time-constrained environment is important. One interviewee reported that “People used to gather around drawings and mockups,” and that this didn’t happen anymore now that everyone is planted behind a computer screen (Kuna, 98). Instead of gathering around physical objects, developers need a digital equivalent. Although this equivalent could offer much more, because ideas could be tested out in real time. If such a centerpiece for discussion were available, designers could ask questions and generate ideas in groups and then learn from the results. In general, the technology will always need to be accommodating for people, and bring things back to a tangible, human-scaled form for evaluation and understanding. Few efforts are being made to make the technology and presentation of information easy for people to learn from and understand. The objective should be to improve informed creativity. Inventors need to be in tune with the available tools and the constraints of the problem.
6.2.4 Ease of Use

Right now, the incentives are going in the wrong direction. Decreasing the development time puts a crunch on people’s time, and they are less likely to do things the hard way. They are more likely to make decisions based on what they already know than to gather all of the unknowns, look up the theory, wait until they have received inputs, or spend time creatively thinking or analyzing the issues. In this list of tasks, the bottleneck is in relating information.

Relating

When data are analyzed, it gets turned into a standard format so that there is a basis for comparison with other information in the same format. This could be as simple as converting all of the testing data into percentages. A comparison is necessary for turning an arbitrary piece of information into something that is meaningful. You need to know where you are relative to the criteria, or customer needs, and how all of the different variables in the design tradeoff to achieve the optimal design. However, it takes work and research effort to find other information for comparison. This is where the discontinuity shown in Figure 6-3 occurs.

As a side note, one of the interviewees would not allow his employees to make presentations with bulleted slides. He wanted a graph or a diagram or something which showed comparisons or connections. In this way, he was forcing people to not just present data and observations, but to work through the information and come to an understanding of the problem. In short, he wanted people to present at the knowledge level. There still may be grounds for debate at this point, but that would allow for progress toward the acceptance of information (Fisher, 98).

Figure 6-3 Discontinuity in Information Maturity.

In general, there is a need to make this part of the process much more efficient. In some cases, information may need to be related or compared across many fields. This is the
case when the tradeoff between the cost of a part and the product quality is being
determined or when the time to market is extended to debug problems. There is a need
for a place where the information necessary for comparison (past results, benchmarks,
target goals) is located as well as a mechanism for showing the relative quantities. If the
cost associated with a delay in getting the product to market is higher than the cost of the
lower quality product, than the product should be shipped sooner rather than later. The
technology is available to keep track of and weigh the tradeoffs between all of the
product and process variables; it should be used to eliminate this bottleneck and to
provide developers with the real-time assessments of tradeoffs for required for decision
making.

Understanding and Accepting

The technology may be used to more quickly relate information, but at the same time,
there is also still a need for the whole design problem and the associated tradeoffs to be
visibly understandable. The technology cannot be a black box which hides all of the
‘reasoning’ behind the results. Rather, people need to be able to see what is going on
inside, so that they trust the system. The system should allow them to check particular
parts of the model to make sure the same assumptions apply if it is to be used on a new
design, or any parameters need to be altered when the assumptions change. Visualizing
the complexity behind the scenes will feedback into informed creativity as well as speed
up the “acceptance” step in the Information Maturity Framework in Figure 6-3.

Applying through Decision Making

How the conclusions are reached is important. If product developers expend the energy
to do things the hard way, the decisions they make will be based on more accurate results.
Figure 6-4, shows the different levels of improved decision making. In the first level,
only known information is used to combat the state of missing information. X and Y in
the box are estimated or guessed in the process of making an intuitive judgement. In the
next level, more knowledge is incorporated through capture and access efforts as well as
the receiving of shared data. In this case, the stockpile of information encompasses the
group’s expertise and an informed decision can be made. In the last level, group
experience is used to put the theories together into an analytical tool which can take X
and Y, do the comparisons, and provide an optimized solution.

6.2.5 Appropriate Infrastructure for All Stages in the PDP

Lastly, the information infrastructure needs to be designed so that it can be used at all
stages in the product development process. It has to have the flexibility to be used in the
initial stages when there is very little information to go on, and have the capacity to
maintain every detail and deal with redundancies and errors in the later stages. The
infrastructure should also be forgiving in the time constraints. There should be flexibility
in using the tools at all levels of completeness. If not all of the analysis in one area can
be completed on time, and it is worthwhile to go on without it, the system should be able
to collapse and operate without having all of the inputs.
Levels of Informed Decision Making

![Levels of Informed Decision Making Diagram]

Figure 6-4 Levels of informed decision making. Improving requires using all of the information available and using it efficiently.

