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Engineering Change Management in Distruted Environment with PDM/PLM Support

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1. Introduction

Globalization has dramatically changed the way in which products are produced by manufactures of all sizes. Small to medium sized organizations are now just as likely to engage in global outsourcing projects as large multinational teams (Tosse, 2005). Global distributed teams need to effectively communicate and collaborate throughout the entire product development process to produce innovative products of the highest quality in the shortest period of time.

In industry, engineering change management (ECM) is recognized as a problem that receives too little attention relative to its importance. Wright's (Wright, 1997) conclusion is that from the manufacturing perspective ECM is a disturbance obstructing smooth product manufacture, but such a perspective ignores ECM's capacity to provide the incentive for product improvement. Wright's conclusion is that a number of coordinated research programs are required to establish the ground rules for maximizing the product design benefits from EC activity. Many and especially late ECs are very costly for any development project. ECs consume one third to one half of the total engineering capacity and represent 20 to 50 % of total tool costs (Terwiesch & Loch, 1999). The key contributors to long EC lead times are: complex approval process, snowballing changes, scarce capacity and organizational issues. Loch (Loch & Terwiesch, 1999) analyzed the process of administering engineering chain orders within a large vehicle development project. Despite the tremendous time pressure in development projects, EC process lead times are in the order of several weeks, months and even over one year (Loch & Terwiesch, 1999). A detailed analysis has shown a low proportion of value-added time in the EC process – less than 8.5 %. An EC spends most of its lifetime waiting for further processing. Loch suggests the following improvement strategies in order to reduce EC lead time: flexible capacity, balanced workloads, merged tasks and sharing resources (pooling).

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Huang (Huang et al., 2003) investigated the current state of ECs in current industrial practice. Huang focused on big manufacturing companies and found that it is necessary to develop methodologies and techniques to improve the ECM practices. There was no evidence that ECM software packages had been used within the surveyed companies. Current ECM practices vary between companies, from formal to ad hoc approaches. Current tools dominating at new product development and introduction process are low-cost, low-function personal productivity tools like spreadsheets, project management and word processing according to AMR Research (O'Marah, 2004).

ECM support can be implemented in commercial PDM/PLM or ERP software. There are web-based ECM systems that provide better information sharing, simultaneous data access and prompt communication (Huang et al., 2001). But even a high level of information technology for ECM is very often paper based, especially in smaller companies (Huang et al., 2001). The reasons for this are that computer aids are not well known to EC practitioners and some of existing computer aids do not reflect good EC practice. In some cases, comprehensive functionality of some systems undermines their focus and imposes intensive data requirements (Huang et al., 2001).

Rouibah (Rouibah & Caskey, 2003) focused on cases in which complex product development involves more than one company – distributed engineering change management. The concurrent design process results in a parameter network that tells us how closely different components are interrelated. The knowledge contained in this network helps manage cross-company activities during the ECM process.

A review of the references emphasizes the problem of engineering changes in companies and offers quite specific solutions for complex products. This paper establishes a general model of engineering change management and applies it to distributed manufacturing and product development teams. Distributed environment requires specific methods, organization, communication skills and information system. The reference ECM model helps engineers recognize the main problems and improve the process. This was also confirmed on examples from industrial practice.

2. Characteristic design and product levels

Product development involves four characteristic levels of design. Each of them requires certain very specific activities (Prasad, 1996). The characteristic design levels could therefore ensure very clear definitions of the activities and thus provide the necessary software and other support for all phases of the design process (Duhovnik at al., 1993). The following four levels of the design process have become established in professional literature: original, innovative, variation and adaptive (Table 1) (Žavbi & Duhovnik, 2001). On the basis of the above design levels, design tasks can be determined and distributed among them.

- **Original design** means the designing of entirely new products, whereby a new working principle is determined for a new or known function. In the process of designing from scratch, one therefore needs to define the working principle, model of shape, functionality and technical shape.

- **Innovative design** means designing products by varying the working principles which fulfil the required function to the optimum degree. In innovative design one needs to define the model of shape, functionality and technical shape.

- **Variational design** means designing products by varying loads, therefore comparable models of shape are obtained. In variational design one needs to define the functionality and technical shape.

- **Adaptive design** means designing products by adapting their dimensions to the technical and technological possibilities for their manufacture. In adaptive design one needs to define the technical shape. This shape is conditioned both by optimization of microtechnology (special features of the manufacturing technology) and by the shape design of details (ergonomics, assembly, etc.). Adaptive design is a dominant type of design (Table 1) and typical of the engineering change process.

