CATERPILLAR, INC.

Visit dates: March 17-18, 1994

Host: Robert Kleiber

Background

Caterpillar is the world's largest manufacturer of earth moving equipment. Its products include tracked vehicles, wheeled vehicles, and diesel engines. A typical tractor product is shown in cutaway in Figure 1. A medium size tractor of this type weighs 40,000 pounds and costs typically $160,000. It comprises about 4500 part numbers including internal parts in the engine and transmission. Add-ons to the rear of this kind of product convert it into a cable layer or winch. Advanced agricultural models have air conditioned cabs with FM radios, car-like interior styling, and comfortable seats. In addition to hardware products, Cat also has a financial operation that provides financing to customers of its products. This aspect makes Cat similar to Boeing and the major car manufacturers, indicating that the ability to serve both the technical and financial aspects of the customer's requirements is essential.

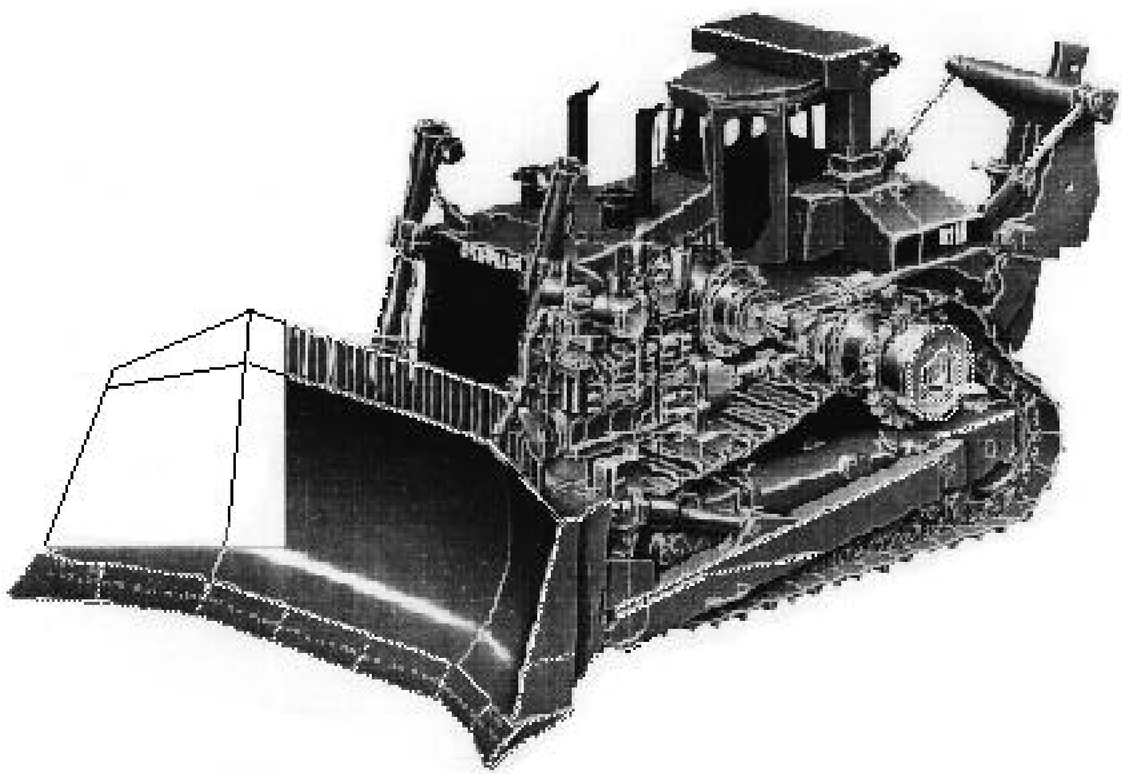

Figure 1. Cutaway View of a Typical Track-type Tractor

In fiscal 1993, Cat had annual sales of over $11 billion, almost half of which were from overseas. It has about 50,000 employees of whom about 13,000 are overseas. Employment in recent years peaked at about 60,000 in 1989.[1] Since then, sales have been flat and profits have fluctuated. The ability to hold sales flat while employment fell is due to a major corporate reorganization begun in 1990 together with significant improvements in design and manufacturing efficiency.