Specifically, estimation tools for early design work is missing in the current infrastructures. CAD and FEA programs need to have all of the dimensions just to show a sketch or analyze the stresses. This is true even when system level parameters in the real design may not have even been chosen. The technologies need to be able to show generalities and ranges. And, they need to be more flexible for the initial brainstorming of concepts. If there were a virtual machine shop, a designer could imagine a part, retrieve an old drawing of one which was similar from an electronic file, make a few changes (without knowing the specific corner radii), and get a sense of the concept. Perhaps this could be connected with other technologies to be able to learn more about the possible weight of the part or heat transfer properties etc. Estimation tools will help people to make more accurate preliminary decisions. This accuracy will propagate throughout the process and result in a higher quality product.
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**List of Interviewees**

**Boeing**

Walt Gillette  
(Director, Airplane Creation Process Strategy)

**Ford**

Paul Blumberg

Stewart Caulfield  
(Associate Director, Quality & Product Information Systems, PD Systems)

Stevie Cote

Ken Kuna  
(Manager Direct Engineering, Advanced Manufacturing Technology Development)

Bob Matulka  
(Ford Automotive Operations, Product Development Process Leadership)

David Roggenkamp

Paul Shank  
(Manager, CAD/CAM/PIM Department Process Leadership Director, PD Systems, Information Technology Process Leadership)

**General Motors**

Dianne Bommarito  
(Planning Information Manager, Midsize Luxury Car Group)

Mary Pickett  
(Senior Staff Research Scientist, Research & Development Center)

Roy Richter  
(Senior Staff Research Scientist, Math-Based Vehicle Development)

Bob Tilove
(Principal Research Scientist, Manufacturing & Design Systems Dept.)

**ITT**

Dick Arra

Rose Boidock

Dennis Fisher

Ron Read
(ITT Cannon, Director Process Development)

Michael Slocum
(ITT Cannon, Senior Staff Engineer, Intl. Space Station, Special Products)

Albert Tien
(ITT Cannon, Vice President, General Manager, Cannon Connectors)

Stephanee West
(Vice President of ITT Night Vision)

**Polaroid**

Fara Faramarzpour

**Xerox**

John Elter
(Vice President, Strategic Programs, Office Document Products Group)

Lou Fantozzi
(Product Manager)

Ralph Faull
(Principal Engineer, Dir. of Robust Design, Manager of Eng. Excellence, Board of Strategic Corporate SME)

Terry Light
(Quality Engineering Manager)

Rita Sherman

Lam Wong
(Xeroxographic Process Integration)
Appendix A

Center for Innovation in Product Development Projects, Fall 1997

THRUJT 2: INFORMATION-BASED DEVELOPMENT

Objective

This research will develop a better understanding of the information-intensive product development process, and will create more effective tools and methods to support product development activities. As a result of success in this research thrust, practitioners will be able to develop high-quality products faster and with less effort than is possible today.

Research Strategy and Organization

Our research is based partly on the following theory of information in the product development process. Product development is a complex activity involving many individuals, multiple perspectives, numerous methods, and countless decisions. These are all linked in complex ways by information. We believe that we can assist a large portion of the product development process through our study of information-based development.

The information-intensive product development process is relatively new. A direct result of the availability of new information technologies is that development teams are today making extensive use of such varied information sources as customer feedback via the internet and global point-of-sales data via satellite links. Communication methods within development teams have also changed dramatically over the past ten years with the use of electronic mail, video conferencing, groupware, and other collaboration technologies.

We have organized our research activities within the Information-Based Development Thrust around four themes, each giving rise to a research program discussed below:

- Program 2.1 Integrated Product Modeling
- Program 2.2 Critical Information
- Program 2.3 Data/Network Visualization
- Program 2.4 Information Flow Modeling

Technology Transfer And Deliverables

We are working closely with several companies which are both assisting with and learning directly from our field work. For example, our current research at Ford, Boeing, Lucent Technologies, and Hewlett-Packard involves direct application of new tools to current development projects. Many companies are experimenting with these methods as
a direct result of our presentations at industrial seminars and conferences. Methods developed in this research can be transferred both to sponsoring companies and to software developers.

Program 2.1 Integrated Product Modeling

Objectives: The integrated product modeling program aims to provide tools for the rigorous, integrated, analytical modeling of product systems. We believe that connection of detailed design decisions with system-level product strategies is required for product developers to consistently achieve timely, effective, and low-cost product designs.