The characteristic design phases are: determination of design requirements, conceptual design, embodiment design and preparation of technical documentation (Horvath & Vergeest, 2000). During their work, designers will require different types of support, depending on the phase of design or abstraction of the product they are working on at the time (Rude, 1998), (Suh, 1990).

The type and number of changes that need to be made later are largely determined already in the phase of product development. If a thorough analysis is not performed taking into account all phases of the product's life cycle, from market requirements and manufacturing technology to maintenance, the number of necessary changes will obviously be greater (Duhovnik & Tavčar, 2002).

	Product levels	Description	Design levels
I.	New product / new technology	New working principles	ORIGINAL DESIGN
II.	New product / known technology	Variation in working principles	INNOVATIVE DESIGN
III.	Variant of an established product	Variation in functionality	VARIATION DESIGN
IV.	Product improvement (change)	Variation in dimensions	ADAPTIVE DESIGN

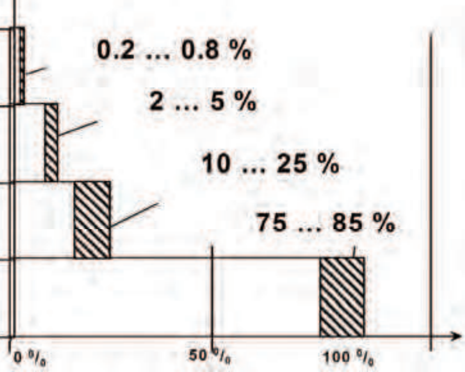


Table 1. Relationship between design and product levels (Duhovnik & Tavčar, 2002).

The entire product family and the possibility of its upgrading have to be envisaged already during the product's conceptual design. A clear presentation of the influence of concurrent engineering methods on the number of changes is given in Prasad's work (Prasad, 1996). For the sake of comprehensive analysis, it should be emphasized that change management begins already during conceptual design and later phases of product development.

3. Generalised engineering change process

Generalized model of engineering change process (figure 2) helps us understand and compare procedures in different types of production and consequently find the most appropriate methods for a specific enterprise. Each change begins with an idea. It is important to stimulate the employees to creativity as well as to ensure an easy collection of ideas and their tracking. Collecting of proposals for changes must be possible and accessible in a simple manner, throughout the company and also from the outside, servicing personnel and salesmen being the most important participants. It is necessary to ensure that proposals are collected centrally and that they are properly documented.

In the next step, the idea itself should be transformed into a proposal for a change. The information system plays and important role in arrangement and collection of the required data. Arranging also includes analyzing and testing, if applicable. It needs to be ensured that each proposal is subject to appropriate professional discussion, which, due to economic reasons, can be conducted in several stages. Each change must go through the process of approval, where the consequences of the change are calculated from all perspectives, e.g. in terms of costs and technical feasibility. Once the change has been approved, it should first be provided for changes in documents and their distribution, following which the change needs to be implemented in the production process, servicing etc.

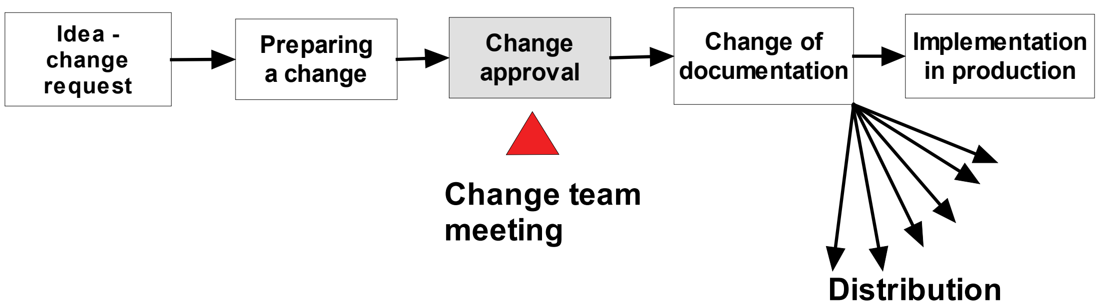


Figure 2. Generalised engineering change process of a product (Tavčar & Duhovnik, 2005)

The objective of this paper is to develop a method that will help distributed companies recognize weak points in their engineering change management system and improve it. Systematic analyses in various companies showed that the criteria presented in figure 3 have to be fulfilled for ECM to be managed well. It is very important for all of the stated considerations namely, communication, decision making, organization, process definition and information system to fulfil the minimum threshold criteria. The impact of an individual criterion depends on the type of production. The quality of communication primarily affects the first three phases of the EC process shown in figure 2. A clear definition of the process and the information system affects all phases of the EC process. Organization has the greatest influence on change preparation, which includes additional research and prototype production.

