2 Life cycle modelling

In order to manage life cycle objects and for actors involved in the life cycle to collaborate efficiently, life cycle objects should first be modelled. This approach forms a basis for implementing product life cycle management (see Figure 2.1).

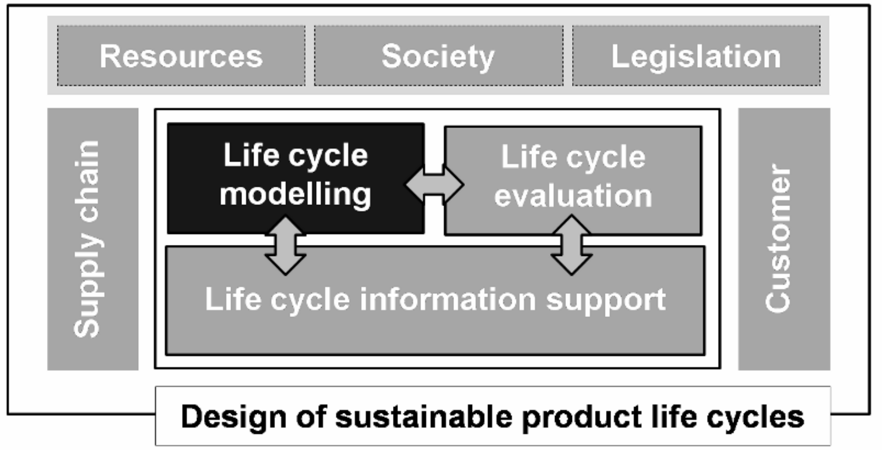


Fig. 2.1: Structure of chapter 2.

To model product life cycle objects during the product life cycle, a research project called PROMISE was carried out. The PROMISE project (FP6 507100 and IMS 01008) was launched by the European Union to develop a new generation of product information tracking and flow management systems. For more detailed information, see (Kiritsis 2004), (PROMISE 2004) and (Kiritsis and Rolstadås 2005) or visit the project website: www.promise.no. The report presents the state of the art regarding product and process modelling methods.

Manufacturing competitiveness supports sustained growth and profits by promoting customer loyalty through the creation of high-value products for the dynamic global market (Biren 1996). The demand for higher-quality and lower-cost products with shorter development times has forced industries to focus on new product development strategies. The well known computer integrated manufacturing (CIM) is an advanced manufacturing system which uses information technology and involves the interconnection of various technical and management functions within a company (Harrington 1973). Concurrent engineering (CE) has been proposed and defined by many researchers as a means of minimising product development times (Barkan 1988), (Chan and Gu 1993), (Winner 1988), (Ou-Yang and Pei 1999), (Zhao 1998), (Bhandarkar and Ngai 2000), (Seltes 1978), (Hunag and Mak 1999).

CE is a systematic approach to the integrated, concurrent design of products for dynamic global markets (Biren 1996).

Other strategies, such as lean production, (Womack et al. 1989), (Clark and Fujimoto 1991), agile manufacturing (Nagal and Dove 1991), (Youssef 1992) virtual manufacturing (Onosato and Iwata 1993), (Iwata et al. 1995), holonic manufacturing (Winkler and Mey 1994), Matheus 1995), continuous acquisition and life cycle support (CALS – formerly known as computer-aided acquisition and logistics support) (Baumann 1990) and knowledge-based intelligent system approach (Aldalondo et al. 2000), all contribute in different ways towards product development from conceptual design to production and distribution in order to enhance industrial competitiveness.

Represented by all the above-named strategies, the integrated product design and development process is the foundation of the final product realisation and involves numerous management and information technologies. However, technology only makes these strategies possible and does not actually create them (Rasmus 1993). Changes in market conditions are driving the implementation of new emerging technologies, which in turn is driven by the changing processes it has to support.

Product modelling is considered to be one of the key technologies that enables the realisation of these strategies during product development activities. Figure 2.2 shows the scope of complete product modelling made up of the four major factors of enterprise objectives, enterprise development strategies, enterprise manufacturing resources and product realisation processes which are related to the development, maintenance and subsequent usage of product models within an industry.

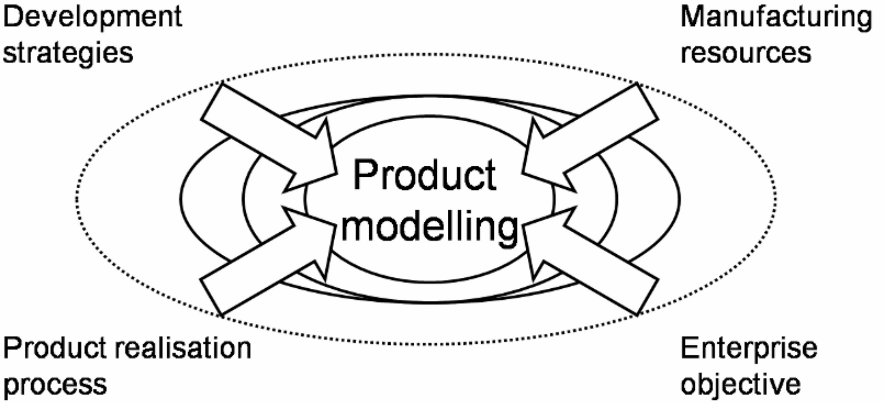


Fig. 2.2: The realm of product modelling.

These four aspects are interlinked with the information flow of product modelling. It is understandable that Krause (Krause and Schlingheider 1993) stated that “the issues of information processing for product modelling are very complex in engineering practice”. The product realisation process models the product life cycle from ideas through to final details. There are a number of parallel subproduct models with varying information contents and structures. Hence, product modelling technology is critical (Trappey et al. 1997), (Murphy 1950), (Quaissi et al. 1999).

The purposes of life cycle modelling are three-fold:

- The model should guide *life cycle design* by identifying, in particular, the holistic nature of life cycles. While we often pay too much attention to individual life cycle processes, it is critically important to consider their holistic nature, such as interferences between product life cycle processes, total life cycle costs and also environmental influences, etc.
- The model should be used in life cycle simulation. The model described in this section was indeed developed to serve as a simulation model based on a discrete event simulation technique (Umeda et al 2000).
- The model should serve as a reference in the evaluation of product life cycles, not only for life cycle simulation, but also for LCA, etc. While a life cycle scenario is typically assumed for an LCA case study, it is generally an average case. However, extreme cases also exist on a number of occasions, especially for consumer products.

The following example shows a life cycle model for evaluating the life cycle design of a product using life cycle simulation. A life cycle model consists of a product model and a process network. Life cycle models, each of which representing a life cycle design, contain multiple processes in the process network such as production, operation, maintenance, disassembly and reuse. It is assumed that a product model is modular in order to reduce costs associated with maintenance, disassembly and reuse. The modular structure of the product of each life cycle model is optimised with respect to multi-objective criteria (e.g., amount of waste, material and energy consumption, corporate profits). Umeda et al. (2000) presents five different types of life cycle model for evaluating life cycle designs which are either commonly used nowadays or potentially used as sustainable alternatives.

- Conventional type: in this life cycle, a customer buys a product and throws the entire product away without having it repaired or maintained when the product becomes faulty or obsolete. This type of life cycle is commonly used for consumer electronics.
- Recycling type: this is similar to the conventional type with the exception that discarded products are recycled. For the sake of simplicity, it is assumed that metals are material-recycled and plastics energy-recycled, reflecting real world practices. For example, automobiles currently belong to this life cycle type.
- Reuse type: in this life cycle, modules from collected discarded products are reused or recycled. This decision is made based on the elapsed lifetime of the products concerned. Printers are one examples of this type.
- Maintenance type: here, the customer continues to use the product after purchase by maintaining it (i.e., replacing defective modules with new modules) and the defective modules become waste. However, if maintenance becomes

too expensive for a customer, the old product is replaced with a new one. For example, machine tools belong to this type of life cycle.

- PMPP (Post Mass Production Paradigm) type (Tomiyama 1997), (Umeda et al. 2000): this life cycle consists of maintenance, modular and component reuse as well as recycling processes. These processes are managed accordingly (for example, products are leased rather than sold resulting in a higher rate of collection than with other types). With appropriate life cycle management, this type can become an ideal sustainable life cycle. The above four life cycle models have in fact been derived from the PMPP type model by changing parameter values.

Although these models have been simplified, they are helpful when considering the essential advantages and drawbacks of recycling, reuse and maintenance options. Here, life cycle simulation is useful to quantitatively evaluate the performance of the models at an early stage in product development.

Andreasen (Andreasen 1992) takes a total life cycle view of product modelling by introducing the notion of product life phase systems. During its lifetime, a product interacts with various life-phase systems such as manufacturing systems, distribution systems or destruction systems. These systems are developed and/or configured concurrently with the product and are referred to as life cycle systems (LCS).

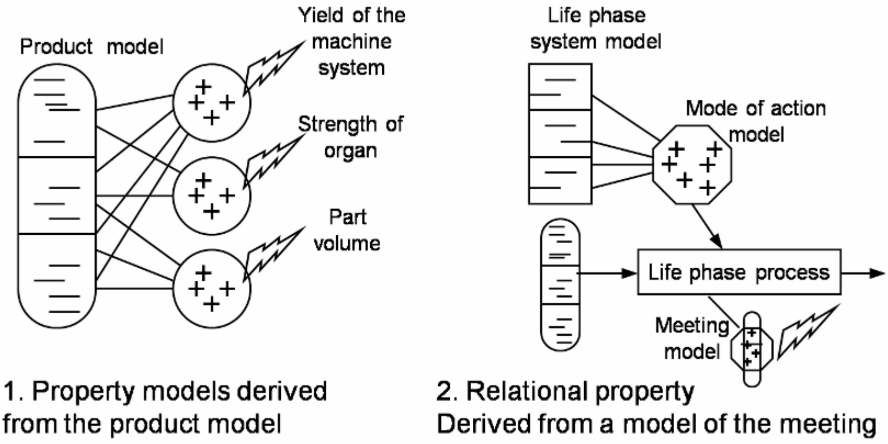


Fig. 2.3: Meeting between a product and a life-phase system.

Mortensen and Andreasen (Mortensen and Andreasen 1996) continue discussions regarding interactions between a product and its life-phase systems by introducing the *meeting theory* where relations between two design objects, synthesised into two separate chromosomes, are called meetings (Figure 2.3). Although it is clear that the product and the LCS are two separate technical systems which - due to high interdependency - need to be developed in harmony with each other, further explanation of the relationship between a product and its LCS is not included in the scope of the original theory of domains.

An important aspect to be considered when applying the engineering design to LCS design is that of transformation processes. A life cycle process could be regarded as being a transformation process which is executed by a transformation system – a life cycle system. In such a process, an operand (product) is transformed from an initial state (e.g. material) into a desired state (e.g. manufactured product).

Product components embody organs which, in their turn, realise functions which carry out the process transforming customer operands. The physical properties of product components are managed in the life cycle processes executed by the LCS.