Caterpillar's main competition for over a decade has been Komatsu of Japan. Komatsu had advantages ranging from a low yen to the ability to package product sales with engineering projects. However, according to Cat engineers, Komatsu appears to have been willing to follow Cat's lead in design and technology. Although the past decade may have been somewhat anxious for Cat, its technological lead has been rewarded in the marketplace,

[1]All time peak employment was 90,000 in 1981.

and currently it does not regard Komatsu as a strong threat, but rather just a competitor.

Cat has sought to lead in a variety of technologies and has had to develop many of them in-house. It designs and builds its own engines and transmissions and makes some of its own transmission clutch friction material. The latter is a very tricky proposition, something that most auto companies leave to vendors. It also makes its own 6000 psi hydraulic hose as well as a vision camera for a seam-tracking robot welder. It made its own CAD software until 1990. Its interchangeable tool socket design for machine tools became a de-facto industry standard in the 1970s and provided the machine tool industry with a uniform way to mechanize automatic tool changing for FMS (flexible machining sytems) and other similar applications. Recently it specified a standard for data interfacing for internal factory use and mandated it for all NC controller vendors for its newest factory.

Cat's main technology is machining high strength steel, although welding is a close second. It maintains testing laboratories for cutting methods as well as metallurgy. It makes most of the major parts of its products from raw stock, buying specialty items. Welding is the main assembly method for the main load-bearing elements, and fatigue of welds is the limiting factor in product life.

In the last four years Cat has had to revisit many assumptions concerning its core business, mostly involving basic make-buy decisions and product development methods. These are discussed in some detail below. In summary, they include abandoning general CAD development in favor of commercial products, retaining a limited strategic capability in applied CAD/CAM software, reorganizing product development to de-emphasize technology and components and focus on top-down system development to meet customer needs, and streamlining factory operations. In its first reorganization of product development since 1970, the process was recast to emphasize Concurrent Product-Process Development (CPPD). This reorganization has had to break the operating habits of employees who knew no other method throughout their entire careers. New CAD software (ProEngineer) from Parametric Technology Company (PTC) has forced Cat to confront software and data linkages as complex as the new human interactions.

Additional Background

It is useful at this point to provide some information about ProEngineer because it impacts how companies organize their design processes. The main features that distinguished ProE from its competitors when it was first introduced are parameters, constraints, and associativity. Parameters are numerical values that a designer can assign to items in the design, such as the diameter of a hole or the distance between the hole's center and an edge. Constraints relate parameters, such as "distance must be 1.5 times diameter." Associativity establishes and maintains parameter constraints during different phases of the design process. For example, a constraint established on the solid model will be kept up to date on the drawings that are derived from that model. If the solid is later edited, the derived drawings will also change. The constraints can apply within parts as well as between them. The size of a bolt can be tied to the diameter of the hole it goes into, or holes on different parts can be related. Similarly, a machining or assembly fixture can be linked to the part being made so that part changes will be reflected in the fixture.

The existence of constraints and associativity has caused some problems for ProE users . They report that it can be difficult to edit a ProE model because a desired change can carry with it some unanticipated changes elsewhere in the design. [D H Brown, 1994] The constraints and linkages cannot easily be made visible. Consequently, in most cases the only personwho can successfully edit a model is the person who originally made it. In some cases the desired edit is buried beneath so many linkages that the only way to accomplish it is to rebuild the model from scratch. As a result, some users have simply turned associativity off.[2]

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[2] Many companies have found that they can overcome editing problems, at least in local geometry, by standardizing how certain features are constructed. Someone editing later can anticiapate the method used and can avoid surprises. [D H Brown, 1994, p. 2-8]

However, turning associativity off removes the main character that ProE brings to the design process. That character consists of elevating CAD use from definition of geometry to creation of engineering representations comprising geometry and the associated numerical relations. More generally, turning associativity off disables the way ProE intends to implement concurrent engineering (CE), namely that parameters, constraints, and associativity are important ways of defining and enforcing design intent throughout the many phases of product and process design.

In the largest sense, ProE has thrown down the gauntlet regarding CE by tightly and explicitly mechanizing communication about basic dimensions and their relationships. ProE users are discovering that actually doing CE in this way is very different from talking about doing it.