State of the Art: Most industries agree that single domain design models and tools are very effective within their scope. However, efforts to develop an integrated understanding of a product system, as is needed for global optimization, have been largely unsuccessful. At best, success stories are case specific and do not provide a general framework. To date, academic research has focused on data models and their management. Historically, there was a focus on geometry, predominantly individual parts and more recently information about assemblies. The insufficiency of pure geometric data is widely recognized and current standards initiatives, such as STEP, attempt to address this issue. These new data models capture information about the item being designed but do not have information about physical models, internal relations, or the status of the design process. Additionally, their use in an integrated product model requires that all participants (who may be distributed over multiple companies, suppliers, and sites) use a common representation and fully share these data models. The objective is to make design decisions, based upon integrated knowledge, that lead to a quality product. Therefore, the integrated models should be seamlessly linked to decision support and optimization.

Hypothesis and Approach: We hypothesize that the new paradigm for integrated product modeling will have three components: integrated model networks, decision support, and search/optimization support. Integrated product models will be created from networks of models corresponding to different aspects of the development problem. These models will interact through the concurrent exchange of information services, each participant using local models to process information and provide services to other models. The information service network will be linked to decision support and optimization systems, thereby enabling integrated product development decision-making. This vision is shown in the figure below.

Research Results: The fundamental basis for the new integrated product modeling framework has been developed by a core of 9 research assistants. A prototype software implementation of the general framework, called Distributed Object-based Modeling and Evaluation (DOME), has been implemented. [Refer to Vol.2-Senin, Pahng, Chung, Kim, Almy.] This implementation allows product developers to rapidly build integrated design tools for product development problems. Examples include a tool for designing product enclosures that links separate geometric models, environmental impact models, electromagnetic shielding models, heat transfer models and cost models. [Refer to Vol.2-Borland, Savage.] Using the tool it is possible to obtain a global understanding of the
interactions between competing design considerations and perform global design optimizations. The framework has also been used to build a tool for configuring cogenerative electricity production systems, linking models at MIT and ETH in Switzerland. [Refer to Vol.2-Senin.] Efforts are underway to develop models to integrate the voice-of-the-customer with product development models. Polaroid has successfully deployed the prototype software in a product development project. [Refer to Vol.2-Almy.]

Program 2.2 Critical Information

Objectives: To provide quantitative and formalized methods to identify, track, manage and improve the "Key Characteristics"(KCs) of a product. KCs are those features in a product that, for their expected process variation will have significant impact on the customer requirements of a product. As a basis for this research it is necessary to develop an understanding of the (organizational, process and information) environment in which these methods are being implemented, the current practices in industry, and the best practices among those companies.

State of the Art: The current state of the art of KC methodologies in most industries we have interviewed was immature and ad hoc. In many of the companies, identification processes are often based on non-quantitative or formalized approaches, and there is no systematic flowdown from system level requirements to feature level KCs. The KCs are not prioritized, nor are they based on quantitative methods. Communication of process capability between manufacturing and design and between suppliers and design is not consistent. Finally, a systematic link between design and quality plans is not done.

Hypotheses and Approach: By understanding and quantifying the risk associated with KCs of a product throughout the product development cycle, better decisions about design tradeoffs, supplier selection, manufacturing processes selection, and quality planning can be made.

Our research is a taking a variety of approaches. The first is to understand the current practices and problems in industry. The second is to outline from this information a set of best practices and methods and use this to teach other industries how to at least match the best in class organizations. The third is to develop tools and methods to assist companies in identifying, analyzing, managing and acting upon the KC flowdowns and the related knowledge.

Research Results: A group of students along with Prof. Thornton, have developed a Key Characteristic maturity model based on interviews at more than 20 companies. The model outlines twenty-two practices that support good KC implementation. Several companies have used this model to evaluate their current capabilities and develop plans for improvements in their processes. [Refer to Vol.2-Jay.]

