Trends in Product Modelling - an ENDREA perspective

[3,5]Ola Isaksson*, [3,6]Freddy Fuxin, [3]Peter Jeppsson, [3]Henrik Johansson, [2]Per Johansson, [4]Timour Katchaounov, [5]Mats Lindeblad, [3]Haoxue Ma, [1]Johan Malmqvist, [1]Samir Mesihovic, [1]Krister Sutinen, [1]Daniel Svensson, [3]Peter Törlind

[1]Chalmers University of Technology, Machine and Vehicle Design
[2]Linköping Institute of Technology, Department of Mechanical Engineering
[3]Luleå University of Technology, Division of Computer Aided Design
[4]Uppsala University, Department of Information Science
[5]Volvo Aero Corporation
[6]Volvo Truck Corporation

Abstract

The success of engineering companies is highly dependent on how well product information is managed, engineered and communicated. From marketing through development to after sales activities, data needs to be accessible and used in the best way. Today, geographical distance, the need for close co-operation and data complexity are all natural parts of the working environment.

Product modelling techniques are continuously evolving with new requirements and opportunities emerging daily. This paper will outline and discuss some of these trends, and at the same time present some of the areas where research is being carried out within projects in the Product Model Cluster in the national graduate school - The Swedish Engineering Design Research and Education Agenda (ENDREA).

---

* Corresponding author. Address: Ola Isaksson, Volvo Aero Corporation, SE-461 81 Trollhättan, e-mail: vac.olis@memo.volvo.se, tel: +46 520 93987, fax: +46 520 98584

1 Introduction

Many companies now function as global enterprises where practically all work is distributed and co-ordinated worldwide. Contemporary product development thus requires information to be communicated between people, organisations and software tools in this global context.

It is easy to think that all the data associated with a product during its life, from conception, design, manufacture, use through to final disposal, could be stored in a single database. However, the reality of the situation is that this is neither possible nor desirable. In practice companies use heterogeneous databases, often distributed geographically.

Numerous software tools exist to help predict and visualise the behaviour of new products and to simulate the way they are to be manufactured, used and maintained. All these activities require digital models of the product. Developing a single description of a product model which included all possible data about a product would, like the monolithic database, be difficult to achieve in practice and, even if possible, would be too large, complex and rigid. Enabling communication between models and definitions of context dependent views are more realistic ways to grasp the whole picture.

Product Models (PM's) are central to Integrated Product Development (IPD) since they deal with all aspects of information and data representing the product. In much product development work, the term product model is most often used to refer to the 3D CAD models that are in daily use in many companies. For more complex products, such as cars and aircraft, digital mock-ups are used to enable co-ordination and parallel development of large scale engineering products.

Efficient definitions, modelling, use and applications of product models in all life cycle phases are required to meet today's needs and those of tomorrow.

1.1 ENDREA and the Product Model Cluster

ENDREA, The Swedish Engineering Design Research and Education Agenda, is a national initiative supported by the Swedish Foundation for Strategic Research (SSF) aimed at enhancing doctoral education within engineering in Sweden. ENDREA PhD students, currently numbering 50 working at five universities, take part in numerous joint activities and courses and benefit from a wide network of both formal and informal contacts from academia and industry.

Within ENDREA, 'clusters' have been formed to allow PhD students and senior academics working on related problems to share experiences and co-ordinate activities. The Product Model Cluster provides focus for the 10 ENDREA projects that have product models as a common point of interest. The cluster members meet regularly, both at their own universities and at companies interested in product modelling.

During the spring of 2000, the PM cluster visited several companies in the USA to learn more about the activities of these companies related to product modelling. Some of the trends reported in this paper are one of the results from that trip.

2 Product models in context

A five-step model is presented in Figure 1 that presents different views of product models. The model is used to organise the rest of the paper. There is a logical link illustrated by the arrows such that one block is affected by the previous block and affects the next.