3.1 Communication

To support developmental-design activities, it is important to be able to identify the relevant communication channels, as well as the frequencies and contents of communication (Frankenberger & Badke, 1998). The predominant type of communication varies considerably with the design level. In new product development, the world outside of the core development team serves as an important source of information, and creative dialogue will predominate. At the level of variants, designers are considerably more limited and dependent on the information that has been organized within the information system; this is even truer in the case of product changes. Poor communication is the most frequent reason for problems in ECM.

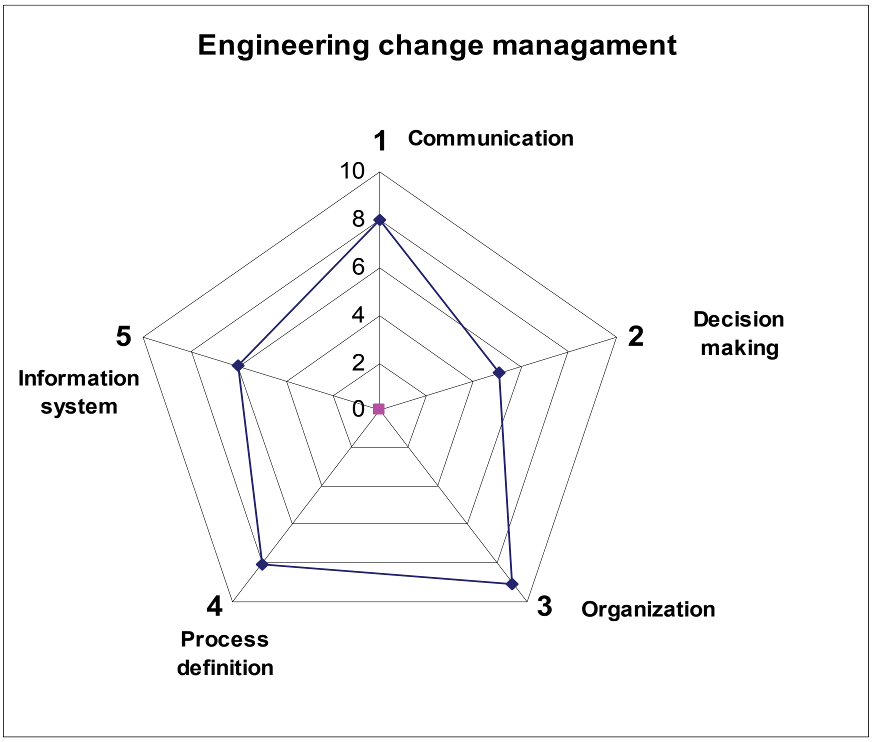


Figure 3. Criteria necessary for effective change management (ECM)

The following forms of communication in EC process were recognized: creative dialogue, review and approval, informing team members and searching for information (Tavčar & Duhovnik, 2000). The type of communication varies with the phase of engineering changes. During initial stages of the engineering change process, there are many considerations to be taken into account and harmonized, and many decisions to be made. This part of the process cannot be formalized. Informal communication is very important, since it is the source of creativity (Prasad, 1996). Physical proximity between project team members is the best way to accomplish a creative dialogue. In the distributed teams is a creative dialogue enabled with videoconferencing. Later during ECM, especially during distribution, the range of people requiring access to product data becomes wider. For this reason, access to the electronic form of documents and communication via the information system is very important.