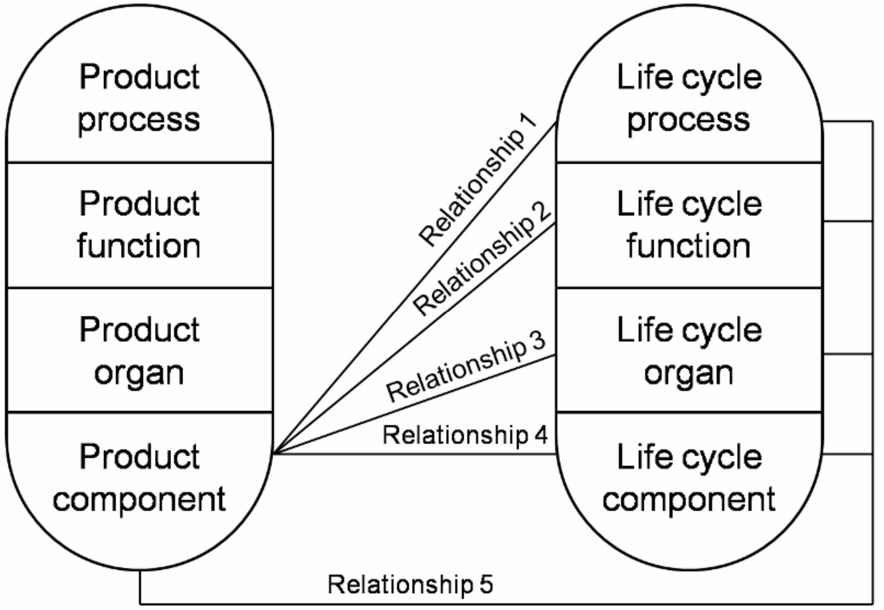


Fig. 2.4 : The relationship between a product and its LCS.

For example, a product's components' physical properties are determined in the manufacturing process executed by the manufacturing resources within a manufacturing system. LCS components embody the LCS organs which realise LCS functions which carry out the life cycle processes. Therefore, it can be suggested that a relationship exists between products and their LCS established during the execution of the development process and expressed in the causality links between the domains of the product system and LCS. (Figure 2.4)

2.1 Process network

A product life cycle is made up of a network of processes. Each process has a specific functionality within a product life cycle such as manufacturing, operation, recycling and remanufacturing. Management of a product life cycle requires understanding of the behaviour of these process and their interdependencies. For example, Figure 2.5 shows important processes within the product life cycle of a modularised product.

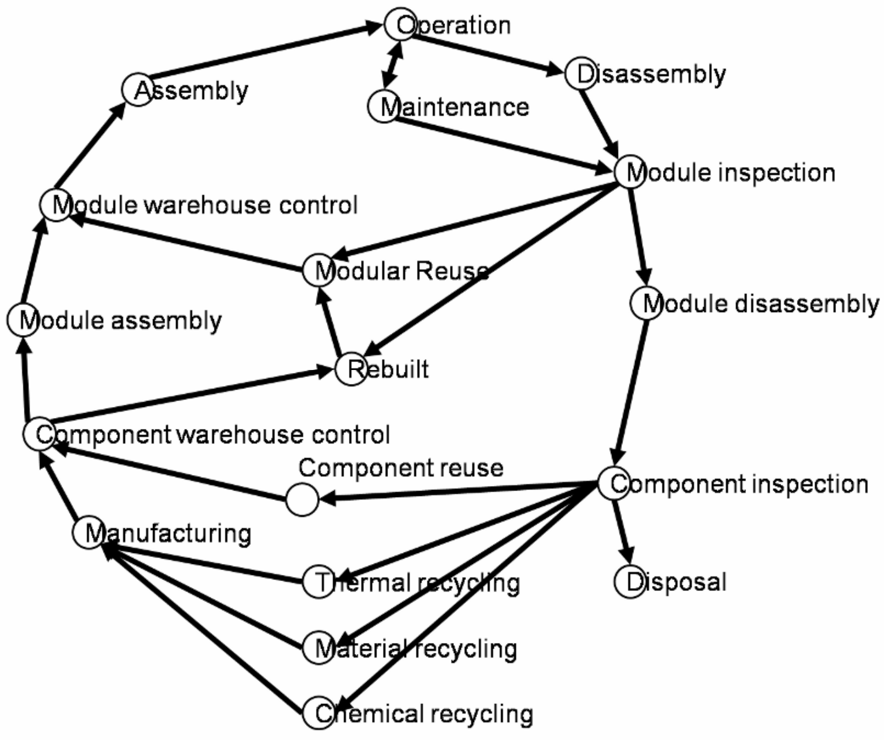


Fig. 2.5: A process network in a product life cycle. (Tomiyama 1997), (Umeda et al. 2000).

The behaviour of a process in the product life cycle depends on the input-output flows of components, modules and products from other processes. Although information can be detailed and quantified to describe these processes such as process parameters and decision criteria (Umeda et al. 2000), the behaviour of each process in the product life cycle can be based on the following description.

- Market: the size of the market is constant or fluctuates dynamically. Only the target product is sold in this market. Once the target product has started to be sold, a consumer can only buy the target product and the market is saturated with the product within a certain period of time. Competition among different products in the same market can be included in the model.

- Operation and maintenance: a customer buys a new product at purchase price. This price does not include maintenance or recycling costs. Each component breaks down randomly throughout its lifetime and the customer repairs the product by replacing a defective module with a functioning one. The maintenance costs paid by the customer pays for each maintenance task are formulated as being the sum of the module price and maintenance fee. However, if the cost of maintenance is too high or the product breaks down too often, the customer replaces the entire product with a new product. This customer's judgement is based on customer maintenance preference and the minimum acceptable Mean Time Between Failures (MTBF).
- Collection and product disassembly: discarded products are collected for the product disassembly process and the rest are simply disposed of. This judgement is parameterised and indicates that the collection system of discarded products is not ideal. The product disassembly process strips collected products into modules and sends them to the module inspection process.
- Module inspection: modules from disassembled discarded products as well as those collected from the maintenance process are sent to the module inspection process. The module inspection process classifies collected modules into the following groups: (1) the module is not defective and can thus be reused, (2) the module contains non-reusable components. In the first case, the module is sent to the module warehouse for light reconditioning (e.g., cleaning). This is determined by evaluating all components in the module using a reusability criterion. The criterion is described as a function of nominal lifetime, operation time, guarantee period and reusability of component. In the second case, the module goes either to the rebuilding process or the module disassembly process. This judgement is formalised as a function of the proportion of reusable components in the module; therefore, if it is easy to recover the module, it goes to the module rebuilding process but if the module contains many non-reusable components, it goes to the module disassembly process instead.
- Rebuilding: in the module rebuilding process, modules are remanufactured by replacing non-reusable components with working ones that came from the component warehouse. Rebuilt modules are sent to the module warehouse.
- Module disassembly and component inspection: modules are disassembled into components which are then inspected in the component inspection process. Thus, if a component satisfies the reusability criterion, it is sent to the component warehouse after light reconditioning. Otherwise, the component goes to the recycling process if it is recyclable and, if not, it is simply disposed of. The recyclability of components is specified by the user in the product model.
- Recycling: in the recycling process, components are recycled either into material or energy. If a component is made of metal it is recycled into material; if made of plastic, it is recycled into energy and other materials are simply disposed of. In the material recycling process, a certain weight ratio of input components is produced as recycled materials which will be used for component

manufacturing and the rest is disposed of. Although the energy recycling process generates energy for other processes, it also generates waste, i.e. a certain weight ratio of input plastic components becomes waste. This ratio depends on the properties of the components concerned.
- Warehouses: modules in the module warehouse are used for maintenance as spare parts and in the assembly of new products. If the number of modules in the warehouse is below a certain threshold, new modules are manufactured. The component warehouse works in the same manner.

Such a representation of the product life cycle makes it possible to explicitly treat all product life cycle processes and parameters as design parameters of the life cycle of products and to view their interdependencies from a systematic perspective.For process modelling, there are many modelling languages available such as PSL, XPDL and BPML. For specific modelling, parts of UML, EPC or OPM can be used. The details are described in the following.

2.1.1 PSL (Process Specification Language)

The Process Specification Language (PSL) (Version 1.0) which was developed at the National Institute of Standards and Technology not only identifies and formally defines but also structures the semantic concepts intrinsic to the capture and exchange of discrete manufacturing process information (http://www.mel.nist.gov/psl/). Process data are used throughout the life cycle of a product, from early indications of manufacturing processes pinpointed during design, process planning and validation right up to production scheduling and control. Additionally, the notion of process also underlies the entire manufacturing cycle, coordinating workflows within engineering and shop floor manufacturing.

2.1.2 XPDL (XML Process Definition)

The XML Process Definition Language (XPDL) is a workflow process definition meta-data model to provide a common method for accessing and describing workflow definitions. This meta-data model identifies entities commonly used within a process definition. A variety of attributes describe the characteristics of this limited set of entities. Based on this model, vendor specific tools can transfer models using a common exchange format (WfMC 2002). A key element of XPDL is its ability to be extended to handle information used by a variety of different tools. However, XPDL will never be capable of supporting all additional information requirements in all tools. XPDL supports a number of different approaches based upon a limited number of entities describing a workflow process definition (the *Minimum Meta Model*). One of the most important elements of XPDL is a generic construct which supports vendor specific attributes for use within the common representation.

2.1.3 BPML (Business Process Modelling Language)

The Business Process Modelling Language (BPML) is a meta-language for modelling business processes in the same way that XML is a meta-language for modelling business data. BPML provides an abstracted execution model for collaborative and transactional business processes based on the concept of a transactional finite-state machine (Arkin 2002). BPML defines activities of varying complexity, transactions and compensation, data management, concurrency, exception handling and operational semantics. BPML provides a grammar in the form of an XML schema to enable the persistence and interchange of definitions across heterogeneous systems and modelling tools. BPML can be used to define the detailed business process behind each service. BPML maps business activities to message exchanges. It can be used for the definition of enterprise business processes, the definition of complex Web services and multiparty collaborations.

2.1.4 UML (Unified Modelling Language)

Among Unified Modelling Language (UML) diagrams, the sequence diagram, swimlane chart and state diagram can be used for process modelling from the object-orientated viewpoint.

Sequence diagrams describe inter-object behaviour, i.e. the way in which single objects interact through message passing in order to fulfil a task. They are also called interaction diagrams. A sequence diagram is mainly used for modelling a scenario to show the flow of an operation or case of use. The diagrams can be extended to describe entire algorithms (there are symbols for distinguishing between cases and repetition) but often lose their clarity if used in this way.

Swimlane charts are often utilised together with activity diagrams where different parts of an organisation or a large system are divided into different swimlanes. A swimlane is a method for grouping activities performed by the same actor of an activity diagram or grouping activities in a single thread. Swimlanes are regions in a diagram which contain active objects and which are separated by vertical or horizontal lines.

State chart diagrams describe intra-object behaviour, i.e. the possible consequences of states which an object of a class may go through during its life, either from its creation till its destruction or during the execution of an operation. State chart diagrams are based on general finite automatons.

2.1.5 EPC (Event Process Chain)

In the years from 1990 to 1992, the foundational conceptual work for an SAP reference model was conducted by the SAP AG and the IDS Scheer AG in a collaborative research project. The outcome of this project was the Event Process Chain (EPC) which has been used for designing reference process models in SAP.

EPCs also became the core modelling language in the Architecture of Integrated Information Systems (ARIS). EPCs are directed graphs consisting of events, functions and connectors to visualise the control flow. Each EPC starts with at least one event which triggers a function and in turn leads to a new event. All functions and events are connected by control arcs (PROMISE 2005). (Scheer 1998a), (Scheer 1998b)

2.1.6 OPM (Object Process Methodology)

Object Process Methodology (OPM) is an approach for modelling a real or conceptual world with the help of an object-orientated approach. OPM takes a fresh look at modelling complex systems comprising of humans, physical objects and information. OPM is also a formal paradigm for systems development, life cycle support and evolution. It can also be used to support the structuring of people's intuition and training of thought.