There are several ongoing projects. One student is working with ITT Industries to develop an new approach to drawings that avoid the need to fully dimension the
drawings. Information about the KCs is attached to the electronic data to aid in design, redesign and inspection. [Refer to Vol.2-Jay.] Another student worked with Kodak to assist them in their evaluation and rewriting of their current KC methodologies. [Refer to Vol.2 - Ardayfio.] Another student is working with Boeing Military Transport Aircraft to help with the redesign of two major sub-systems. In addition to formalizing their KC processes and working with the dimensional management group, she analyzed the two team structures and approaches taken. [Refer to Vol.2-Ertan.] An intern at Ford has been tracing all of the key design characteristics of what appears at first to be a simple purchased part. Statistics show that 50% of the time the vendor cannot meet the specifications, causing lengthy negotiations between different constituencies with conflicting needs. These results are beginning to be incorporated in a knowledge-based design system. [Refer to Vol.2-Judson.]

Program 2.3 Data/Network Visualization

Objectives: This research area focuses on the need to retrieve knowledge from large databases of information quickly and effectively. This need is ever increasing because of the growing mass of information that is stored. During the conceptual phase of product development, product teams must be knowledgeable of current trends in technology and be able to establish the state of the art and prior art. Currently obtained through laborious literature and patent searches, the resulting information is difficult to assess in terms of relativity and completeness. The goal of this project is to develop a graphical tool to let users visualize the relationships and trends among documents in databases based on genealogical graphs.

State of the Art: Current searches of the databases consist of keyword searches which return lists of documents. Users must mentally sort through these lists for project relevance, document relationships, time relevance, and information content. Graphing programs exist which make linkages between items but these tend to be user manipulated. Internet search engines are an example of research being conducted on the clustering of information based on the textual content of documents.

Hypothesis and Approach: We hypothesize that if a system is developed which could display the relationships among documents based on content, product development teams could quickly assess the current technologies and be empowered to make effective decisions. Below is the scenario for this system applied to the patent database.

Our approach is to develop a demonstration program which creates a citation graph showing the family relationships (a family tree showing siblings/cousins/nieces/etc.) between a patent and patents in a given set. Within this citation graph, the program can identify familiar or distant relatives of the given patent. It can also provide the ability to manipulate these graphs. Portions of the tree may be highlighted for content similarity and key patents may be targeted by the system as being extremely relevant to the project. The program will make the processes of establishing prior art to avoid infringement and of finding concepts useful for ideation more productive for design teams.
Research Results: We have created a test system which automatically organizes document nodes according to their citation/reference relationships in three dimensional space. [Refer to Vol.2-Yang.]

Program 2.4 Information Flow Modeling

Objectives: Our objective is to provide roadmaps through the data describing products and design processes so that members of a development team can find the information they need and communicate it to other team members. Additionally, we hope to provide project managers with an overview of flows and exchanges of information so that they can manage their projects more effectively. We aim to develop a science of information flow modeling in product development.

State of the Art: Complex projects are typically modeled by constraint networks that capture task precedences and relate them to schedules. Such models miss a number of key elements: iteration (repetition of the same task); resource contention (clash of demands for design activity from several players in one project or from several projects); and/or information precedences; and information clusters. Each of these characteristics of real product development cause projects to be late or to misuse key information. Recently developed modeling tools based on the Design Structure Matrix (DSM) focus on information that is exchanged between team members. Past research has shown how to use these tools to identify highly interacting information or design tasks, predict total project time, capture ebbs and flows of activity, and recommend organizational changes to shorten communication lines.

Hypotheses and Approach: We hypothesize that we should focus on information that is exchanged and seek to make such exchanges explicit. We further assume that the content and exchange structure of this information is highly contingent on the product being developed and therefore that each product will need its own distinct information flow model. What is generic is the set of tools for generating, manipulating, and displaying these models for the benefit of development team members. Finally we assume that the organization of companies and development projects need to be aligned to patterns of information flows in those areas where the flows interact highly. Case studies and theoretical model development are being employed.

Research Results: A six week study was conducted to construct a DSM model of subsystem interaction in automobile door design at Ford Motor Company. The study recommended forming four new "interaction teams" to deal with previously unrecognized clusters of highly related information connecting aspects of moveable glass, door sheet metal, and electrical systems. If these teams are implemented, a follow-up study will be conducted to measure improvements, if any, in door design time and quality. [Refer to Vol.2-Dong.]