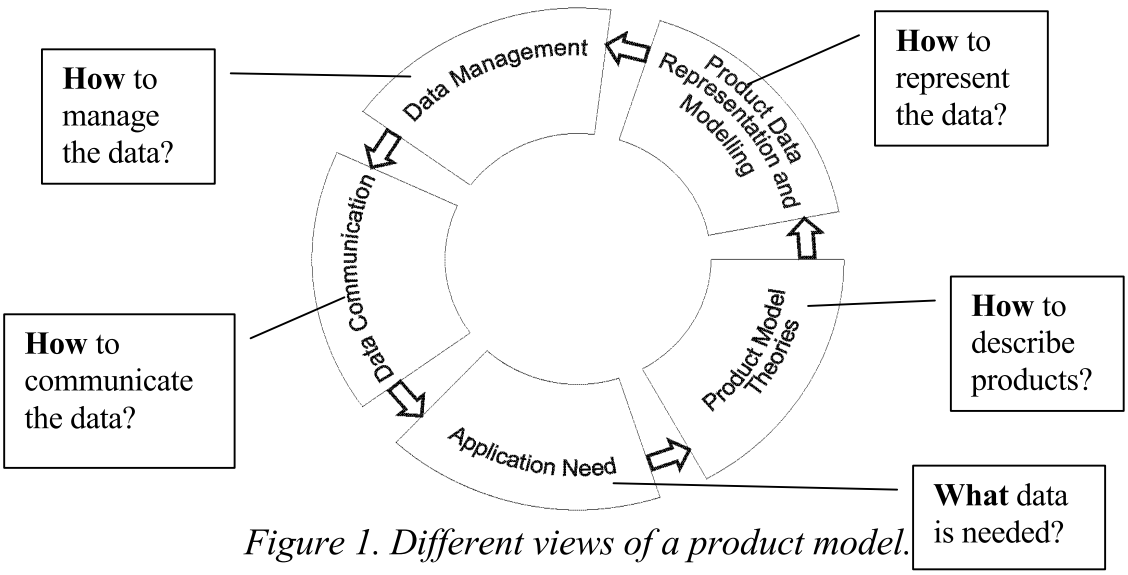

Figure 1. Different views of a product model.

Going counter clockwise starting with data communication;

In order to *communicate* data it is necessary to retrieve data from some *product data management* system (PDM). The data in the PDM system needs to be well organised and structured. If it were not, it would be impossible to find and extract the information needed. The way data is organised can be described on a higher level by an *information model*, often defined in an object-oriented information modelling language such as EXPRESS or UML. Which data structures need to be modelled depends on an underlying idea of how to represent product models. There are several *theories of how to represent products* which are related to the data that is needed to perform the various activities during the life cycle of a product. The *need for product data comes from the activities performed*, such as design, analysis, manufacturing or maintenance. Within each of these activities data need to be shared and communicated in many ways.

Each block will now be presented in more detail.

2.1 Application need

The many different activities, techniques and tools associated with the product development process (Figure 2) all use product data. In other words, there is an *application need* for product data.

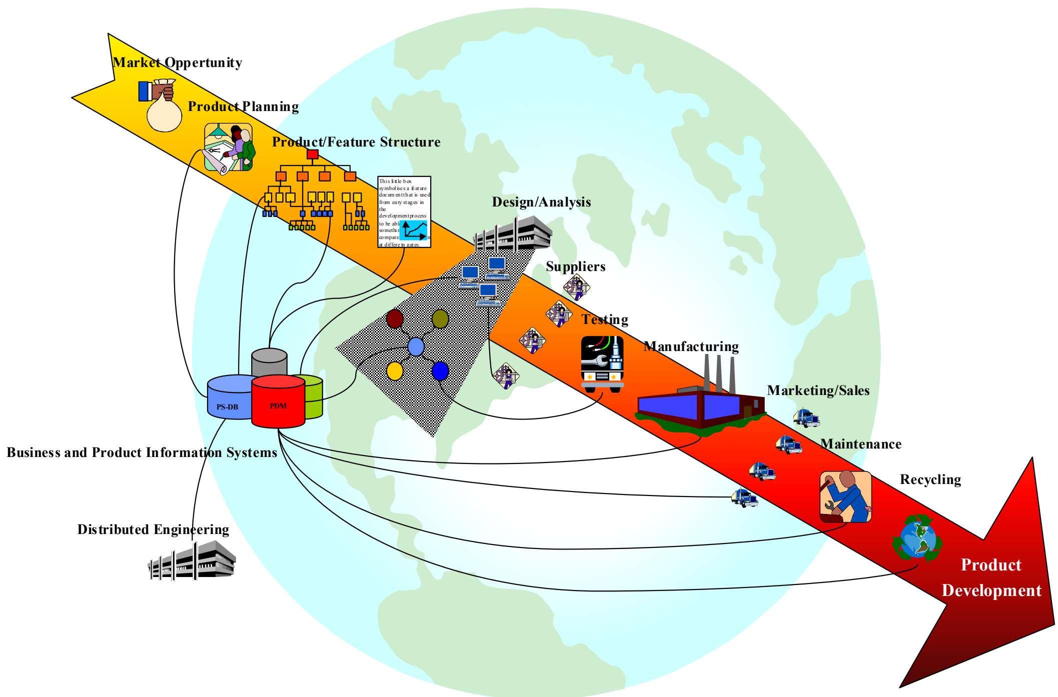

Figure 2. Activities in the product development process.