Regular and effective communication is the necessary prerequisite for the functioning of virtual teams. Virtual team members need specific skills to communicate and work well (Tavčar at al., 2005). In addition to technical knowledge required to use the communications equipment, special features of work in a virtual team also need to be taken into account, e.g. regular responses, which are important for building trust. Each virtual team member must be independent and must show initiative. Individual skills, such as, for example, knowledge of a foreign language in a multilingual team, cannot be mastered overnight, which should be taken into account as early as team formation. Training in the use of unified software in the entire team (e.g. 3D viewer and red-lining) is needed. The EC leader must prepare the schedules and rules for regular meetings (Kayworth, 2000). Team members must take the time to get to know each other well, because this improves communication and increases the level of effectiveness. In strong personal relationships, communication is frequent but short. Relationships in virtual teams are developed and strengthened through a proactive effort to solve problems (Hart & Mcleod, 2003). Product development and engineering change management requires intense communication; the use of a video system is therefore essential. Based on studies (Harvey & Koubek, 1998), there is no difference between personal face-to-face and video communication in product development. A large difference is seen, however, if only audio or text communication is used. In complex tasks, such as change approval, the type of communication medium employed (e-mail, audio, and video) has a strong impact on effectiveness, while in simpler tasks this has no marked effect (Kayworth, 2000). Communication becomes more effective once the team develops a common vocabulary (Kayworth, 2000).

Successful work in virtual development teams requires certain special skills for team members (Tavcar at al., 2005):

- Willingness to cooperate and work in EC team.
- Effective communication in a virtual team (trust building).
- Initiative and ability to find information and make decisions.
- Mastery of a common spoken and written technical language (similar background is an advantage in communication).
- Working with the communications software
- Ability to access and work with product data.
- Specialised knowledge (compatible with other team members)

As a rule, communication involves a feedback loop between the sender and the recipient. It is very important for effective communication that the sender immediately receives a confirmation that the recipient correctly interpreted the information. Whenever one writes a message, a reply is needed in order to know that the intent of the message was achieved. In a conversation, however, confirmation is often expressed simply through mimics. Within a familiar team, even a small hint will suffice and everyone will understand the message. However, recipients from different cultural environments or different types of expertise will require a clear, modified explanation. Effective communication in an EC team requires as many communication channels as possible: audio, video and textual.

Creativity requires an optimum level of communication (Leenders at al., 2003). Overly intense or overly limited communication reduces creativity. Communication is the driving force of development teams. Both individuals and the team as a whole require an appropriate level of autonomy to develop their creativity. These needs can be fulfilled with regularly scheduled formal and informal communication. Good dissemination of information and distributed communication (each member with all of the others) must be ensured. This is in agreement with a German study (Frankenberger & Badke, 1998) that reports that 80% of a designer’s time is composed of routine work that individuals perform independently, and 20% of conflict situations, which need to be solved, and decisions that have to be made. According to studies, designers solve 88% of all problems in co-operation with others (Frankenberger & Badke, 1998), by relying on the experience and knowledge of their co-workers and the synergy effect of the team.

Trust in a virtual team

Individual studies have confirmed that well managed preparation can accelerate the building of virtual teams and thus increase their effectiveness (Huang at al., 2003). During their life cycle, virtual teams pass through various phases, which need to be taken into account during team management. Members of each virtual team are initially strangers to each other, with a considerable degree of mistrust. Effective communication and functioning of the team as a whole begins only when trust develops between the members. Team management must always take into account the phase the team is undergoing at the time. Kasper (Kasper & Ashkanasy, 2001) builds trust in virtual teams on a common business understanding and business ethics. Common business understanding includes a correct understanding of the virtual team's goals, distribution of roles, clear definition of tasks, management, and a joint identity. This needs to be clear right from the start. A virtual organisation requires clearly set rules to enable trust to be built.

3.2 Decision-making in a distributed engineering change management teams

Decision-making is the bottleneck point during the ECM process. Work is more efficient if decisions are made by one person. However, it is difficult for one person to have all of the complex knowledge that is required for such decision-making. It is common practice for decisions to be adopted by a team, an EC committee. However, in this case the danger is that responsibility could be shifted from one person to another. A good process also contains clear delimitations of competencies concerning decision-making and interventions in the case of complications.

The leader of distributed ECM team needs to be additionally trained for work in a virtual team. To ensure engineering change execution, a constant overview over the current status and activities of the individuals is necessary. Appropriate division of work is essential - the interdependence of tasks serves as a source of creativity, but it also brings about greater problems in coordination. The change approval is the main mile stone in the EC process. Representatives from all phases of the product life cycle should be involved in the EC team. At approval process EC team members should have a chance to exchange their opinions. Videoconferencing has more channels of communication and therefore has advantages compared to approval by e-mail. A clear decision-making structure helps to speed up decision-making and EC process (Vilsmeier, 2005).