A current doctoral student is extending our theories of project information flow. We are extending our prior models of task activity overlapping to include feedback and effects of communication frequencies, and also integrating these models with models of design
iteration. Implementation at Hewlett-Packard has provided us with valuable experience to improve the transfer of these methods to other industrial situations. [Refer to Vol.2-Carrascosa.]
Appendix B

Faculty Research Areas

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<tr>
<th>Faculty</th>
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<tr>
<td>Steven Eppinger</td>
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<tr>
<td>Woodie Flowers</td>
<td>Data/Network Visualization</td>
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<tr>
<td>Anna Thornton</td>
<td>Critical Information</td>
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<tr>
<td>David Wallace</td>
<td>Integrated Product Modeling</td>
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<td>Dan Whitney</td>
<td>Information Flow, Critical Information</td>
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Project Listing

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<tr>
<td>Low Volume Verification of Process Capability</td>
<td>Thornton</td>
<td>Basak Ertan</td>
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<tr>
<td>Capturing Design Assumptions Using Key Characteristics</td>
<td>Thornton</td>
<td>Mark Ardayfio</td>
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<td>Key Characteristics Definitions and Uses</td>
<td>Thornton</td>
<td>Don Jay</td>
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<tr>
<td>Integrated Tools and Methods to Measure Variation Risk</td>
<td>Thornton</td>
<td>Tony Chen</td>
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<td>Product Development Process Planning using Web-Based Technology</td>
<td>Murman,</td>
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<td>Integration Mechanisms in Dispersed Development Teams: An Empirical Study</td>
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<td>PDP Information Flow Modeling</td>
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<td>Tyson Browning</td>
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<td>Integration Analysis of Product Architecture to Support Effective Team Co-location</td>
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<td>Randal Pinkett</td>
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<td>Product Data Model that Captures Relationships</td>
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<td>Qi Dong</td>
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<td>Product Development Process Decomposition</td>
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<td>Jen Jootar</td>
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<td>Visualization Trends and Relationships in Large Information Spaces</td>
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<td>Julie Yang</td>
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<td>Applying Goldratt’s “Critical Chain” Method</td>
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<td>Modeling of Information Quality and Granularity</td>
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<td>Problem Decomposition and Coordination</td>
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<td>Context-Dependent Model Visualization</td>
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<td>Interactions in the Distributed Design Environment</td>
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<td>A Strategy for Collaborative, Knowledge-Based Systems Engineering as Applied to Multi-tiered Supply Chains</td>
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<td>Feature-Based Analysis of Selective Limited Motion in Assemblies</td>
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<td>Assembly Oriented Design: Concepts, Algorithms, and Computational Tools</td>
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<tr>
<td>Algorithm for Aiding the Design of Complex Assemblies</td>
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<td>Set-Based Causal Models of Automotive Design Problems</td>
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Note: Some authors listed as None may have been omitted due to the nature of the table.
Appendix C

Terms and Abbreviations

CAD  Computer Aided Design.

CAE  Computer Aided Engineering.

CAM  Computer Aided Manufacturing.

CIPD  Center for Innovation in Product Development at MIT. CIPD is an interdisciplinary program devoted to the “creation and deployment of breakthrough product development science, processes and tools.” The Center has organized its research efforts into four thrusts: Designing Successful Products, Information-Based Product Development, Enterprise Strategy, and Accelerating Capabilities Improvement. The sponsoring companies include Xerox, Ford, GM, ITT, and Polaroid.

CP  Critical Parameter. This method is similar to Key Characteristics.

DOME  Distributed Object-based Modeling and Evaluation. A prototype software implementation of a framework for integrated product modeling. This is one of the research projects within Thrust II.

DSM  Design Structure Matrix is a tool for information flow modeling.

IBD  Information-Based Development. This is the primary focus of Thrust II in the Center for Innovation in Product Development.

IT  Information Technology.


KC  Key Characteristic. KC’s are those features in a product that, for their expected process variation will have a significant impact on the customer requirements of a product.

KJ Method  This is a tool that structures detailed information into more general conclusions. The methodology was outlined by Jiro Kawakita. It is used to provide initial structure in problem exploration. The KJ method is similar to affinity diagramming in customer needs evaluations.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>PDM</td>
<td>Product Data Management.</td>
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<tr>
<td>PDP</td>
<td>Product Development Process. The PDP includes the following phases: concept development, system-level design, detailed design, testing and refinement, and production ramp-up.</td>
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<tr>
<td>Thrust I</td>
<td>The Designing Successful Products research thrust within CIPD.</td>
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<td>Thrust II</td>
<td>The Information-Based Development research thrust within CIPD.</td>
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<td>Thrust III</td>
<td>The Enterprise Strategy research thrust within CIPD.</td>
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<tr>
<td>Thrust IV</td>
<td>The Accelerating Capabilities Improvement research thrust within CIPD.</td>
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<td>VLE</td>
<td>Vehicle Line Executive teams at General Motors.</td>
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