Many of the activities traditionally performed early in the process are more innovative, that is entirely new data is *generated*. For it to be of value, this data must be accessible to downstream activities. One of the primary objectives of the product model is to make application-specific data available for each of the different phases and activities in the development process

The product model contains much of the data related to the product. A key element of this is a geometric representation, but also configuration and product structure data as well as engineering analysis and manufacturing planning information are needed. (See Figure 3)

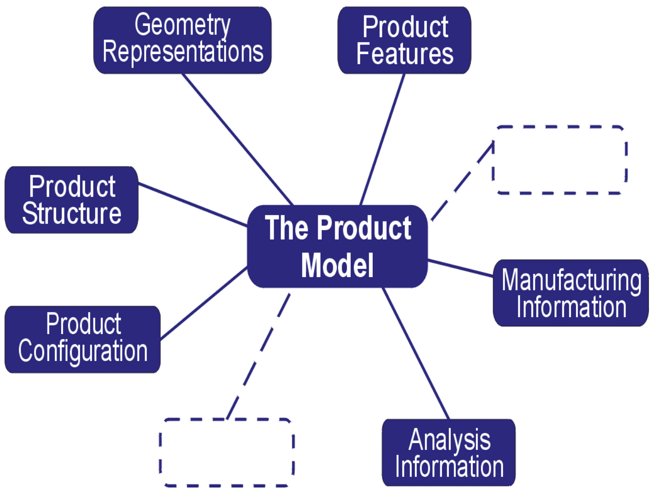

Figure 3. Possible content of the Product Model

The characteristics of the product data required vary considerably depending on issues such as:

- *Length of the product life cycle.* The extremes encountered in the life of today's engineered products range from aircraft engines, with a life measured in decades, through to mobile phones, where new products seem to appear every few months.

- *Internal or distributed.* Information may only need to be accessible within a single company, however, extended and virtual enterprises place demands on being able to share data over company boundaries.

- *Mergers and acquisitions.* It is not uncommon for companies to merge or be taken over. This can have immediate consequences over the strategies and systems used within a company.

- *Product complexity.* Products are becoming increasingly more complex. This is due to several factors including higher levels of customer adaptation, greater use of integrated electronics as well as increasing part commonality and product modularisation.

- *Digital Product Models.* Digital product development is today a reality. Such techniques reduce the need for physical prototypes to a minimum and allow sharing and reuse of digital product data throughout the product lifecycle.

2.1.1 Trends within "Application Need"

Systems generating and using digital product models are a key feature of many aspects of the product development process. The trends presented below are a direct consequence of the need to integrate, manage and effectively use these systems.

Digital Prototyping. It is today feasible to carry out most product development work entirely digitally. A geometric model can be used to support activities ranging from product design, engineering design and analysis, manufacturing and assembly, service, sales and marketing. Whilst these different activities require different strategies for visualising product data, today's product models are increasingly able to cater for these varying needs.

Resource, Constraint and Data Management. In addition to the need for geometric product data, development projects must also handle administrative product data related to managing variants and constraints resulting from specifications, customer requirements and marketing information. These in turn define configuration, functions and features of the product.

Reuse of parts. It is not uncommon for several development projects run in parallel; overlapping each other in time. When working in this way, it can be beneficial if components and systems that are developed and used in one project can also be used in parallel projects. In order to support these staggered development activities, product model data must be accessible over project boundaries.

Capturing product and process knowledge. Ever increasing lead-time pressure in combination with raised quality requirements have motivated the development of new design systems capable of capturing experience. Intelligent CAE systems and Knowledge Based Engineering (KBE) systems are being increasingly adopted in engineering companies.

Examples of these trends can be found in the automotive and aerospace sectors. Over the past five years, Ford has developed a corporate environment C3P, which stands for CAD/CAE/CAM and PIM (Product Information Management). By allowing all participants in a development project, including suppliers and other strategic partners, to work in the same system, lead-times have been shortened and the quality of early prototypes improved. Whilst the initial effort concerned unification of CAD system usage and nightly updating of mock-ups, the company is now focusing on engineering (CAE), manufacturing (CAM) and management of other types of product information (PIM). Aerospace giant Boeing has worked closely with several engine manufacturers to develop a digital pre-assembly system (DPA) based upon data exchange between different CAD systems using the STEP standard. Boeing continue to participate in the development of neutral formats, including STEP, as one of their basic philosophies is that data in neutral formats should be the source for all types of product information, including all types of geometry representations.

It is clear that levels of collaboration, both within companies and over company boundaries, is becoming more intense and globalised. The systems supporting corporate product development activities are now recognised as being critical to a company's success.

In ENDREA, most projects have taken these trends as a basis for research. From different perspectives, all projects use industrial partners for observations, case studies and tests.

2.2 Theories of product modelling

Until relatively recently, an engineer's view of product modelling has been a purely technical one; concerned with the problems of how to create a robust geometric model in a CAD or CAE system. However, as computer aided design and engineering environments have improved and data management systems allowed this data to be more easily shared, new problems have emerged.

An increasingly important consideration is how to create a stable yet flexible model capable of representing the entire product. Since today's CAD/CAE systems are generic tools, there are many different ways of using them to model a product. A feature of many CAD systems is that geometry is created in a number of steps. A designer may choose to create geometry using many simple steps, a few complex steps or any strategy in between. If changes need to be made, it can be difficult with a model with many steps to choose the correct point in the geometry development history to make the change whilst the complex steps used to generate a model with a more compact history tree may be impossible to change. It is not unknown for engineers to simply start from scratch and recreate the geometry rather than to try to modify geometry created by someone else! As parametric and knowledge based modelling techniques are introduced, the need for modelling theories and strategies become even more pronounced.