Distributed EC teams change their team members often. Special attention should be put to activities at initialisation of a new EC team. The goals should be set clearly, adequately trained individuals should be selected, and the necessary infrastructure for communication and work should be provided. For good co-operation, the team members should have complementary, and partially also the same, knowledge. Virtual development work requires careful planning and monitoring. The EC leader should know how work in the teams is going, and distribute information between team members about the project as a whole. Independence between teams makes work more productive, but cross-team communication offers new potential for creativity. Inter-team communication is therefore indispensable. For good functioning of the EC team, personal contacts between the members must be well developed and should provide mutual support. Technology will make work easier, but will not be crucial for the effectiveness of virtual teams (Lurey & Raisinghani, 2001). Another role of project leaders in virtual teams is to ensure building of the team, taking into account the cultural specificities of individual members (Kayworth, 2000). Complex tasks require very intense communication, which can be ensured only in a systematic way. Virtual teams are more effective when they deal with less demanding tasks (Leenders at al., 2003).

3.3 Organization

The organizational structure should support the EC and design processes. For more effective work, it is necessary to separate changes in already products undergoing manufacture from the projects intended for developing new products (Tavčar & Duhovnik, 1999). This division of work can ensure shorter response times. One should be aware that ECs are very unpredictable, which causes variable loads and long response times (Loch & Terwiesch, 1999). Additional research can be especially time consuming. One of the possible solutions in distributed teams is flexible working hours, which are adjusted to the amount of work. An additional useful measure may be for projects to share their employees (sharing resources). This would mainly involve specialists for individual areas, e.g. surface treatment, noise and vibration, especially in the case of technically demanding products. It is recommended that team members should be prepared in advance to tackle typical problems. For good use of the capacities, it is necessary to ensure a good overview over the occupancy and flexibility when work is assigned.

The analysis of changes requires an interdisciplinary approach and excellent communication between the participants. Close connections between the sell, R&D, service, purchase and production departments are very important in the decision-making process, especially when individual variants are discussed. The organizational structure should encourage good communication and quick inclusion of individuals when necessary. An EC passes through several team members and suppliers at various locations. An appropriate approach is usually to assign several persons responsible for implementation of each change; these persons monitor the change and initiate appropriate actions if the process is stalled anywhere. The response should be quick and reliable and capacities should be flexible.

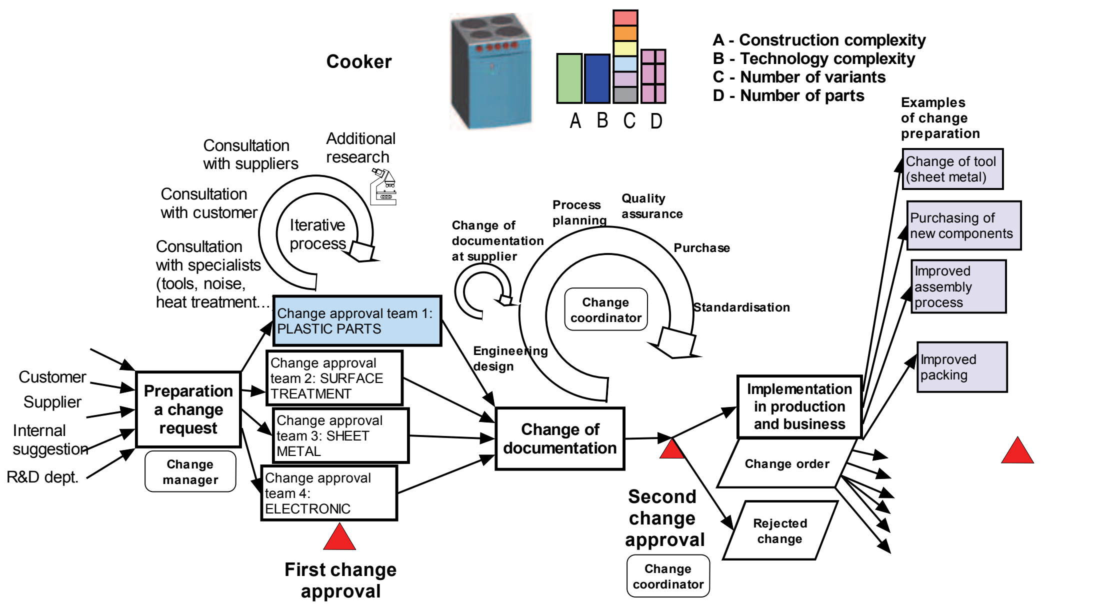
The EC management starts at initiation of a new product development process. An early inclusion of strategic suppliers in the first phases of product development opens new technological possibilities and reduces product development time. If possible, the purchased components which will be used in the serial product as well, should be incorporated already in the prototype. Similarly, tools suppliers are included in the conceptual design phase and minor corrections of the product's shape often prevent unnecessary problems. Developmental teams must be provided with the best possible communications facilities. It is important to keep records on justifications for decisions, for example, and predetermined developmental phases. There records are indispensable in the EC process in the case EC is not executed by the same people as product development. Product development yields product data; these should be documented in an appropriate format and should enable controlled electronic access through all phases of the product life cycle. Figure 6 shows extended product structure with all the necessary documentation. PDM systems (Product Data Management) were developed to enable controlled access to technical documentation (3D models, drawings, documents).