OPM supports not only language but also graphical notation – OPD (Object-Process Diagram), making it very helpful for conceptualising people's thoughts and communication with each other. Graphical notation can be translated into OPL (Object-Process Language) which represents the model. Two CASE tools are available for supporting OPD and OPL: OpCat and Systematica.

As OOA/D is a well-known methodology, anyone can easily understand OPM by making a comparison between two methodologies. OOA/D is generated in the software engineering domain while OPM is a top-down representation of a system without the constraints of a programming language.

2.2 Framework for a networked life cycle management

The whole product life cycle includes all phases from product generation and usage right up to product disposal. It consists of the following life cycle activities: design (conceptual design and detail design), production (procurement, manufacturing and assembly), logistics (distribution), usage, maintenance (service), collection, remanufacturing (disassembly, refurbishment, reassembly, etc.), reuse, recycling and disposal (Hong-Bae et al. 2005a). Figure 2.6 shows the conceptual model of the whole product life cycle.

The product life cycle generally has complicated flows of activities and information. Therefore, it is important to describe them in order to make it possible to control and steer the process and information flows of the product life cycle. The description can be used a basis for process and data integration. For this purpose, modelling issues require consideration.

First of all, the necessity of a life cycle modelling framework needs to be described, followed by the modelling issues of product life cycle data.

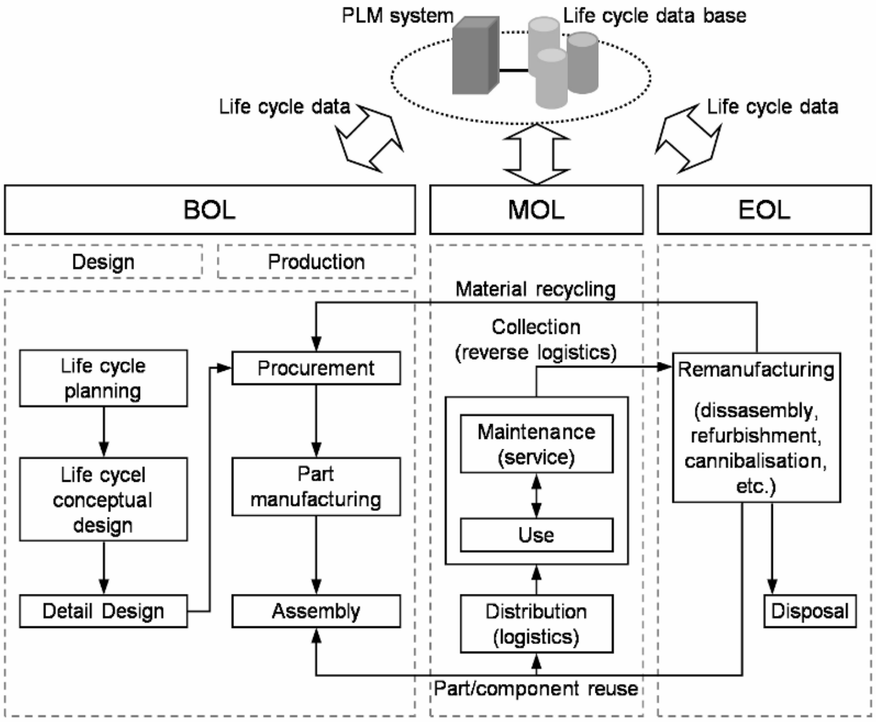


Fig. 2.6: Whole product life cycle.

2.2.1 Defining the product life cycle modelling framework

To enhance the performance of life cycle operations over the entire product life cycle, all life cycle objects performed along the product life cycle have to be designed and coordinated and their efficiency managed. The numerous modelling works in existence can be classified into two categories: enterprise modelling methodologies and product life cycle modelling, as shown in Table 2.1.

Although considerable research work concerned with enterprise or product life cycle modelling has been carried out in the past, up till now little attention has been paid to the whole life cycle modelling framework (Nonomura et al. 1999), (Kimura 2002). Although CIMOSA and PERA consider the life cycle concept, they focus on the development of manufacturing systems or enterprise business. Moreover, previous product life cycle modelling methods lack integrated views throughout the enterprise life cycle (Tipnis 1995), (Kimura and Suzuki 1995). For example, Ming and Lu (Ming and Lu 2003) addressed the architecture for PLM but only focused on the process viewpoint. As a result, enterprise modelling frameworks were too sizeable to describe PLM models and the previous life cycle modelling research was too conceptual and implicit.

Classification	Previous Research
Enterprise modelling	IDEF (Integrated computer aided manufacturing DEFinitions methodology) (Mayer 1994), IEM (Integrated Enterprise Modelling) (Vernadat 1996), PERA (Purdue Enterprise Reference Architecture) (Vernadat 1996), CIMOSA (Open System Architecture for CIM) (Bruno and Agarwal 1997), ARIS (Architecture for integrated Information System) (Scheer 1998a, 1998b), UEML (Unified Enterprise Modelling Language) (Vernadat 2002)
Product life cycle modelling	IDEF (Integrated computer aided manufacturing DEFinitions methodology) (Mayer 1994), IEM (Integrated Enterprise Modelling) (Vernadat 1996), PERA (Purdue Enterprise Reference Architecture) (Vernadat 1996), CIMOSA (Open System Architecture for CIM) (Bruno and Agarwal 1997), ARIS (Architecture for integrated Information System) (Scheer 1998a, 1998b), UEML (Unified Enterprise Modelling Language) (Vernadat 2002) Conceptual life cycle modelling framework with IDEF (Tipnis 1995) Conceptual architecture and the key components for total product life cycle design supporting system (Kimura and Suzuki 1995)

Table 2.1: Modelling methods.

As a result, it is necessary to develop the life cycle modelling framework to describe the behaviour of whole product life cycle objects: product, process and resource. Within this framework, a definition for representing the product life cycle objects is required. For each life cycle object model modelling constructs and methods need to be defined in a standard and flexible way for adaption to various application domains. In addition to this, the interactions between three life cycle object models (product, process and resource) should also be described, taking the integration of life cycle object models into account.

2.2.2 Modelling product life cycle data

Product life cycle operations contain the planning, execution, control and documentation of all processes throughout the entire product life cycle (Abramovici et al. 1997). This means that the scope of information during a product life cycle is extended beyond the product itself and encompasses all intellectual capital including products, processes and resources (Collaborative visions 2002). Therefore, during the whole product life cycle, a great deal of life cycle information such as CAD drawings, technical documents and structured and unstructured data is created, changed, transferred, stored and converted by and between different people and application systems. This results in complex information flows over the whole life cycle (Figure 2.7).

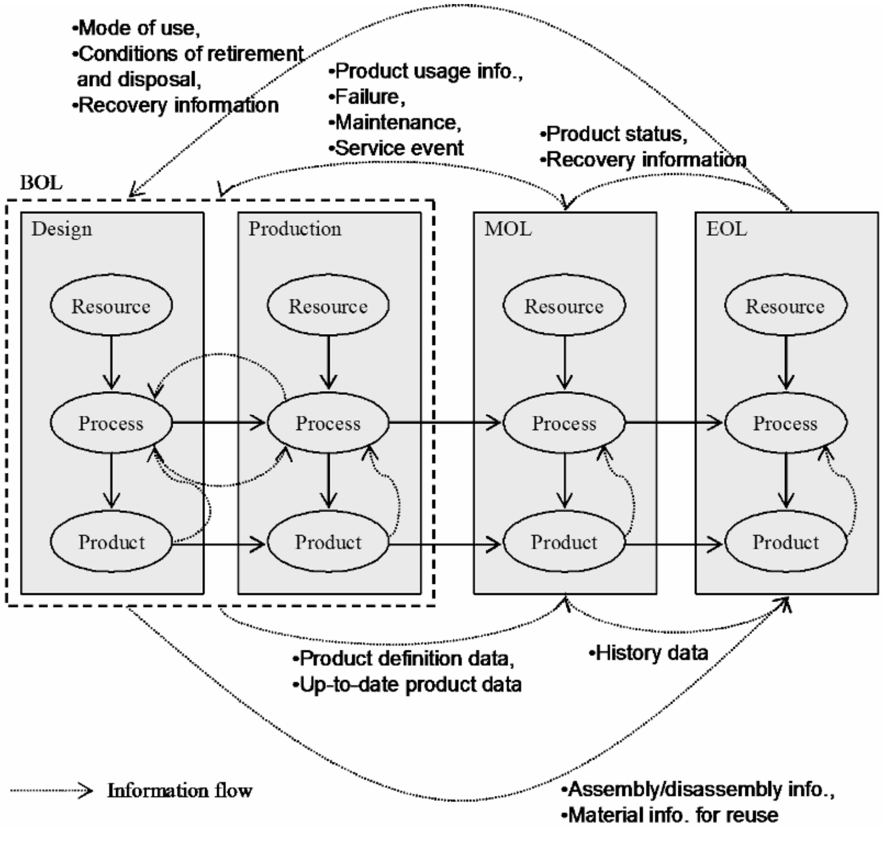


Fig. 2.7: Example of a life cycle information flow.

Efficient management of the product life cycle information is essential and this can play an important role in the analysis and decision-making of various operational issues in the product life cycle.

Up till now, considerable attention has been paid to the information modelling issues of product life cycle data. For example, Scheidt and Zong addressed the structure of life cycle history data to achieve the reusability of electronic modules (Scheidt and Zong 1994). Klausner and Grimm described the data processed by ISPR (Information System for Product Recovery) at a product's EOL (Klausner and Grimm 1998). Goncharenko et al. proposed an approach for gathering and utilising product feedback information over the product life cycle through the use of life cycle design methodologies (Goncharenko et al. 1999).

Furthermore, (Fangyi et al. 2002) proposed a conceptual information model to define and describe product life cycle environment characteristics. (Schneider and Marquardt 2002) defined the product life cycle of chemical processes and described elements of design life cycle: activities, all kinds of information, resources - mainly software tools - and the organisational unit. They also proposed an information modelling method in the chemical design life cycle for capturing the objects and concepts characterising the life cycle together with their relationships and interdependencies. (Kiritsis et al. 2003) defined the data recording structure which allows maintenance personnel to store relevant data obtained during maintenance operations for use in design. Additionally, (UGS PLM 2004) proposed an open standard, called PLM XML, to facilitate high-content product life cycle data sharing over the Internet. On the other hand, there have also been several research works related to information interoperability. For example, (Fenves et al. 2003) proposed a framework for product information interoperability to access, store, serve and reuse whole product life cycle information. (Terzi et al. 2004) reviewed interoperability standards along the product life cycle. In addition to this, (Lubell et al. 2004) described an overview of STEP (Standard for the Exchange of Product Model Data), XML and UML (Unified Modelling Language) for application in PLM.

However, previous research works have some limitations. Despite the importance of product life cycle data, most did not address the subject of representing the bulk of product life cycle data efficiently, especially that of MOL and EOL. Only a few works were concerned with MOL life cycle data. Previous works which focused on EOL life cycle data did not deal with information modelling methods. Moreover, in the past very little attention has been paid to clarifying the structure and semantics of product life cycle data. Many researchers also used XML to describe product life cycle information. XML schemata have the limitation that they do not provide any information about the content, i.e. meta-information (Hong-Bae et al. 2005b).