In order to generate a sound product model, it is important to have a clear idea of how to decompose product geometry. Whilst the science of engineering design has created elegant theories, such as the Theory of Technical Systems (TTS)[1] , describing how product models should be structured, these are hardly, if ever, used in industry. More widely implemented techniques used to organise and structure information is Systems Engineering (SE) [2] [3]. It was initially created to support development of complex systems whilst the TTS is the result of European research into engineering design. Whilst sharing some features, SE is more concerned with analysis and lifecycle management and has been formalised in at least two standards, IEEE 1220 and EIA 632, whilst the European Design research has a more product oriented view, decomposing specification into a component structure using a, so called, chromosome model of a product [4]. See Figure 4.

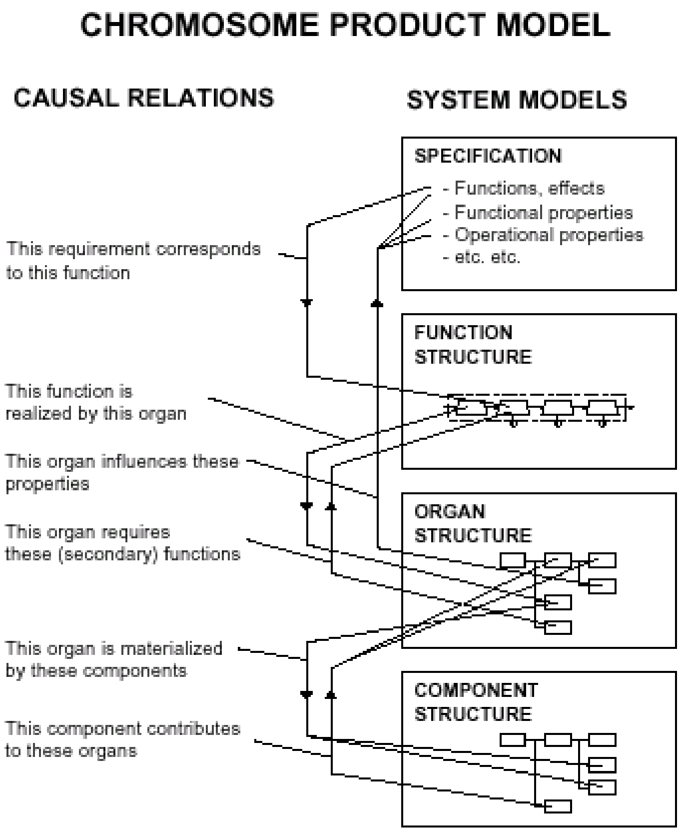

Figure 4. The chromosome product model.

The chromosome model has been extended by inclusion of requirement specification model [5] together with life phase process model to derive properties as weight, cost etc.

These techniques (TTS and SE) are concerned with high level structuring of product data. At a more detailed level, interest in techniques to formalise engineering know-how, often referred to as knowledge based engineering (KBE), is increasing. KBE has been around for many years; one of the best known systems being iCAD which dates from the mid 1980's.

It is clear that the need for a systematic way to describe products is increasing in importance since product models now include complex constructs such as rules, variants, requirements and product configuration possibilities.

In ENDREA PM, the requirements engineering methods and configuration design and management are emphasised.

2.3 Product Data Representation and Modelling

Product data must be represented in a complete and unambiguous way to facilitate the storage, sharing and exchange of information, as well as searching for information. This representation, which is a formal specification defined by information modelling techniques, is called the product model. Information modelling has become a discipline of its own because the definition of complex datasets needs to be methodically designed. Information modelling is used to define information requirements for a wide range of application areas, e.g. PDM systems and product model standards in different industries.

One core concept for information modelling is that it must be both human- and machine-interpretable. A well-defined information model is one way to ensure that data can be interpreted and used over a long time. Historically, system requirements have been defined in textual languages, which have had to be interpreted and translated to computer code by humans. No matter how carefully defined the rules are, there is always room for varying interpretations in implementations. To communicate data then becomes a problem. This is the main problem with standards such as IGES, which is used for geometry definitions.

2.3.1 Representation

The capabilities of representation have evolved with the development of object-oriented techniques. The capabilities progressed from lists of values defined by text documents to product models that also take care of the semantics, internal relations, within the model. The modelling language that describes the product model must therefore also be able to define these semantics. It is important that both humans and computers can interpret the modelling language, so that misunderstandings and misuse can be avoided. One way to solve this problem is to define rules within the model, and thereby use the language as a "correction-parser" of the content.

There are a number of languages that are capable of handling product information together with semantics. The two languages used most today are the lexical language EXPRESS [6] and the visual language UML [7]. Both these languages are defined by international standards and are not based on any specific implementation technique or specific programming language.

The advantages of EXPRESS, compared with UML, are its capacity to handle rules and the fact that it specifically was designed to describe product information. UML was originally designed to describe software development projects, but the general structure of the language also makes it suitable also for describing product information. UML also has the capability to describe processes and display different views of the product information.