Cat has committed to ProE as its corporate CAD system and is now one of the largest users of that product.

New Product Introduction Process

The New Product Introduction Process (NPI) has been introduced at Cat in phases starting in 1989.[3] It aims to reduce development time in half and cut field failure incidents in half. The old organization was a classic functional setup dating from 1970, characterized by 5 - 7 year development times, a serial process, high costs and less than desired product reliability. People functioned in their organization only and did not understand the entire process.

To launch the new process, extensive cross benchmarking was done with companies like Ford, Hewlett Packard, Honeywell, and Johnson & Johnson. Dealers and customers were consulted. From twelve major recommendations, the following were the top seven:

- Early involvement in the process by everyone

- NPI accountability - each one should know his part in the process

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[3] Others dated the change from early 1990. As is typical in my company visits, there is disagreement about when a change began, when a design was initiated, when planning for a new plant started, etc.

• Frozen specifications - no more creeping specs

• Reduced time between product updates

• A standard NPI review process to see that each new product is on track technically and financially

• Reliability of the product

Cultural change is a big part of the NPI. As indicated below, a lot of long-lived habits of design methods and organization have been attacked. A team process is in place and participants are rewarded based on their contribution to the product. Design change policies are in place, intended to enforce some discipline and review. People are being drawn away from loyalty to their functional expertise and committment and toward the overall product's objectives. Co-location of multi-discipline teams is a major component of the procress. A common electronic database is being established, though it is not complete. The past legacy of design optimization and process planning tools remains to be integrated with ProE but is in progress.

Figure 2 indicates the timescale that the NPI seeks to impose on product development.

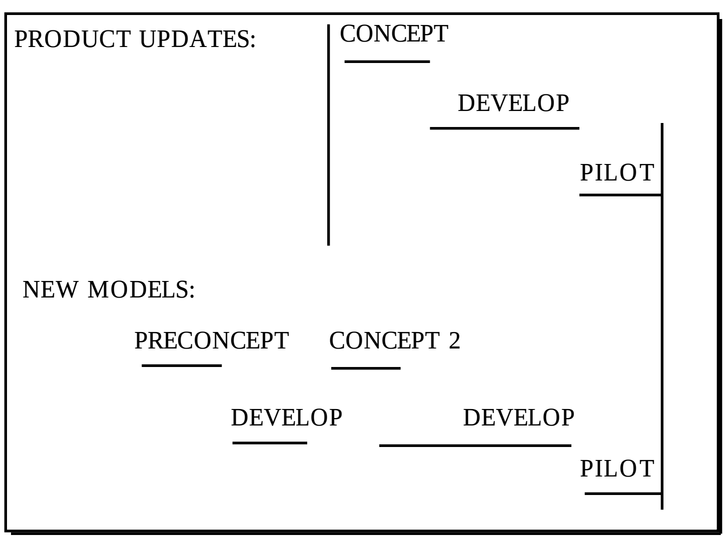

Figure 2. Sketch of New Product Introduction Process. New models undergo a two phase process while updates make use of technology proven during new product development.

Each product is intended to have a multi-year design life with roughly three updates during that time. This significantly shortens the time between updates in direct response to customer and dealer requests. The amount of new content in terms of parts or technology is limited in order to keep reliability high. The new content contributed by an individual component or system is scaled by its impact on the product's overall reliability as well as by how much it has been redesigned. The number of prototype vehicles built during the pilot phase depends on the degree of new content. A systematic risk reduction program is in place to monitor more advanced developments.

The reliability of mechanical structures is very high and is supported by years of experience and well-developed finite element software. Most reliability problems are experienced in hydraulics, structural-load dynamic interactions, and control systems.

Increased reliability of components is achieved by developing them first and then introducing them into new products. This means that component development is some years ahead of product development. Reliability has replaced novelty as a criterion. This switch is part of a longer term effort to convert Cat from being components-driven to being customer-driven. In both cases, components are developed first, but in the old process the component innovations drove new product requirements; under the new process the customer is supposed to drive the requirements. By developing components ahead of products, Cat runs the risk of not being current in new component technologies. Shortening the product development process will help but the urge to develop advanced components concurrently instead of ahead could still rise.