To overcome these limitations, a modelling method for product life cycle data needs to be developed. In order to trace product life cycle information efficiently, it is necessary to design and manage it in a systematic way. This requires an in-depth understanding of the semantics and structure of product life cycle data over the whole life cycle. First of all, the information relevant to product life cycle data needs to be clarified. It is also necessary to know what product life cycle data is required for each operational issue and each life cycle phase and to classify the information into different types depending on its characteristics. In addition, it is essential to design the data structure which describes the contents of product life cycle data, i.e. meta data and to develop an information modelling framework for managing product life cycle meta data. Finally, methods for retrieving the information and knowledge from life cycle meta data and for analysing it also require discussion.

2.3 Product models

Information exchange in the manufacturing domain is an issue which is becomingly increasingly important to resolve as the manufacture of parts becomes more and more dependent on the use of computerised information systems. Many studies have been performed which show how standardised information models can be utilised to enable information exchange between computer systems. (Al-Timini and MacKrell 1996), (Johanson 2001), (Nielsen 2003)

However, the information models developed for specific areas of manufacturing are too specific. The specific nature of the models means that they are unable to cope with developments in the area. There is also a danger in over-generalisation as the benefit a standardised model is lost if different implementations use it in different ways.

The duality problem can be solved by combining a general model with a reference data library containing the specific concepts within a domain. The specific information items necessary to represent information in a domain are accessible while still enabling the use of a general model. The general model allows for stability over time because the model does not have to be updated as often as a more specific model. It is the specific concepts of domains of applications - ideally represented as an ontology - which have to be maintained.

Many modelling works related to product models have been written and these are described in the following chapters.

2.3.1 Definition of product modelling

In 1950, Murphy made a classic definition of the term *model*: “A model is a device which is so related to a physical system that observations of the model may be used to predict accurately the performance of the physical system in the desired respect” (Murphy 1950). This definition applies mainly to describing the behaviour of physical systems. With the increasing importance of computer-aided technologies, in 1960 Ross introduced the concept of modelling by mathematical means including data, structure, interface and algorithms within the context of CAD/CAM with more relevant behaviours. A model is thus defined as being an abstract specification for domain functions which perform operations.

Modelling simulates the various options in order to make informed decisions early on in the relevant process. It has become the dominant design tool in all aspects of current design. In this work, the term *product* refers to a unit of a function with exact materials, fixed form, designated colour and other features, which is made by an enterprise to satisfy the requirements of a customer. By combining the above definitions of model, modelling and product, the term *product model* can be described as being the sum of all useful information related to a product within the life cycle of its development.

Therefore, product modelling includes all the important processes used to design and develop the product on the basis of product specifications. It has now become the key technology in computer-aided product design and development. Product model data are the result of product modelling action and in different modelling phases, it provides different interrelated model data.

2.3.2 Types of information representation

In the basic derivation, all the information within the product development cycle can be reduced to a modelling process involving different kinds of product models which are interrelated by nature. According to Biren, three types of representational schemes are often employed in this modelling process (Biren 1996):

1. Physical model.
2. Conceptual model.
3. Analytical model.

As shown in Figure 2.8, physical, conceptual and analytical models are used to represent objects (the product) from different points of view and to introduce various aspects of the information. For example, a physical model is useful for conventional physical representation. A conceptual model is more relevant when dealing with the information in the conceptual design phase during product realisation, while an analytical model is more useful for supporting conventional CAD/CAM applications by using parametric or solid modelling.

In this book, the term *product model*, which is used as a mechanism for representing the valid combinations of product information more efficiently, belongs to the category of analytical models. Central to the success of product modelling is the fusion of computer-aided techniques with the designer's knowledge.

Krause and Schlingheider summarise the development of product modelling and the proposed categories of product models, as presented in Figure 2.9 (Krause and Schlingheider 1993). There are five types of product models:

1. Structure-orientated product models
2. Geometry-orientated product models
3. Feature-orientated product models
4. Knowledge-based product models
5. Integrated product models

The structure-orientated product model is the first actual application of a computer-supported product modelling technique in the representation of product structures.

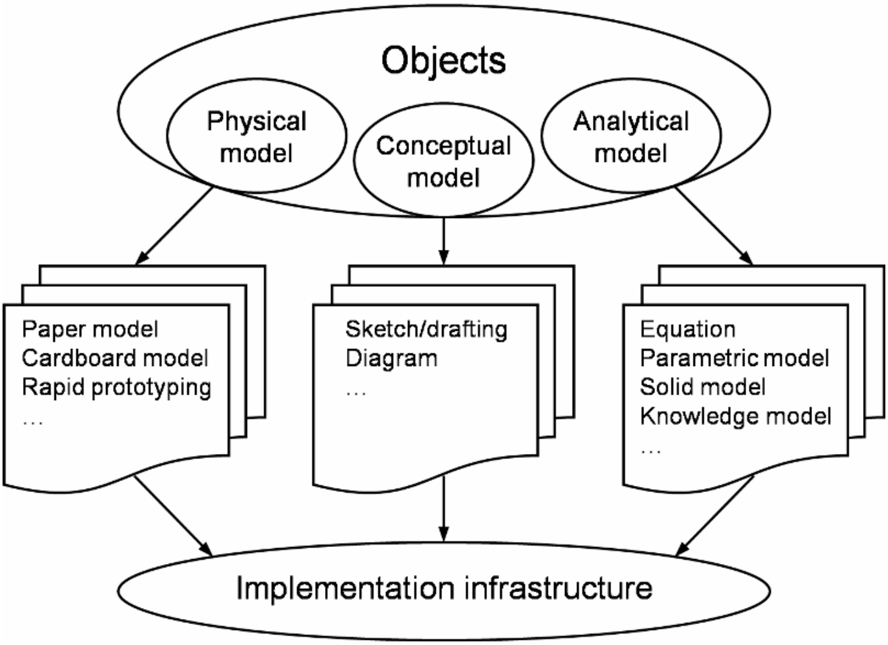


Fig. 2.8: Models representing various types of information.

As the product structure is the core of development activities, such things as specific product data and formats can be stored within this structure-orientated model. Although this kind of model has many limitations with regard to product representation, such as the lack of representation of product shape, it is important in that it provides a basis for further enhancement by other modelling techniques.

The geometry-orientated model was developed as an extension of the structure-orientated model and contains such functions as the representation of product shape including wire frame, surface, solid and hybrid models.

The geometry-orientated model has been widely used to support CAD/CAM and CNC programming applications. It satisfies the requirements of the computer-based representation of the shape of a specific product but is unable to describe non-geometric product information.

The concept of features, usually a form feature, was first put forward for the purpose of representing the general shape patterns of the surface and form of a product as coherent geometric items (Seltes 1978).

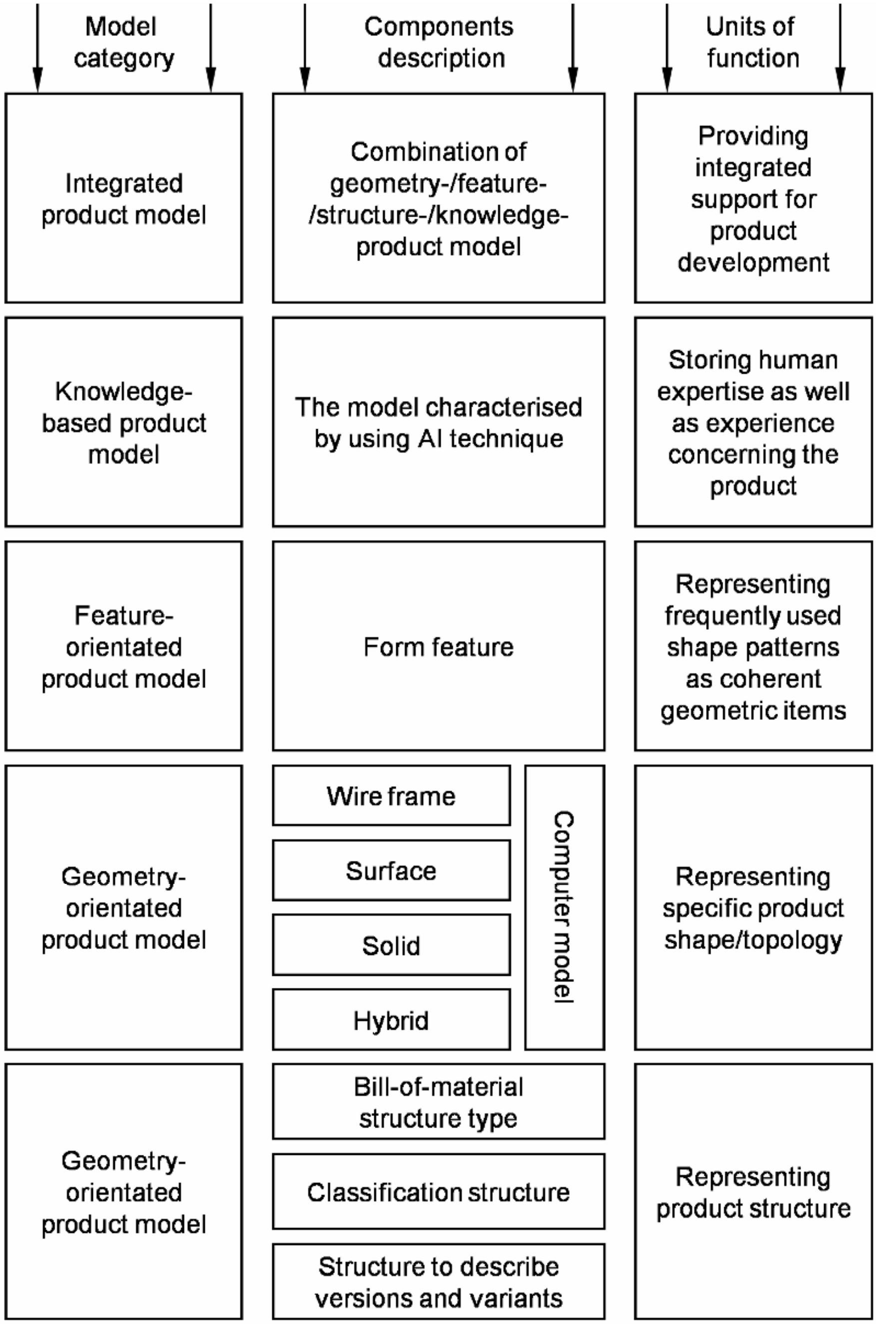


Fig. 2.9: Descriptive summary of product models.

With the subsequent wide use of feature techniques in CAD applications, a feature has become a general information mode for representing a part of a product (Bhandarkar and Ngai 1978).

In the process of product modelling, features can be classified as design features, machining features, assembly features and also abstract features. Each feature has its specific domain of implementation, Figure 2.10.

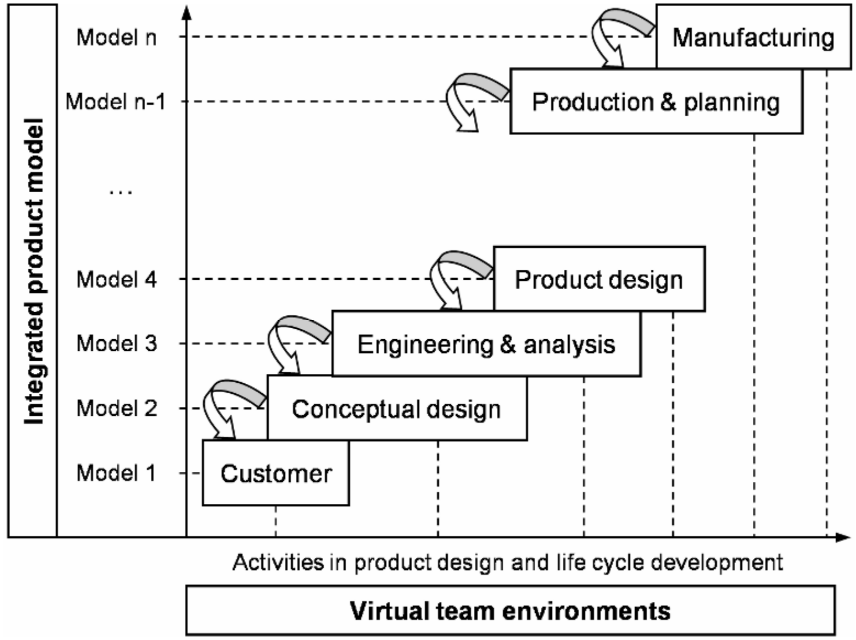


Fig. 2.10: Product models and geometry.