2.3.2 Information exchange

The information used and produced by the activities in a product development process must be accessible to the different activities. The results from one activity are often used as input parameters for others. Even though all activities are based on information belonging to a single product, each of the different activities needs its own “view” of the information.

The product model must support the information that is needed to produce the “views” that are needed in all the activities. The model must also contain enough product information to support the needs that arise throughout the development process and the life cycle of the product. A product model that is capable of meeting these requirements enables and facilitates the sharing and exchanging of product information within the development process.

Defining a structure on which the information will be based and which will support and satisfy all the activities involved is often the problem. There are different ways to address this problem, some of which are: [8]

- Direct links between the different programs that are used
- Using de facto standards
- Using tools from a specific vendor
- Implementing a corporative standard
- Persuading vendors to implement support for standards

2.3.3 The STEP Standard

Different projects have addressed the issue of formal representation of product models for supporting the different activities within the development process. The project that has attracted most attention is the one that has resulted in the STEP standard.

The STEP standard [9] "...is an international standard for the computer-interpretable representation and exchange of product data. The objective is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving."

The STEP standard is divided into many parts, each part supporting different types of product information and their usage. The existing parts include support for Drafting, Solid modelling, FEM and CAM, whilst new parts are under development to cover more product information. STEP and related ISO standards under development, such as ISO 13584, 15531 and 14649, will support emerging requirements, such as parameterisation and module thinking.

2.3.4 Examples of different approaches at companies

Different companies use different approaches to the exchange of information, both within the company and with its sub-contractors. Here are some examples of approaches that were found during the trip to USA and visits to companies in Sweden. It is not likely that all parts of the companies use this approach to communicate information, but rather the general approach is presented.

Ford Motor Company standardises its development environment by using only tools from one vendor, or tools that is possible to integrate within this environment. They also support their sub-contractors with the migration to and usage of these tools.

The Boeing Company's strategy is to support the usage of international standards in all their data exchange activities. They are currently demanding that STEP files should be used to exchange geometry and are also deeply involved in the development of the STEP standard, especially in the area of engineering analysis area.

Lockheed Martin Aero, like Boeing also use STEP. From a data management point of view the use of application protocol AP232, Packaging Technical Data, is particularly interesting. AP232 is used to distribute files and data in a single package instead of as single files. Lockheed Martin is also uses STEP to transfer data between PDM and ERP systems. The STEP PDM schema is used as a middle format, in which mappings are made between the two systems.

Volvo Aero Corporation is currently developing an infrastructure for the exchange and archiving of computational results. The infrastructure is based on an in-house developed information model that supports both the in-house codes and commercial programs that are used in the development process.

It is clear that the IT revolution has created a need to define and control product models using computer-interpretable descriptions. Meanwhile, computer techniques can be developed to meet the needs from product model applications.

In ENDREA PM, the techniques being developed in the area of computer science are being explored as enabling technologies to enhance PM's. Also, information-modelling principles are used to define strategies for data integration strategies between engineering systems.

2.4 Data Management

Once the information has entered the product model, it must be possible to handle it. Different kinds of systems are used to manage this task. PDM systems keep track of the masses of data and information required to design, manufacture and then support and maintain products during their entire product life cycle [10]. They also ensure that the right information is available for the right person at the right time and in the right form [11]. PDM systems also provide support for modelling of processes used for data management. Today PDM systems are used by project managers, designers, engineers, administrators, manufacturing, sales, marketing, purchasing and other personnel in the companies. Product-related information controlled by nel in the companies. Product-related information controlled by PDM systems includes part definitions and other design data, engineering drawings, project plans, software components of products, product specifications, NC programs, analysis results, correspondence, bills of materials etc.

2.4.1 Commercial systems

Some of the major PDM systems on the market today are Metaphase [12], Enovia [13], iMAN [14], Windchill [15] and eMatrix [16]. There are also a number of smaller PDM suppliers with specific solutions that are often oriented towards small and mid-ranged companies.

Commercial PDM systems have been used in companies for more than a decade now. The functionality of PDM systems has increased considerably from file management and CAD file vaults in the middle eighties, via change control and configuration management in the early nineties, to process management and improved user interfaces in the late nineties. Recent developments of the PDM systems have been oriented towards web-based solutions that support the full product definition lifecycle and eBussines [17].

Many companies today have realised the strategic importance of a PDM system implementation. PDM investments (software and services) in the industry continuously grow, from $1.1 billion in 1997 to $ 1.7 billion in 1999. Market shows growth in all major industries. Automotive and electronic industries are leading investors. Then come the aerospace industry, the mechanical machinery and other discrete manufacturing [17]. But the implementations have often been associated with problems and large costs. Services account for a greater part of the implementation cost. However during the last years more successful implementations have been achieved. That can be explained with software and hardware development and the growing PDM interest in industry that results in a stronger commitment to the PDM projects.