3.4 Process definition

Quick and reliable implementation of ECs requires a detailed process definition, which should be well understood by all participants. The EC process has characteristic milestones, which are presented in figure 2, but the execution should be in line with the company's special features and goals. A common mistake in practice is to use the same process for small changes and for new products. This causes a great deal of waiting and long lead times during change implementation. A clear division of processes and people who are in charge of them has been proved to be successful. Workflow in an information system significantly contributes to tractability and transfer rates between individual workplaces. It should be taken into account that changes always involve a large degree of unpredictability. It also often turns out that additional research is necessary, as well as cooperation with external suppliers, customer approvals etc. An effective ECM system ensures reliable operation, especially in such exceptional cases.

Case study: Engineering change process in serial production

After completed product development, product data are determined in detail and can be changed only according to strictly defined procedures. There should be no hold-ups in the serial production process. Since the correlation between different fields is high, the production process must be carefully planned and the communication channels must be provided for. Product changes cause a chain of corrections and costs related to tool change, already purchased components, servicing etc. Communication via workflow increases productivity and reliability.



1. Change requests and suggestions come from different sources to change manager.	2. Collecting of product and component stock data and change pre-assessment.	3. **First change approval** by an expert team at adaptive or variation design levels.	4. Change of technical and business documentation serves as additional test of feasibility.	5. Change coordinator controls workflow, stops change process or perform **second change approval** and coordinates change implementation.	6. Change order triggers change implementation.	7. Distribution of technical and business documentation.	8. Date D - change is applied in production.

Figure 4. Engineering change process in the manufacture of household appliances

Serial production of household appliances is usually based on assembling of elements and modules produced by different suppliers. The quality and timing of delivery by several suppliers should be guaranteed. Umbrella companies should be in charge of marketing and development of end products. The product development time is reduced by the transfer of component development to strategic suppliers. The manufacture of household appliances is an example of distributed engineering change management.

In the case of less complex products, the commission for approval of changes can be always the same. In the manufacture of household appliances, however, the range becomes so huge that it is more sensible to form distributed groups for characteristic types of changes, e.g. sheet metal, plastics and surface treatment (figure 4). In this way the working process in smaller groups is more effective. Flexibility can be achieved in different ways: a group of selected specialists can be called according to the problem; virtual group is defined throughout the flexible workflow. The documentation about changes should be transparently accessible in the information system.

In the manufacture of household appliances, there are many design related changes (consumer needs). From the technical standpoint, it is more difficult to control a vast number of changes and the entire logistics than individual changes. A change of documentation simultaneously also constituted a feasibility study, in order to reduce the product development time. With PLM systems and program solutions, the two-phase approach became established: change review and approval in the first phase, and entry of the change in the documentation in the second. Based on the analysis of household appliance manufacturing, the following has been established: Approval regarding the feasibility of a change in a two-phase chain is not the best approach. The most effective way for making a definite decision on change approval is a creative dialogue between the team members. The dialogue can be conducted by means of a video conference (figure 4). Flexible workflow is vital for the process of modifying documentation.

- There is a high degree of unpredictability. Therefore, workflow must be flexible, so that the way can be defined simultaneously, according to the needs.
- An overview of each individual document's status should be provided in terms of its current location. Easy access and user-friendliness are important.