A knowledge-based model is an advanced model which adopts AI (artificial intelligence) techniques. This model supports information reasoning by referring to former designs, human expertise and past experience about a class of products stored in the internal model during the product modelling process.

At present, some implementation methods can be used in the knowledge-based model, such as rule-based reasoning, constraint-based reasoning and object-orientated techniques. The introduction of knowledge in the product modelling domain denotes great progress because the degree of automated reasoning is still an important research topic.

The integrated product model - or global product model - is the functional combination of all the product models discussed above, including structure-, geometry-, feature- and knowledge-based models. The integrated model is used to support all product development activities from the product requirement analysis, conceptual design, detail design, process planning, CNC programming, machining and assembly right up to quality assessment. It can be structured into interrelated multi-view logical models, such as design models and a machining model. Product modelling was also integrated into one of the systematic methods.

The integration of CAD/CAM applications based on the shareable common product information model, including the functions of product data and workflow management, is considered to be one of the key links in the implementation of CE (Qu-Yang and Pei 1999), Zhao 1998).

2.3.3 Existing standards

However, the integration is not fully implemented due to the lack of a unified, single and complete representation of the product and process information model. Consequently, the transfer of product design information from one system to the other often fails because of incompatible or incomplete data (Chan and Gu 1993). Therefore, it is necessary to build an integrated product model for supporting the various activities during the product development cycle, i.e. realising the sharing and exchange of product information within the computer-integrated environment of the enterprise concerned.

2.3.3.1 STEP (STandard for the Exchange of Product)

The STEP (ISO 10303)-Product Data Representation and Exchange standardisation initiative covers the computer-interpretable representation and exchange of product data. STEP is a synonym for all aspects of the international project to develop the technology of product data representation as well as the methodology for creating information model standards and the standards themselves. The method proposed in ISO TC184/SC4 for the ISO 10303 (STEP) suite of standards is to develop a domain-specific model which uses the terminology of that domain and to subsequently map it to a more generic model (IS0 1998). It is becoming more common to create the initial model in a more generic way (ISO 1999), (ISO 2000), (ISO 2005a), (ISO 2005b). This move has been prompted by the realisation that it is an information requirement to represent information generically. Thus, information requirements for the standard go beyond the concepts in a domain.

In the area of product life cycle data where interaction between several different actors is inevitable, the need for a standard is even greater than in most other cases. A standard is already in existence which supports the life cycle aspect of product data: ISO 10303-239, Industrial Automation Systems and Integration – Product Data Representation and Exchange – Part 239: Application Protocol: Product Life Cycle Support, commonly referred to as PLCS (ISO 2005a).

PLCS provides a generic information model which supports the breakdown of the structures of products, processes, requirements etc. with additional information about properties, states, life cycle stages and much more. Together with a reference data library which provides specific concepts such as work order, PLCS forms a solid foundation on which product life cycle data management can be built, based on standardised information representation. The fact that it is a standard will enable different systems from different vendors to be integrated into a common information base for product life cycle data.

The objective of STEP is to provide a means of describing product data throughout the life cycle of a product which is independent from any particular computer system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing product databases and archiving data. In practice, the standard is implemented in computer software associated with specific engineering applications, making its use and function transparent to the user. The descriptions are information models which capture the semantics of an industrial requirement and provide standardised structures within which data values can be understood by a computer implementation.

2.3.3.2 PDML (Product Data Markup Language)

Product Data Markup Language (PDML) is an Extensible Markup Language (XML) vocabulary designed to support the interchange of product information between commercial systems (such as PDM systems) or government systems (such as JEDMICS). PDML is being developed as part of the Product Data Interoperability (PDI) project under the sponsorship of the Joint Electronic Commerce Program Office (JECPO) and is supported by several other Federal Government agencies and commercial entities. Three major PDM vendors are active participants in the PDI programme who are developing prototype implementations of PDML. The initial focus of PDML development is legacy product data systems which support the operation of the Defense Logistics Agency (DLA).

PDML is a suite of domain-specific vocabularies integrated into a single, abstract vocabulary. The vocabularies are related via mapping while the specification and translation between the vocabularies is accomplished via the PDML toolkit.

2.3.3.3 Product condition model

Life cycle orientated product design as well as the planning and operation of ecologically and economically optimised product life cycles require the phase-spanning communication and cooperation between all participants in the product life cycle. An increase of the life cycle productivity of resources cannot be achieved through isolated applications, but only through continuous data exchange between IT-systems supporting such fields as design, maintenance, disassembly planning and disassembly.

It is therefore necessary to overcome the heterogeneity of these systems on the one hand and the spatial and chronological differences of the life cycle phases on the other (Kind 2000). In order to achieve this, a data model must be created.

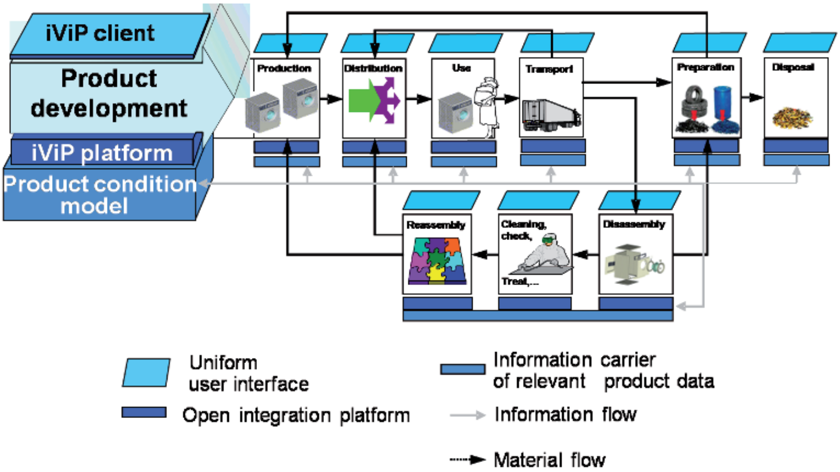


Fig. 2.11: Product life cycle supported by the product condition model.

By defining a model which is able to acquire and represent product condition information in such a way so it can be processed throughout the product life cycle, an information carrier which reduces interfaces and merges systems can be realised (see Figure 2.11) (Krause 2004).

2.4 Applications using product condition data

The application potentials of gathering and supplying condition data in the product life cycle can be categorised into individual product and cluster-based cases. For individual products, maintenance and adaptation processes can be planned or a disassembly simulation carried out. By clustering similar products to form large lots, it is possible to optimise transport routes for maintenance and return, as well as the utilisation planning of disassembly facilities. Furthermore, knowledge about clustered products can be applied in the early adaptation planning stage of the systems in disassembly factories. The provision of product condition information also becomes more important against the background of the modularisation of disassembly systems and factories because its application leads to the fulfilment of requirements regarding module flexibility. (Krause, F.-L. 2004)

With regard to evolving concepts for selling product use instead of the products themselves, clusters of the same product type can support market-orientated adaptation planning and the selection of modules and assemblies for product configuration during re-assembly. The combined consideration of all condition models allows a holistic assessment of ecological and economical parameters. Finally, a data model as a connector linking the product to the integrated IT platform provides a channel for the feedback of information concerning maintenance, use and disassembly to product development.

2.4.1 Conception of the product condition model

An existing physical product manufactured according to the product model has features which deviate from the nominal values as well as features which are not regarded at all in the digital model.

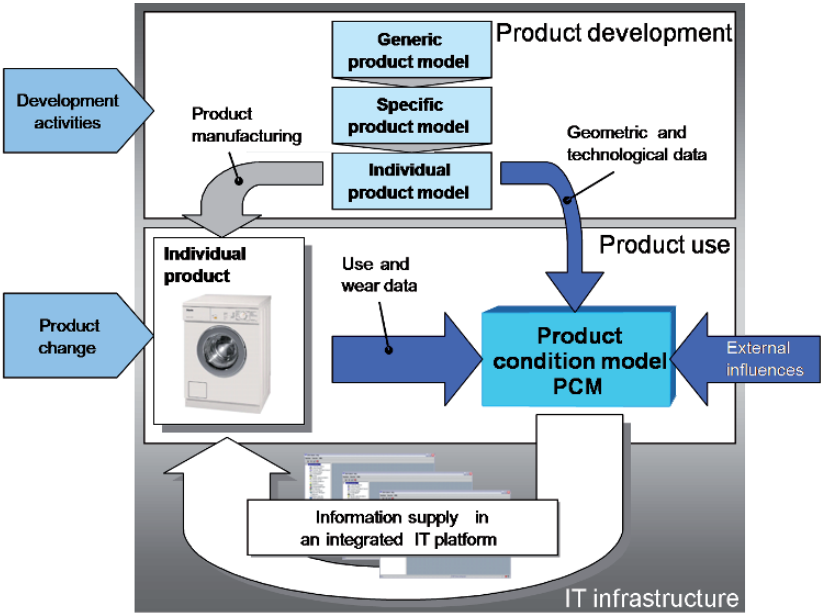


Fig. 2.12: Product condition model for the representation of product changes.

One function of the product condition model (PCM) is to represent these deviations and modifications in a computerised model (see Figure 2.12). The PCM essentially consists of geometric and technological data from the product development and incorporates product- and time-related use and wear information as well as external changes made to product, for example caused by adaptation processes. It can thus be seen as being an extension of the product model beyond the product creation process (see Figure 2.13). (Krause 2004)

The application potentials described above can be classified into online and offline applications. Online application means the acquisition of condition data of a specified product and its use for the operation of the life cycle of the same product, for example initiating a preventive maintenance action or making an end-of-life-decision. In the case of offline application, information from the past is analysed in order to gain knowledge for implementation in the life cycle of new products.