Still there is lot of work to be done in order to improve PDM systems functionality and to develop methods for their proper implementation and use in various areas of the product development and sales-delivery process. There is a gap between the need for product data management in industry and the knowledge available in this area. There are not enough skilled people available at the PDM consultancy firms and the research and education performed at universities in this area is not sufficient to fulfil the needs. Research has been focussed mainly on the technical aspects of data management, such as computer systems and data representation, while questions related to the data management processes have not gained much interest yet.

2.4.2 Examples of companies that use PDM

Ford Motor Company has with their C3P concept standardised the CAD and PDM systems and use SDRC's IDEAS for CAD and SDRC's Metaphase for information management. C3P is used in 42 car platforms out of 60, and there are 8100 Metaphase users and 5200 IDEAS licences at Ford and 4000 IDEAS licenses at Ford's suppliers.

The benefits experienced from the C3P project at Ford are shortened lead times from 50 to 36 months, prototype costs reduction by 50%, increased re-use of components by 30%, and reduction of late and expensive changes by 50%.

Boeing's approach is different from Ford's, since Boeing standardises the formats used to exchange data between systems rather than standardising the computer systems. Boeing claims that no single commercial PDM system can meet their requirements and therefore use a number of systems including Metaphase, Sherpa, IMAN and Windchill.

Although PDM systems have been around for a good while, the capabilities are not sufficient yet. Again, the complexity of data needed to be managed continuously increases, and the integration between engineering systems is not trivial to achieve. In the ENDREA product model cluster, one project investigates the product structure management issues of PDM and another project is about the implementation of PDM based support for product configuration.

2.5 Data communication

Tools, methods and techniques to help communicate product data are developing rapidly. Communication is concerned both with accessing a defined subset of data in a suitable form as well as human to human communication.

Digital prototyping currently has its main focus in the late concept and engineering analysis stages of the product development process. Digital prototypes should, however, also be used in earlier concept stages in order to evaluate as many concepts as possible before the product becomes too well defined.

2.5.1 Computer-supported cooperative work

The tools used to help individuals work together via computer are known as groupware or computer-supported cooperative work (CSCW). Key functionality in CSCW systems includes multi-user interfaces, concurrency control, group awareness, communication and co-ordination within the group, shared information space and the support of a heterogeneous, open environment that integrates existing single-user applications [18]. CSCW applications are often categorised on a time/location diagram. (See Figure 5.)

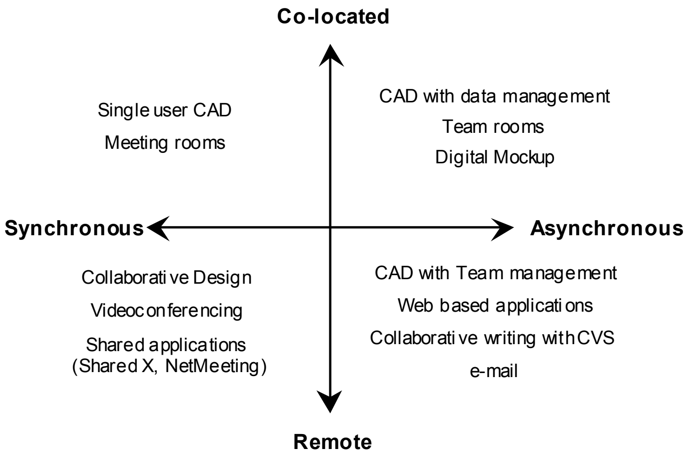

Figure 5. Use of CAD and other design tools across time and space, from Maher and Rutherford [19].

Many research systems for asynchronous distributed engineering based on Internet or world wide web solutions have been developed including Madefast [20], WebProM [21], and the CPD system [22]. Many commercial PDM and CAD systems are also "web-enabled" which enables access to product data via the Internet where it can be used for discussions, collaboration and marketing. Such systems, however, were not originally developed to support collaborative design. For this to take place, synchronous distributed collaboration is required where where people can share, interact and communicate product information using Internet based systems in real time. Several research systems such as CAIRO [23] and VPE from Fraunhofer IGD [24] have been developed.

Shared application systems such as VNC, SUNForum and NetMeeting enables people sitting in different places to share applications (i.e. windows). The shared 3D viewer [25] (commercialised by CoCreate) can be used for sharing 3D-geometry and allows limited interaction with the geometry.

Another trend for communicating product data is using ASP (Application Server Providers) using centralised applications for the storage and sharing of product data. An example is 3Dshare.com, from PlanetCAD [26], where users can translate and heal 3D models via their website. 2Dto3DCAD.com [27] is another ASP that converts 2D CAD drawings to 3D parametric models.

2.5.2 Digital mock-up

The use of digital mock-ups (DMUs) allows companies to share and communicate information between different users, departments and companies. The use of DMU's in mechanical engineering makes it easier to communicate information to other "non engineering" domains such as management and customers. However, one of the main applications remains creating digital mock ups of large scale assemblies, often with data from several sources and in different formats such as native CAD data, STEP- and IGES.