- A change should be implemented in a predefined sequence; however, those included in the process should be able to consult anybody, including external suppliers. In this way, a virtual group is formed and it can function effectively, as if it was located in the same place.

With the large number of variants and also of participants in the process, computer support becomes indispensable for communication. No individual alone can have a good overview of the numerous processes that take place simultaneously. The EC process must be determined with flexible workflow, so that each participant receives only those documents in which he or she needs to make changes. There should be also a user friendly link to related documents, for example product data of the assembly where the changed part is build in. The inclusion of external suppliers in the information system is especially important for good flow of information and effective decision-making, so that these can be independent of the location.

3.4 Information system

The information system constitutes the necessary infrastructure for effective ECM. Based on data from (Huang et al., 2003), (Huang et al., 2001), the analysis of changes in the information system appears to be more an exception than a rule. This is because during any EC, areas from sales and production to development are interwoven. An orderly information system should be upgraded so as to fulfil the specific requirements regarding adaptability of development and orderly production, and this is a very difficult task. The PLM system proved to be very suitable for this purpose, because in addition to change descriptions, all other documentation and product data is also available (figure 5). One must keep in mind that electronic communications have their limitations. This method of communicating is very convenient for informing the team members, but it cannot replace a creative dialogue within the team. Engineering Change approval require an intense communication via videoconferencing.

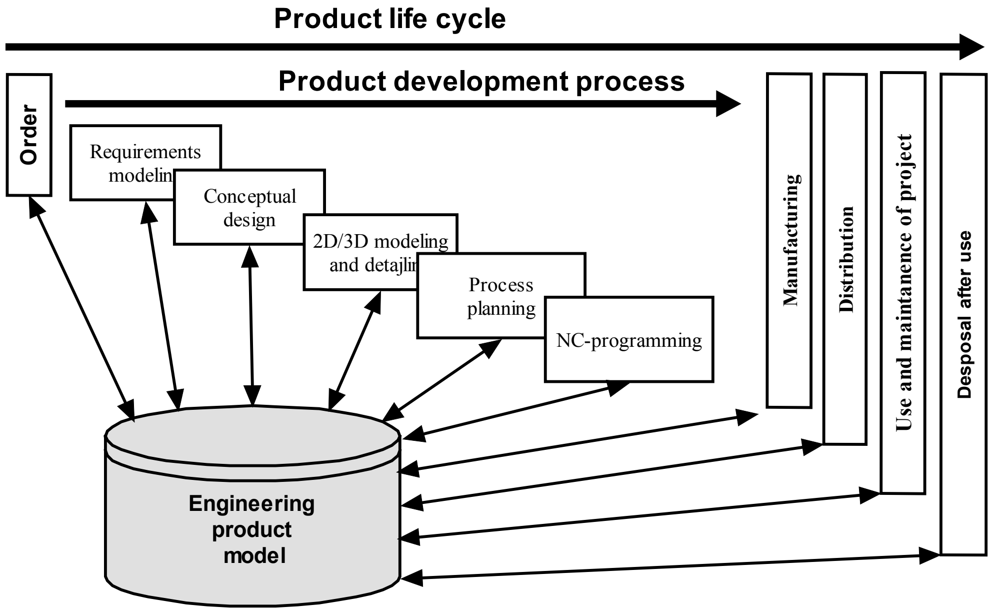


Figure 5. Ready access to product data and close connection to supply throughout the whole product life cycle is important for EC process (Grabowski, 1993)

Comparison and overlapping between PDM/PLM and ERP

A database about the building blocks and products with key information about the products is the main part of the ERP (Enterprise Resource Planning). Software usually allows standard monitoring of material management and production planning process. The use of PDM systems was initially limited to technical departments, support to storing and to accessing files, generated during computer aided design processes. The PDM system later became a tool for management of information on products throughout their lifecycle. PDM (Product Data Management) has been renamed into PLM (Product Lifecycle Management). The physical boundaries of an enterprise are not also a boundary to the information flows. The basic PDM systems user functions are: monitoring the design process and control of later changes, management of products structure, classification and project management.

The PDM and ERP systems are often overlapping (e.g. products structure) during the engineering change process. A good coordination between the two systems is a pre-requisite for a successful work. It is necessary to be able to take advantage of each of the systems and connect them into an effective system (Bartuli & Bourke, 1995).