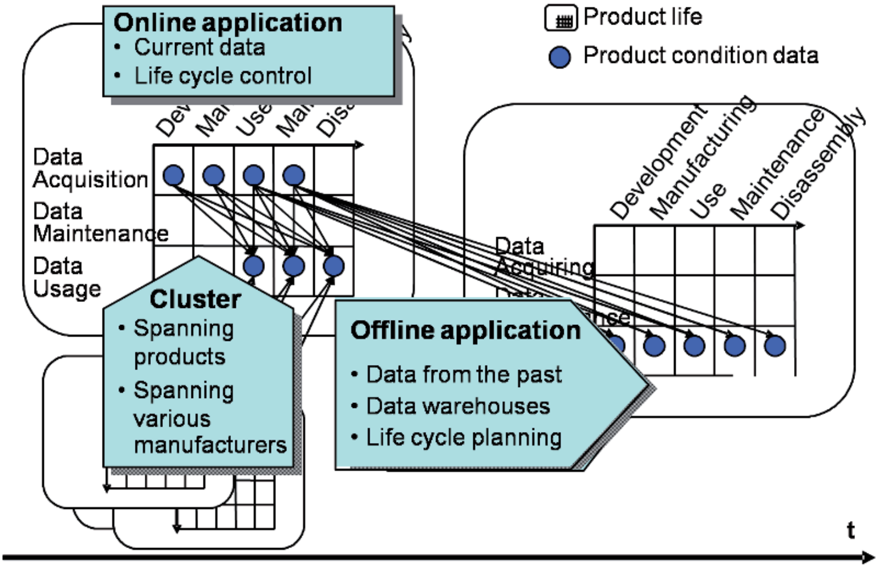


Fig. 2.13: Application principles for condition data

Since the attributes of a product in use change continuously, the PCM has to be adapted dynamically. This requires an information flow from the physical product to the model. The matching between the real product and the digital model is referred to as synchronisation. Synchronisation is carried out within certain intervals, whose frequency and regularity depend on the planned application. The information technology link has to be configured in order to fulfil the respective synchronisation needs. Between two synchronisation points, the divergence of 'real' and 'virtual' conditions increases over time. During synchronisation, the divergence is reduced to the extent the PCM has been designed for. The acceptable tolerance essentially complies with the requirements of the application. Therefore, the PCM exclusively represents product attributes which are relevant either for online or offline applications. As application requirements may change during the life cycle, the model must be both flexible and reactive. Flexibility means the ability of a PCM to represent a large spectrum of possible attributes and reactivity denotes the ability to change as a result of unplanned application needs.

2.4.2 Class structure of the condition model

In order to be able to assign condition data to components of a product, attributes are linked to product structure elements. These elements are modelled in different levels of abstraction to enable clusters to be formed by generalising objects of the product structure. The specification levels distinguished here are the generic level, specific level and the individual level. For example, the generic level may correspond to a product concept. The specific level can be regarded as being a specification on whose basis the production planning is carried out. The individual structure represents the materially-existing product and is assigned using serial or charge numbers.

Each attribute has a predetermined parameter value type. With regard to further STEP processing, these are basically EXPRESS data types. Attributes may relate to direct or indirect condition information. While indirect attributes record influences on a product, such as the rotation count of a bearing, direct attributes express the impact, for example information on the volume of wear. Utilising appropriate transformation methods, indirect attributes can be transferred to direct ones (Martini 2000). A smaller amount of indirect information is needed in order to derivate a multitude of direct condition attributes, making indirect attributes more efficient in terms of acquisition and storage effort. Several research projects focus on the necessary detailed knowledge about product behaviour and physical coherences (Gruzien 2002), (Buchholz and Franke 2003) The transformation of use information into direct condition attributes also allows product conditions to be predicted by projecting the current use mode into the future. (Figure 2.14)

2.4.3 Shifting viewing levels

The attributes assigned to the product components can be processed using miscellaneous aggregation methods. Aggregation in this context means summarising a range of single values. A cluster is formed using a horizontal aggregation method which spans various products. Here, an amount of values of the same attribute but different products is merged. It is also possible to aggregate time series of attributes in a statistical way corresponding to industrial measurement value logging. Vertical aggregation means processing the attribute values of sub-components within a product structure to reach a conclusion regarding the superordinate component. For example, the weight of an assembly equates to the sum of weights of the individual parts. An analysis of the presence of materials requiring separate disposal could also be realised with a vertical aggregation method. The use of aggregation methods makes it possible to transfer information about the condition of an individual product to specific and generic levels. On the other hand, attributes on higher levels can be regarded as being part of the condition description of lower levels. The methods are embedded in the model and remain translucent for the accessing systems. A user is able to access data at his level of viewing, although it may have been generated on another level.

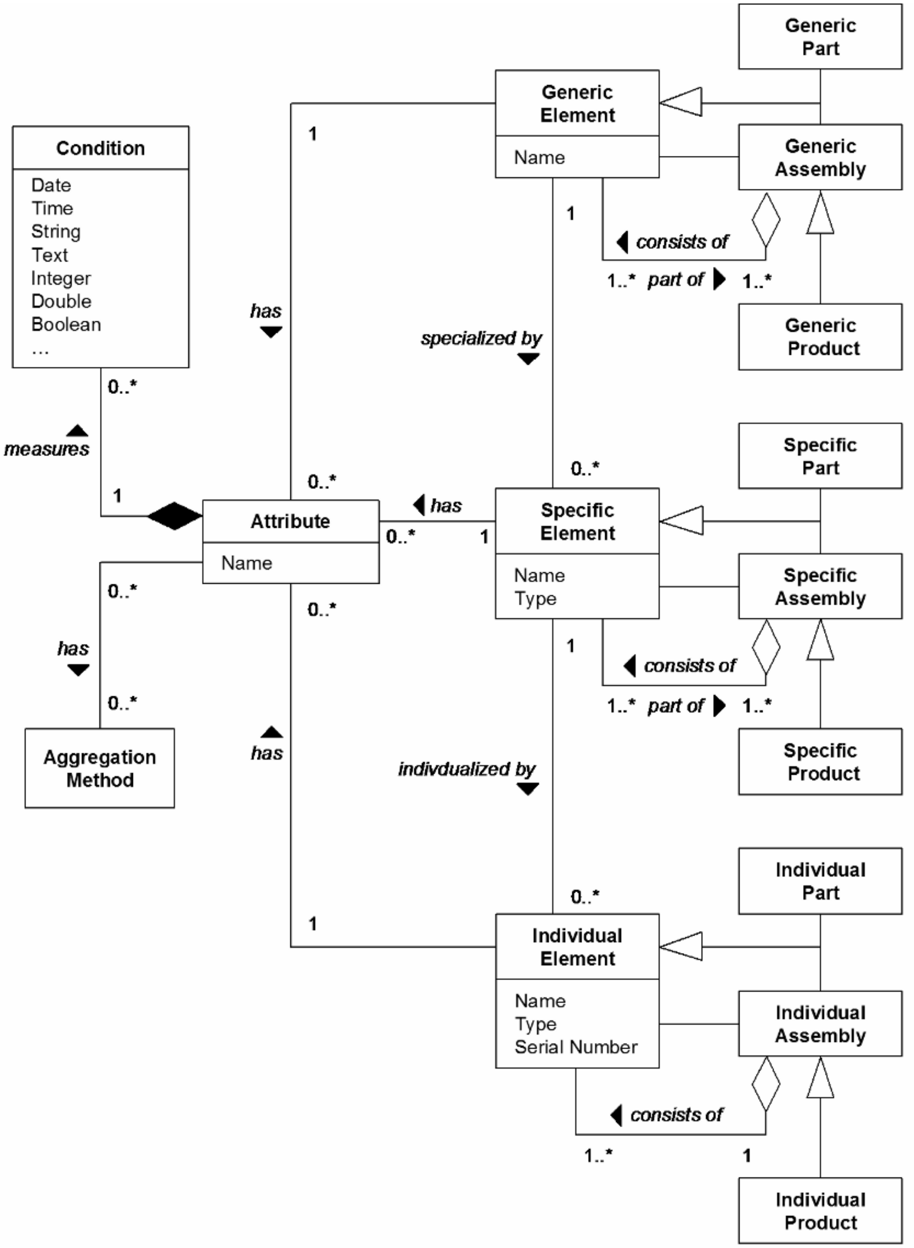
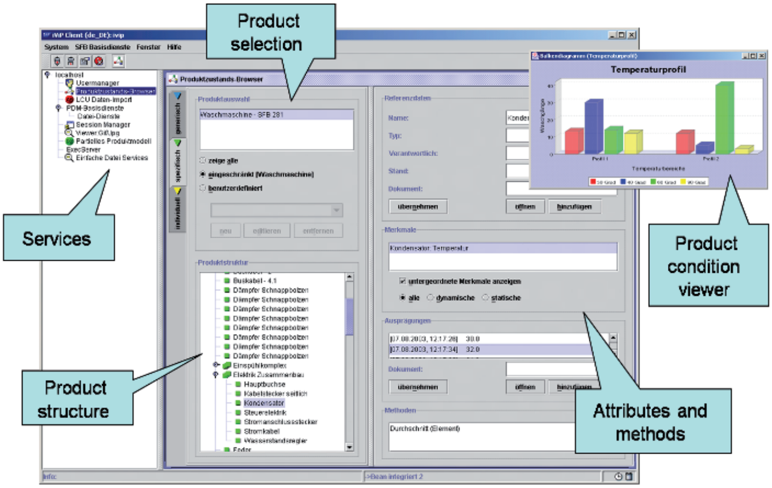


Fig. 2.14: Base classes of the product condition model.

2.4.4 Implementation of the product condition model

A Life Cycle Unit (LCU) is used to acquire condition data directly from the product and to pass them on to the platform. The LCU therefore consists of sensors and a memory chip which buffers the data between the synchronisation intervals. (Gruzien 2002), (Buchholz and Franke 2003) (Figure 2.15)



Waschmaschine - SFB 281

○ zeige alle
● eingeschränkt [Waschmaschine]
○ benutzerdefiniert

Name: Konder

Kondensator: Temperatur

☑ untergeordnete Merkmale anzeigen

● alle ○ dynamische ○ statische

[07.08.2003, 12:17:28] 30.0
[07.08.2003, 12:17:34] 32.0

Durchschnitt (Element)

Fig. 2.15: Product condition browser.

A product structure browser enables product condition data to be accessed from the different perspectives. Products which are or have been in use can be selected and navigated in their element structure on the generic, specific or individual level. Closely linked with the browser is the user manager for defining roles. This way suppliers and individual users have access rights and configurations corresponding to their roles. The responsibility for a specific product spectrum with respect to product type, manufacturer and period, viewpoint level as well as access permission to methods and services all need to be determined for the users of the system.

2.4.5 Product model for manufacturing

Today the manufacturing process is a complex phenomenon which requires knowledge of different fields of science such as mechanics, management, economics, etc. In order to build a model, the phenomenon to be modelled should be specified (Figure 2.16, 2.17). The principal tools for simulating the manufacturing process include:

- Installation of a Product Model (PM) for manufacturing,
- Validation of the model by trade experts.

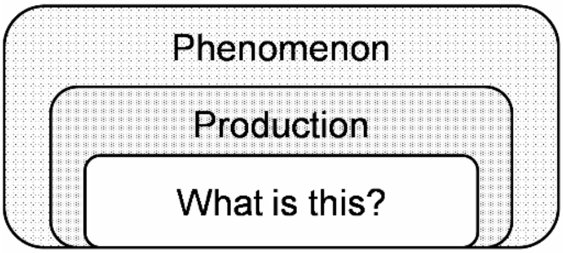


Fig. 2.16: The phenomenon of production.

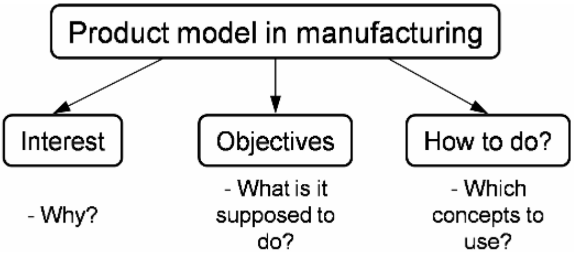


Fig. 2.17: Why the product model for manufacturing?