2.5.3 Virtual Reality

Virtual Reality (VR) is another area that has been used for many years and is increasing in importance in engineering applications. Geometrical modelling is normally done in a conventional CAD program which is then imported into a VR system such as MultiGen, dVISE or Opus. The VR system allows detailed visual real-time simulations of the virtual product using textures, lightning, reflections and shadows. The visual simulations can be used for mechanical design as well as numerous applications of simulation and training [28]. VR-models can be experienced at all levels from single computer screens through to large screens (so-called Power Walls) or Caves. Virtual reality can be used as a tool in collaborative work settings, where people can visualise the designed parts, interact with them and simulate and verify the function of the product [29].

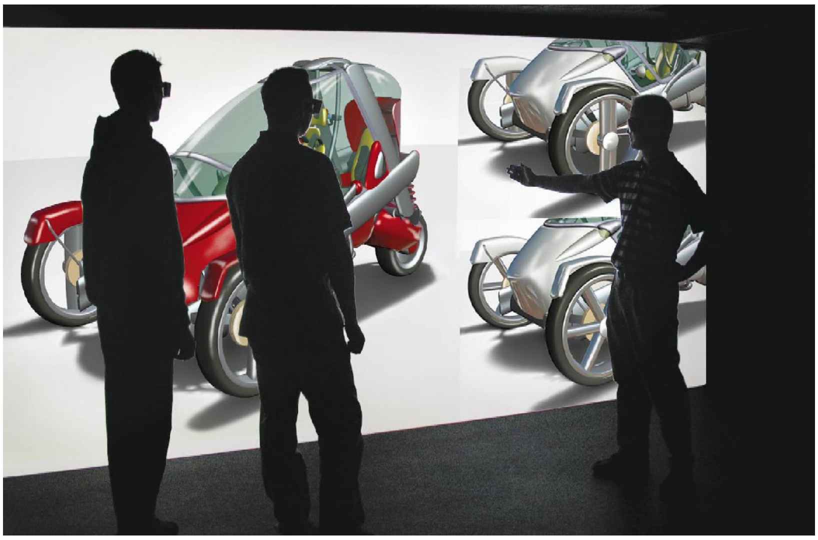

Figure 6. A presentation using large screen displays and the Opus software from Opticore.

The use of a distributed team and one shared virtual world makes it possible to be at different geographic locations and still work together in the virtual "room". Such systems can also combine DMU functionality, allowing assembly or fit of components to be tested interactively. Research systems include Distributed Collaborative Engineering Environment (DCEE) [30] and the DING environment [31]. Other research topics in VR today is augmented (mixed) reality, haptics (the sense of touch) [32] interface- and display design. The world wide market for visual simulation and VR is currently valued at $24 billion; with 50% annual growth. [33]

Distributed Collaborative Engineering is a reality, and the technology supporting this work is under rapid development.

In ENDREA, one project focuses on the distributed engineering environment while another developed a methodology for development using VR technology.

3 Conclusions

This paper has presented and discussed trends in the area of product modelling. The driving *need* for developments in this area is the fact that a wide range of activities associated with product development is within the scope of product modelling. For this reason, models are required that will support work during all phases of a product life cycle, ranging from identification of customer needs to planning final disassembly. Digital product models increasingly need to be globally accessible and encompass increasingly complex, multi-technological, variant-rich products.

It has been argued that the contents of the product model should be based on a *product modelling theory*. Well-defined and accepted standards as STEP exist for geometry models. However, there is a need for better representations of abstract data, such as requirements, function and product families. While, some useful theories exist in these areas, there is less consensus in the research community.

To implement the product model theory, standards for *information modelling* are needed. Here, there is a trend towards the use of open formats such as STEP and XML, and towards standardised modelling languages like UML. The use of open formats is advantageous for managing data over long product life cycles and for communication with partners and suppliers.

To *manage* the data, companies are increasingly using PDM systems. There are many problems associated with PDM systems still to be addressed including implementation, interfaces to other corporate systems, such as ERP and requirements and variant management.

Finally, there is a need to *communicate* the best view of product data for a given user and situation. In this area, the use of digital mock-ups for analysing large assemblies is becoming more common. Other important trends are the use of VR, large screen displays (> 3x2 m) and broadband videoconferencing to support collaborative work.

Within the ENDREA PM Cluster, there are currently projects emphasising all these different views on product modelling.

4 Acknowledgements

This work was financially supported by the ENDREA graduate school and by The Swedish Board for Technical Development, NUTEK. This support is gratefully acknowledged.

References

[1] Hubka, V., Eder, W.E. *Theory of Technical Systems*. Springer-Verlag, Berlin, Germany, 1988.

[2] Blanchard, B.S., Fabrycky, W.J. *System Engineering and Analysis*. 3rd ed., Prentice-Hall International Ltd, London, UK, 1998.

[3] International Council on System Engineering (INCOSE) http://www.incose.org

[4] Andreasen, M.M. *Designing on a "Designer's Workbench" DWB*. Proceedings of the 9th WDK Workshop, Rigi, Switzerland, 1992.