The only way to resolve the conflict is to make component development part of the evolutionary model strategy. This is a systems engineering approach, and is illustrated in Figure 3. New technology needs are identified as part of the long term strategy rather than originating with designers. The main drivers of the new process are determining customer requirements, having a good cost predictor and a good reliability predictor, and unifying product geometry, engineering analysis, cost estimating, and process planning.

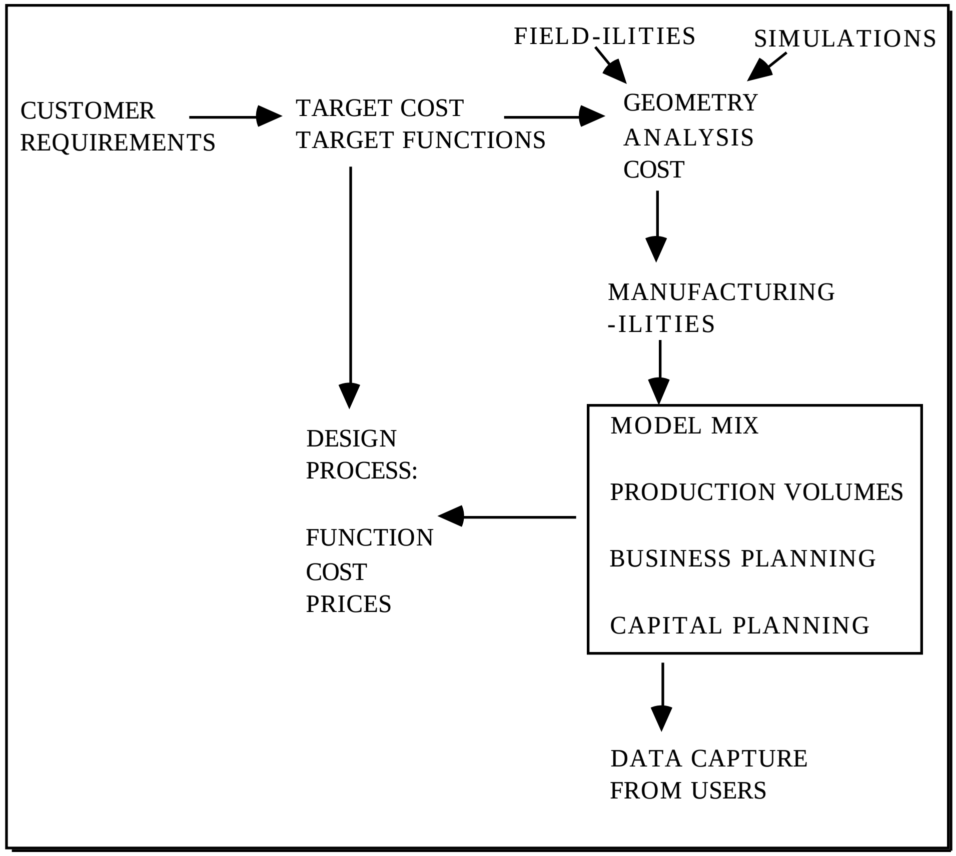

Figure 3. Sketch of Systematic NPI

There are major differences in execution between this process and the old one. First, everyone has access to data, including cost predictions. This permits more rational decisions to be made and defended. In the past, people had access only to the data relevant to their small part of the process, and a separate group of cost estimators held all cost information. Second, both manufacturing and outside sourcing decisions are made or considered earlier. Third, a digital definition is being built early and computer tools are being used much earlier. There was a tendency to "optimize" via the computer in the past, but not until late in the process. Errors were found late, and lack of a digital database permitted the specifications to creep. Now there is a definite database so a freeze can be declared.

Even though Cat had a well-developed corporate graphics system dating back decades, its operation was compartmentalized. The tools were excellent but the results were not communicated to other designers. The desire for isolated design excellence still persists, but a view of the whole design permits designers to see better how to fit their work into the overall objectives.