As well as containing information about its manufacture, the PM also has to be suitable for piloting the manufacture of the product. (Mitrouchev et al. 1998), (Brissaud and Tichkiewitch 2001)

Thus the goals of the model are to:

- Attach descriptive parameters to each product,
- Attach to each product the treatments which it will undergo,
- Launch production in a rational way,
- Trace the product in the course of manufacture (represented by a token),
- Bind each product to its destination (until its delivery),
- Represent the product by a batch of parts (problem of batch bursting),
- Take into account any incidents which may occur,
- Gather information about the quality follow-up,
- Design new products with standards ranges.

The parameters of manufacturing are defined in a similar way as the parameters of design. Both are used later in the Product Model as shown in Table 2.2 below:

Product Model	
In Design	In Manufacturing
Parameters of Design	Parameters of Manufact.
Function (of use) / Need	_
Structure	_
Relations with partners	Relations with partners
Parameters (of Manufact.)	Parameters (of Manufact.)
Quality of product	Quality of product
Control	Control
Ranges (of machining)	Ranges (of machining)
Operations	Operations
Situations	_
Appointment	_
Process	_
Tools	Tools
State	_
Performances	_
Operational time	Operational time
Tool changing time	Tool changing time
History	_
Material	Material
Family of product	Family of product
Geometry	Geometry
Quantity	Quantity
Life cycle / Recycling	_
Times of launching	_
Environment	Environment

Table 2.2: Parameters of manufacturing.

Four hierarchical levels of definition of product parameters are then specified, as summarised in the following table:

Hierarchical levels (by priorities)	
Level 1 (highest)	Life cycle
	Cost
Level 2	Function/ Need
	Geometry
	Structure
	Ranges
	Quality of product
	Control
	Recycling
	Environment
Level 3	Family of product /sub- families
	Material / Characteristics
	State
	Performance
	Appointment
	History
	Situations
	Relations with partners
	Process
Level 4 (lowest)	Resources tools by operat.
	Parameters (of Manufact.)
	Operations
	Quantity

Table 2.3: Levels of product parameters.

The product is defined as being the object which will be transformed. The Product Model is considered both as the *tool* and as the *actor* of manufacturing. Being the link between design and manufacturing, it is intended to accompany the product over its whole life cycle. In fact, the aim is not to await the final description of the product before making information accessible to all the actors of the manufacturing. Consequently, the different aspects of the Product Model are developed which relate to the advance of the product among the various stations of manufacture and the follow-up of the course of operation. This raises the question: what knowledge is required about the product for its manufacture?

- operations of the product range (in which order),
- assignment of the operations,
- sub-operations,
- problem of machine non-availability

The manufacturing knowledge and know-how are distributed among several trade associations. The entities in manufacturing allow each user to work and to express himself in his own language (Brissaud and Tichkiewitch 2001). The essential question is how to achieve this.

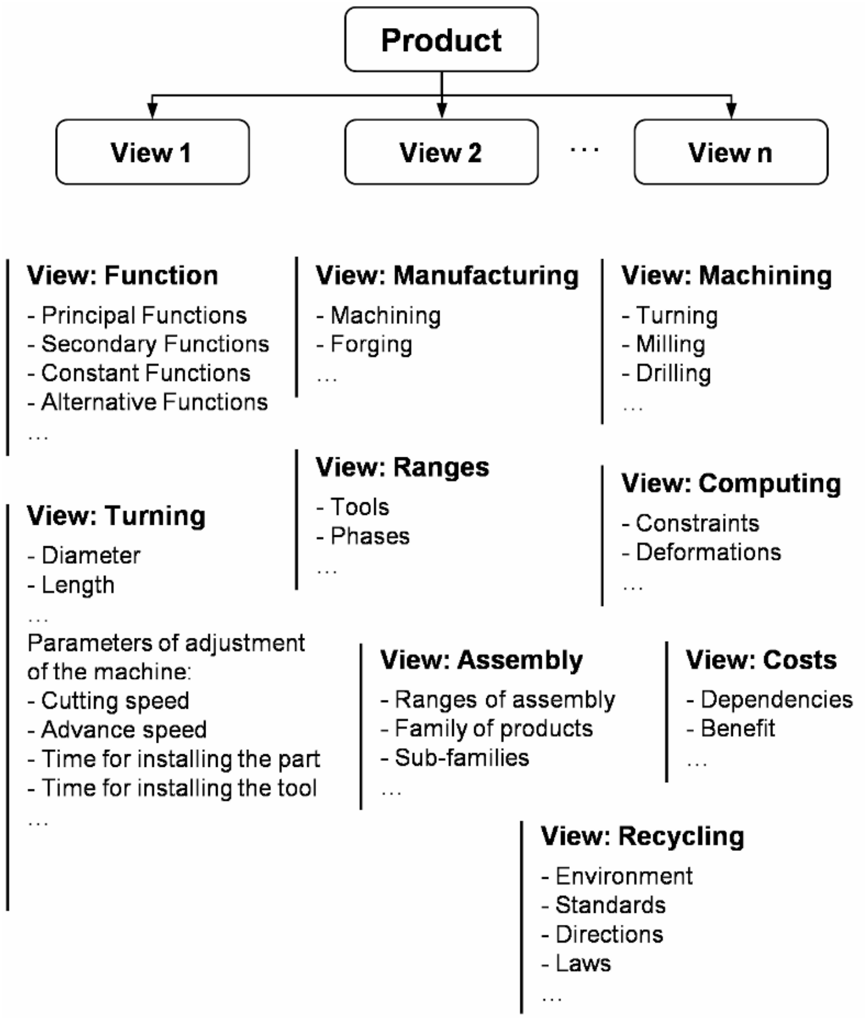


Fig. 2.18: Description of the product as seen from various views.

The following are recommended:

- To build a graph around all the references of production
- To describe the part (object) from the perspective of the manufacturer.

A dictionary of manufacturing rules is compiled to help manufacturers by consolidating their knowledge of manufacturing techniques. A description of the product by views is recommended. The multi-view model for integrated design (Tichkiewitch et al. 1995) was adapted to manufacturing problems.

The Product Model is separated into two parts: *graphic* and *structure of data*. The graphic part represents the structural decomposition of the product by using the concepts of *component*, *link* and *relation* proposed by our *Integrated Design Team* of the "Soils, Solids, Structures" Laboratory and recalled in (Tichkiewitch and Brissaud 2000) (Figure 2.18).

The second part regarding the structure of data gives the types of operations to be undergone by the product as well as the manufacturing parameters as viewed by the manufacturer.

To illustrate this, Figure 2.19 shows the graphic part of the guidance system of a vehicle.

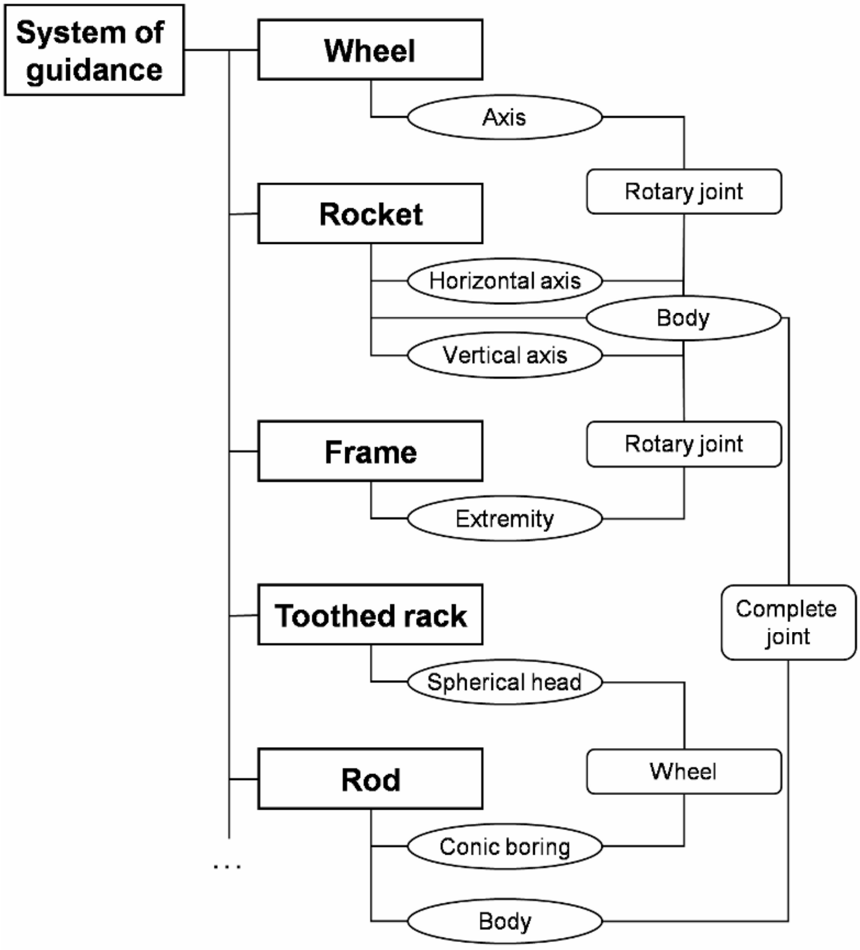


Fig. 2.19: Flow diagram of the product model: graphic part.

The next figure (Figure 2.20) shows a part of the operations which the product has to undergo at the various stations of machining such as turning, milling, drilling etc, as well as the parameters of these operations.

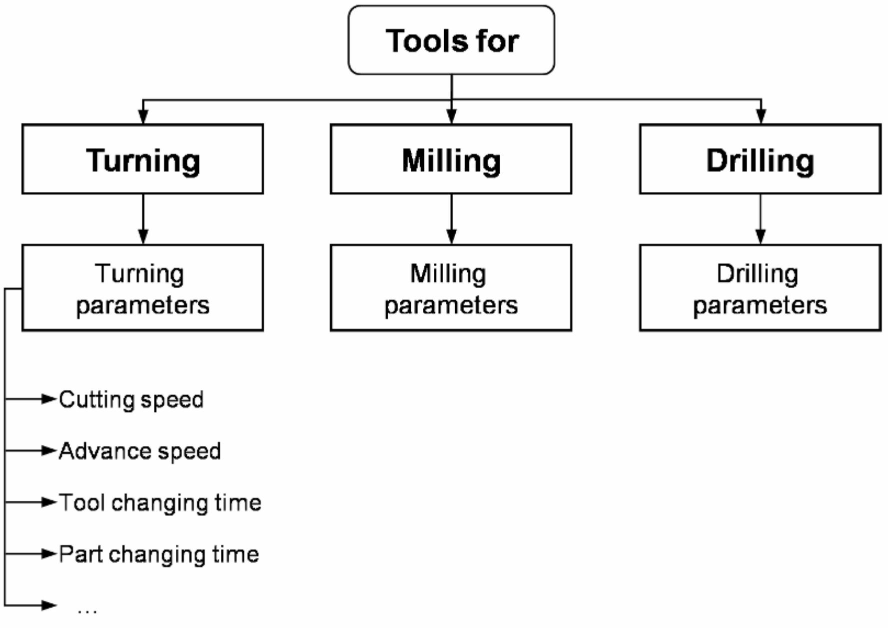


Fig. 2.20: Flow diagram of the product model structure: structure of data.

The product model is not static and can evolve in manufacturing in response to unforeseen elements (Figure 2.21, Figure 2.22). The parameters of design authorise additions and changes to the manufacturing parameters. The actors of manufacture are able to change the product model in agreement with the others actors of the design. The product model is unique in the fact that all modifications and additions can be read by all the actors concerned.