[5] Malmqvist, J., Schachinger, P.: *Towards an Implementation of the Chromosome Model – Focusing the Design Specification*: Proceedings of ICED-97, Tampere, Finland, 1997, vol. 3, pp. 203-212.

[6] ISO 10303-11 (1994), *The EXPRESS Language Reference Manual*, ISO

[7] OMG, (1999), OMG – *Unified Modeling Language Specification version 1.3*, Object Management Group

[8] Lindeblad,.M., Isaksson, O., Abrahamsson, H., *Standard Based Integration of Computational Data for Multidisciplinary Engineering Analysis*, Proceedings of Produktmodeller 2000, 2000

[9] ISO 10303-1 (1994), *Overview and fundamental principles*, ISO

[10] CIMdata: *Product Data Management - The Definition, An Introduction to Concepts Benefits, and Terminology*, CIMdata Inc., Fourth Edition, 1997.

[11] Miller, E.: *What's PDM?* Computer-Aided Engineering Magazine, September 1997.

[12] SDRC:Metaphase, http://www.sdrc.com/nav/softwareservices/metaphase/configure.html, 2000-09-20.

[13] IBM: Enovia, http://www3.ibm.com/solutions/engineering/esenovia.nsf/public/enovia_overview, 2000-09-20.

[14] UG Solutions: iMAN, http://www.ugsolutions.com/products/iman/products/, 2000-09-20.

[15] PTC: Windchill, http://www.ptc.com/products/windchill/prodplanning/ds_factor.htm, 2000-09-20.

[16] MatrixOne: eMatrix, http://www.matrixone.com/products/applications.html, 2000-09-20.

[17] CIMdata: *CIMdata Europe'99 - Conference Proceedings*, Nice, France, 1999.

[18] Ellis, C. A., Gibbs, A S. J. and Rein, A G. L.: *Groupware -- Some Issues and Experiences*, Communications of the ACM, vol. 34, no 1, 1991.

[19] Maher, M. L. and Rutherford, J. H.: *A Model for Synchronous Collaborative Design Using CAD and Database Management,* Research in Engineering Design, vol. 9, 1997, pp. 85-93.

[20] Cutkosky, M. R., Tenenbaum, J. M. and Glicksman, K.: *Madefast: Collaborative Engineering over the Internet,* Communications of the ACM, vol. 39 no. 9, September 1996, pp. 78-87.

[21] Krause, F-L. and Doblies, M.: *A Communication Environment for Global Automotive Engineering,* In: Proceedings International Symposium on Global Engineering Networking, Antwerpen 1997, band 21, pp. 211-226.

[22] Roy, U., Bhardwaj, B., Kodkani, S. S. and Cargian, M.: *Product Development in a Collaborative Design Environment*, Concurrent Engineering: Research and Applications, vol. 5, no. 4, December 1997.

[23] Peña-Mora, F., Hussein K., Sriram, R. D.: *CAIRO: A system for facilitating communication in a distributed collaborative engineering environment*, Computers in Industry, vol. 29, 1996, pp. 37-50.

[24] Jasnoch, U. and Andersson, B., *Integration techniques for distributed visualization within a virtual prototyping environment*, In: Proceedings of SPIE - The International Society for Optical Engineering Visual Data Exploration and Analysis III, San Jose, Jan 31-Feb 2 1996, vol. 2656, pp. 226-237.

[25] Schroeder, K. and Kress, H.: *Distributed Conferencing Tools for Product Design*, In: Rix, J. and Schlechtendam, E.G (eds.): Proceedings of the IFIP-Workshop on Interfaces in Industial Systems for Production and Engineering, Elsevier Science Publishers, 1993.

[26] 3D Share: Model sharer and heeler. WWW page: http://www.3Dshare.com/, accessed 2000-09-08.

[27] 2Dto3DCAD.com: ASP that converts 2D CAD drawings to 3D parametric models. WWW page: http://www.aspire3d.com, accessed 2000-09-08.

[28] Bryson, S.: *Virtual Reality in scientific visualization*, Communications of the ACM, vol. 39, no. 5, 1996, pp. 62-71.

[29] Rowell, A.: *The design benefit of group VR*, Computer Graphics World, vol. 20, no. 2, 1997, pp. 21-28.

[30] Maxfield, J., Fernando, T. and Dew P.*: A Distributed Virtual Environment for Collaborative Engineering*, Presence, vol. 7, no. 3, June 1998, pp. 241-261.

[31] Törlind, P., Johanson, M., Stenius, M & Jeppsson, P. (1999), *Collaboration Environments for Distributed Engineering- Development of a Prototype System*, presented at CSCWD'99 - Computer Supported Cooperative Work in Design 99, September 29 - October 1, 1999, Compiègne, France.

[32] ReachIn: Haptic Human Computer Interface. WWW page: http://www.reachin.se, accessed 2000-09-08

[33] Delaney, B.: *The Market for Visual Simulation & Virtual Reality Systems*, Cyber Edge Information Services, Inc., 2000.