ProEngineer has had mixed effects on this process. Cat can see the long range benefits, especially as ProE's software in support of manufacturing improves. Cat must still integrate its existing library of optimization software into ProE so that improved designs can be made earlier in the process. Until that is done, designers will still be able to optimize their part of the design and avoid integration with the rest. ProE reinforces the individual designer's urge to optimize his small part of the design because it is so efficient at getting drawings made. Data sharing and associativity have not yet been exploited enough to overcome this well-entrenched priority.[4]

Evolution of CAD and Its Role in NPI

ProE is the latest in a series of CAD systems used at Cat. Starting in 1972, a 2D drafting system was used. From 1975 to 1985 Unigraphics was the standard, but in parallel, from 1981, Cat's own system called CAPT was developed and used. In 1990 a decision was made not to further develop CAPT while a search of the marketplace was made to find both a data management system and a new CAD system. In 1992 ProE was selected, but it is being introduced gradually due to the large legacy of CAPT datafiles. Also, ProE has yet to replace or link in a lot of functions done by stand-alone software. These include finite element analyses, assembly drawings, dynamic analyses, design of NC programs and cutting tools, bills of materials and shop floor instructions. Cat developed many of these programs and still feels that they are better than what is commercially available.

Cat is still working to understand how to exploit associativity without suffering its downsides. Engineers agree that associativity is easier to comprehend inside single parts and harder to keep under control when it extends over many parts. However, a good example was given that uses multi-part associativity. It concerns design of a fuel tank. The existing tank design blocked the driver's view of a cable laying tool in the rear of the tractor. The tank was modified as shown in Figure 4.

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[4]An executive at an automobile company said "ProE encourages the draftsman's instincts."

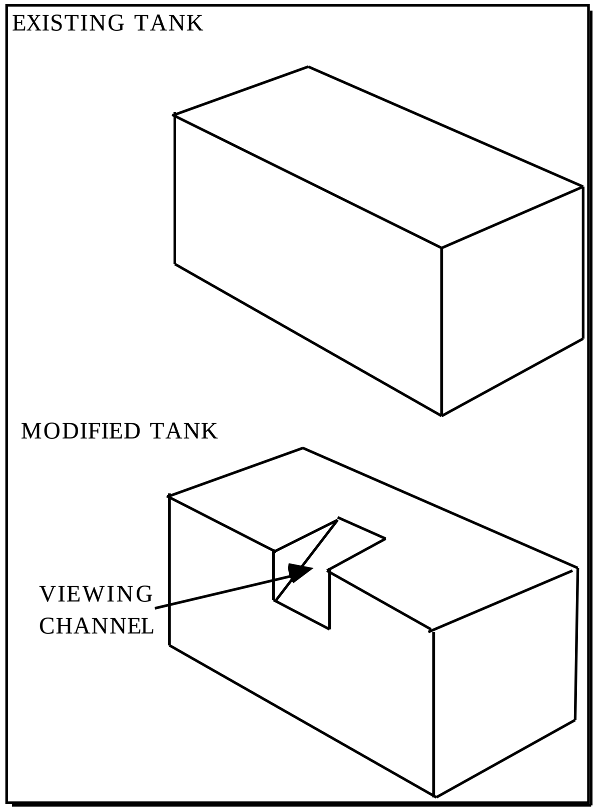

Figure 4. Two Fuel Tank Designs

When the tank was originally designed, the welding fixtures were also designed and linked by associativity to the tank's shape. When the design had to be changed, the fixtures changed along with the tank. The solid modeling capabilities of ProE also permitted the tank's fuel volume to be calculated easily, permitting the designer to retain the original volume while inserting the viewing channel.

In another example, a ProE model was used to explore the maintenance implications of hydraulic hose routing. Parts suppliers and dealers were shown the alternatives, and an agreeable one was selected. This is an example of a growing trend to design hoses and wires in advance, an improvement over routing them on the prototypes and then documenting the routing. The resulting designs were used as illustrations in the service manual.

Process Development

Process development at Cat mostly means machining, although assembly is also being planned with computer aids. The method of design-build-test must be avoided in process development just as it must be in product development. So simulation of both machining and assembly are being used.

The greatest challenge is in machining process planning. The main problem is to understand process capability and find the right process to achieve the required tolerances. Cat is not only trying to systematize this with parts made in-house but is also trying to apply the idea to parts procured from suppliers. This requires setting standards for machine tool performance and communicating those standards to suppliers along with the part designs. A set of library features is being developed with the aim of providing them with verified process plans and predictable tolerances and costs.