Consequently, it can be stated that the relation “order givers/subcontractor” changes. The credibility of a subcontractor does not only depend upon the quality of the products provided and the strict respect of deadlines but also upon his ability to react to inevitable dysfunctions. The industrial product of today “is more and more designed” by the subcontractor (supplier) and “less” by the client. Thus there is a need for:

- Reliable communication support to reactivate exchange information essential to management production,
- A model of the dysfunctions and risks in order to pre-empt their propagated effects.

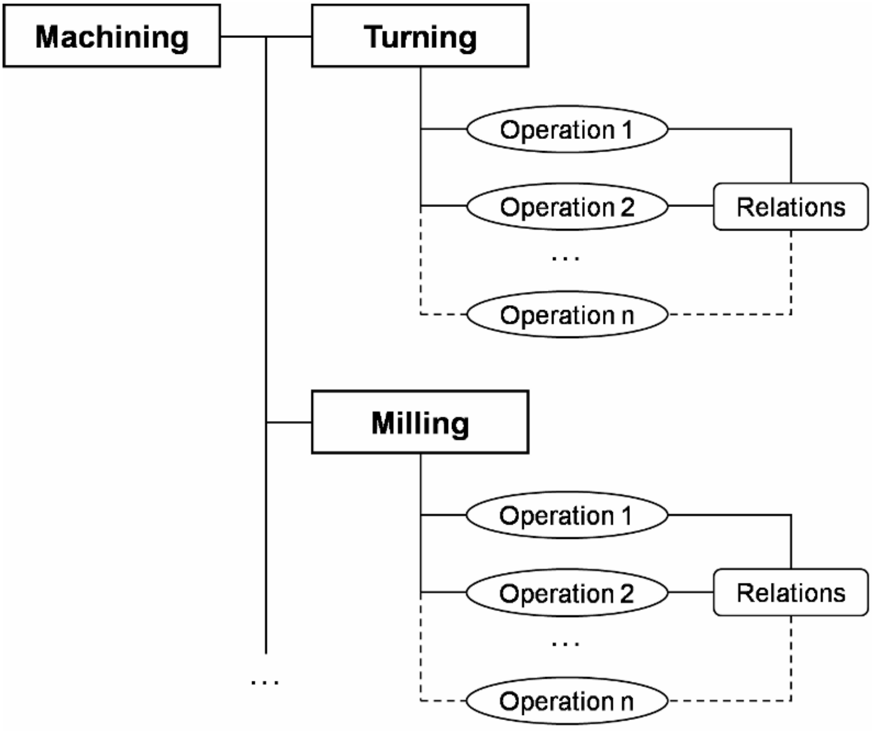


Fig. 2.21: Operation flow diagram of the manufacturing process.

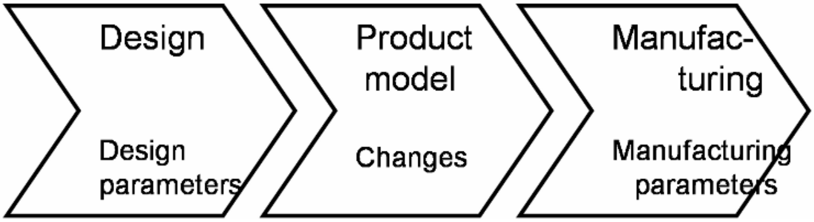


Fig. 2.22: Evolution of the product model.

Therefore, the production system becomes *reactive* and is characterised by a *synchronous approach* rather than interactive and characterised by an asynchronous approach. The impacts of these approaches at the organisational, economic and operational level of the installation also require assessment.

2.4.6 Product model from the market life cycle perspective

As product also consists of accompanying services, the model needs to be extended to become a core section with a surrounding shell. The proposed model for extended products takes the product perspective on the market and its evolution in the market context into consideration. Figure 2.23 shows the development of the product concept from the narrow sense to the broader one.

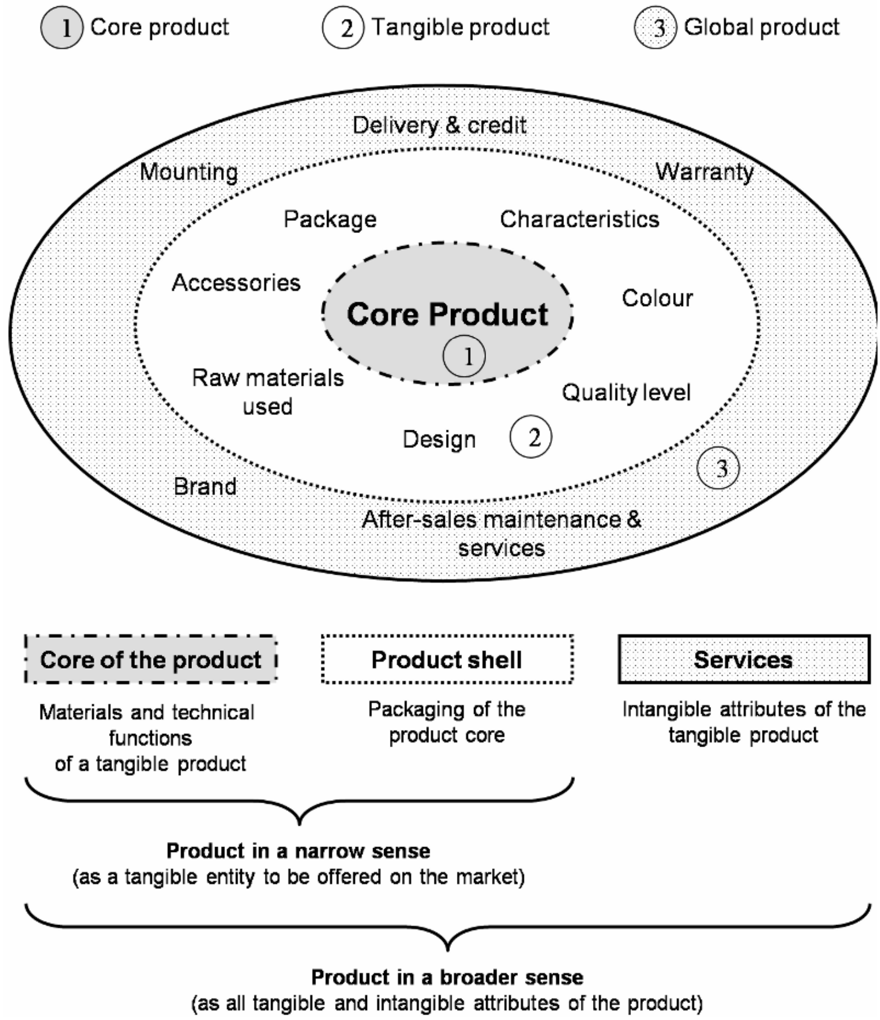


Fig. 2.23: Extended product model for the market life cycle.

The product model is based on the product life cycle and is used for elaborating a methodology for customer-orientated design.

2.4.7 Case study of a life cycle product model

This case study shows a product model from a life cycle perspective. The product model consists of the following types of attributes in order to incorporate variations in the service options during and at the end of the life cycle.

- Modularity: a product is modelled as a connectivity graph of modules. In turn, the modules are modelled as a connectivity graph of components forming the basic elements in this model (Figure 2.24). Modularity can be also used to explicitly classify the separation between the core and shell of a product.
- Life cycle related attributes: a component is modelled as a set of attributes, such as the options of recycling and reuse, cost of manufacture, manufacturing energy, lifetime, weight and material. The attributes define services which are available during and at the end of life cycles.

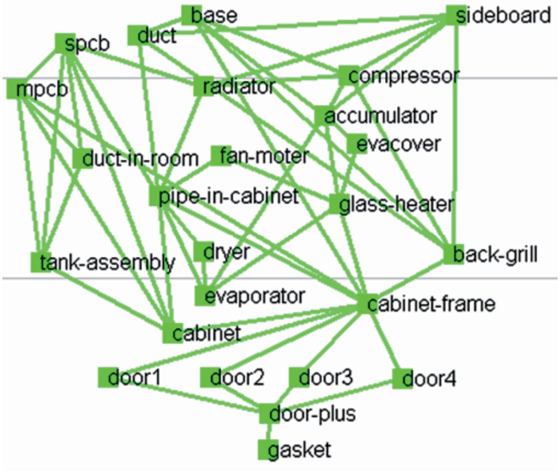


Fig. 2.24: Product model of a refrigerator (Umeda et al. 2000).

The model assumes that a module can be repaired by replacing defective components with working ones and that a component cannot be disassembled or repaired. In other words, used components which have been collected can be reused as they are, recycled or simply disposed of.

This modelling technique enables an appropriate modular structure to be designed based on the design parameter of products, modules and components such as usage, lifetime or material selection for recyclability. Figure 2.25 shows the optimised product models with respect to alternative life cycle types (reuse, maintenance and PMPP types) (Post Modern Manufacturing Paradigm). (Tomiyama, 1997) (Umeda et al. 2000)

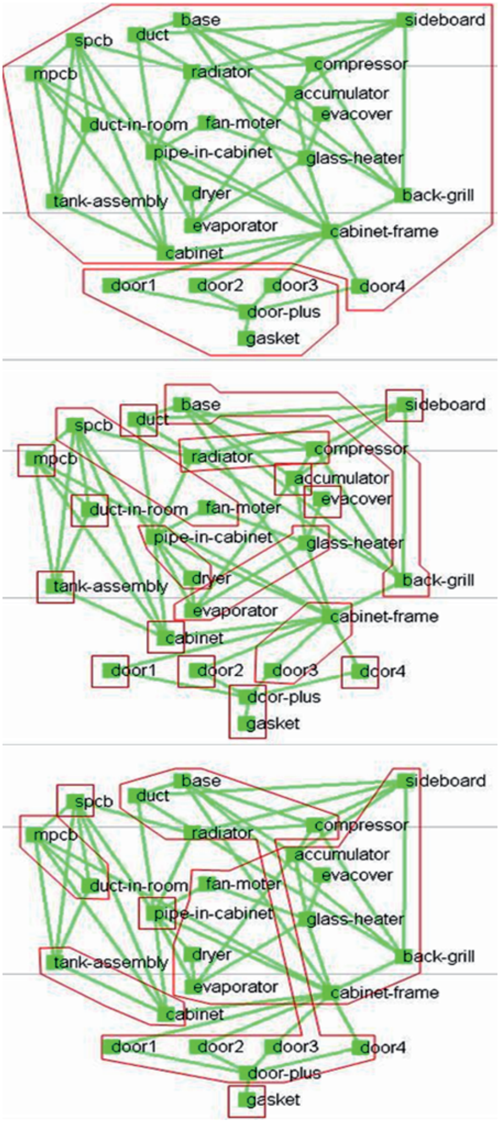


Fig. 2.25: Optimised module structures of a product model with respect to alternative live cycle types: Reuse type (above), maintenance type (centre) and PMPP type (below). (Tomiyama 1997), (Umeda et al. 2000).

2.5 Interim summary of life cycle modelling

Life cycle modelling represents the basis of a successful life cycle design. A number of methods, modelling techniques and international standards relevant to this can be found in literature and in industrial practice. The identification of factors affecting the life cycle and their adequately precise mathematical formulation is especially important in order to obtain valid information in a superordinate, holistic life cycle model.. Due to the long-term planning horizon, efficient models are required which depict the total life cycle of a product. The models need to be designed in such a way so that they are capable of showing various perspectives relevant to the situation concerned, thus permitting alternative product configurations and their development possibilities to be evaluated. Only then is it possible to identify holistic optimisation potentials in the early stages of product development and implement them to create a successful life cycle strategy.

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