Project and Data Management

Most CAD companies view design as creation of geometry and make that the strong point of their software. Most large companies see design as data management and find that CAD vendors are not experts in that area. As a result, product data management software must be bought from a different sector of the software industry. Only in the last two or three years have CAD vendors begun to offer strong product data management systems.

Cat sees product development as data management and has identified the main kinds of data that must be managed. It then examined its software and found that the software was managing Cat rather than Cat using the software to run the company. In addition, different departments had their own tools for process and data management.

An internal study showed that of all the things that might be managed, Cat was really managing only part numbers. Among the vital things not being managed were:

- gages
- assemblies

- tools
- layouts
- requests for action
- NC programs
- lifiting devices
- etc., etc.

Of all these items, the one that seems out of place but is in fact the most interesting is the request for action (RFA). It turned out that the RFA was pervasive across Cat, arising in design processes, customer requests, factory floor operations, sales, and so on. As a result, Cat is focusing on the RFA as a unifying principle in project management.

CAD/CAM Demonstrations

The visit included demonstrations of several recent applications of ProE and other commercial software. These included:

1. A complete ProE model of the frame of a tractor. The frame is the crucial element of the tractor since all the power train and traction equipment mounts to it. It takes all the major loads and is responsible for maintaining all critical alignments in the power train. It must be strong and light and have a long fatigue life. The frame model contains about 200 different parts, each of which requires a separate set of drawings and process plans for machining. The frame is then welded together and more machining is done. Using this frame, Cat explained to PTC what a large design is.

Even though NC programs could have been made directly from the solid model, the factory wants drawings. Direct NC flame cutting of the stock is also possible, however, and is done routinely.

2. Direct NC programming of lathes: ProE is being used to link part designs to NC programs. When the part design is changed, the NC changes automatically. To do this properly requires the "part" design to contain a

model of the chuck and other fixtures to ensure that the cutter does not collide with them. The chucks and tools are made from a library of standard elements. A separate machine simulation program can predict the overall time required to make the piece. Using this program the process designer can try out different cut sequences, check the program for errors, and avoid collisions.

3. Computer-aided process planning: This really comprises logistics, that is, mustering all the parts, materials, fixtures, tools and instructions needed to do some machining or assembly job. One can plan a new job and be sure all the needed items will be available when and where needed. A product can be exploded into its subassemblies and component parts, and each can be associated with the tools, drawings, and other resources needed to get it made and delivered where and when it is needed.

4. Design for manufacture and assembly: The Boothroyd-Dewhurst design for assembly software was recently connected to ProE. The first test at Cat was applied to redesign of a driver's seat. This is a technically unsophisticated but complex assembly. The B&D software was used in part as a device to bring a team together and focus it on assembly issues. The implementation of B&D DFA on ProE is relatively straight forward. In most cases, the user sees a screen similar to conventional stand alone DFA and must answer the questions manually. ProE will display any part or subassembly under consideration and will calculate certain mass properties needed for answering questions. The original implementation used assembly times that were relevant to finger assembly of small parts, so the predicted times and costs did not make much sense. B&D has been working with Cat to provide data more relevant to the sizes of Cat's parts.

The group's experience using this software was revealing. "We didn't learn much about cost or time to assemble but we really understand that design now. Assembly is CPPD-rich." Yet real design for assembly is still not available. What they want is the ability to plan assembly early in the process, before there are finished part designs. They want to be able to explore subassembly options, and to use DFA on skecthes rather than finished parts. They also wish that the part designs in ProE were not so hard to edit. The whole design process needs to be inverted; right now one designs parts and then assembles them, whereas one should lay out assemblies and attach parts to them.

Summary

Caterpillar is in the midst of maturing into a data-driven company after being an iron-driven company for most of its history. There is general agreement that this is an evolutionary process. Yet Cat has decided to cast its lot with commercial software for this purpose, retaining internal expertise in a few specialty areas. Among these are various stress analysis packages and a method of compiling customer requirements. The computer support manager estimates that 10 years ago he would have identified over 100 "strategic" programs under his management. Today he would put the number at 10 to 20. A considerable fraction of them are financial, not technical.

References

[D H Brown, 1994] "Status of Modeling: PTC Drives Technology," an annual survey of the largest ProE users, dated July, 1994. D H Brown Associates, Inc., Port Chester NY.