The higher the integration the larger the volume of data transferred between the PDM and ERP systems, which cause overlapping to a certain degree. It is necessary to make a decision about the prevailing system and how is the master data transferred forward or linked between both systems.

Some ERP systems designers expanded the functionality of their systems also to the PDM sphere (example: SAP). It is necessary to check if the functionality is not limited because production systems are based on different principles.

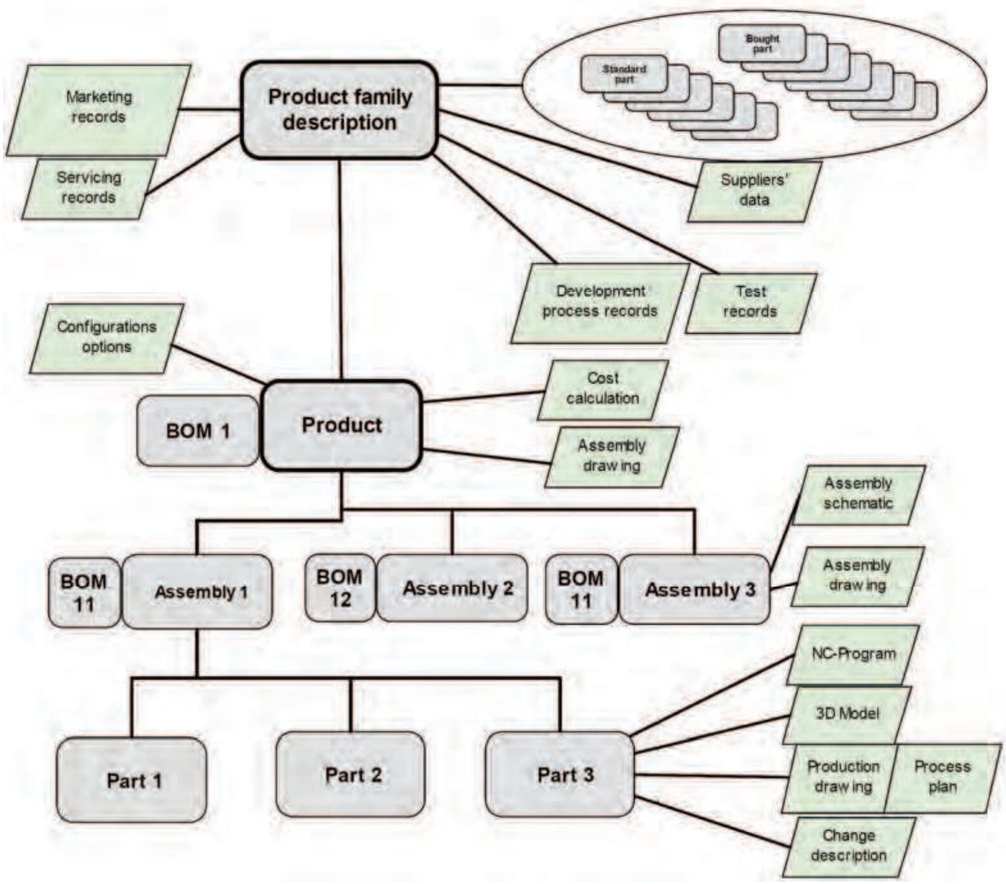


Figure 6. Expanded product structure.

Among the known cases it is not so much about the support during the development phase as it is about storing the results – the verified documentation and control of access for a wide range of users. For the purpose of changes management, a uniform information system is an advantage

Documents change in PDM/PLM system

PLM system is indispensable tool for documents change management. PLM system is with the access control and workflow useful first of all in distributed environment. Figure 7 shows an example of various document statuses of a design drawing from serial production. Access rights, for example, also vary based on the document's status. In the phase Under development, a design engineer can change a 3D model or drawing as much as he wants. Once the document is completed, a design engineer changes its status to Prototype. The document's owner can make changes only if he goes back to the Under development phase. Changes in the document status function as electronic signatures. Document status can be changed only by selected users: only standardiser can change the document status to Approval, and only head of the product development group to Issued. From this stage, the only possible status change is to Invalid or to new version (Revision). This approach ensures that all issued copies are stored. As soon as a document's status is changed to Issued, a TIFF drawing file format is created – this is intended only for viewing and printing. The history of document status changes is also recorded, i.e. their dates and names of the persons who made them. Originals are no longer stamped paper drawings, but PLM computer files with appropriate statuses.

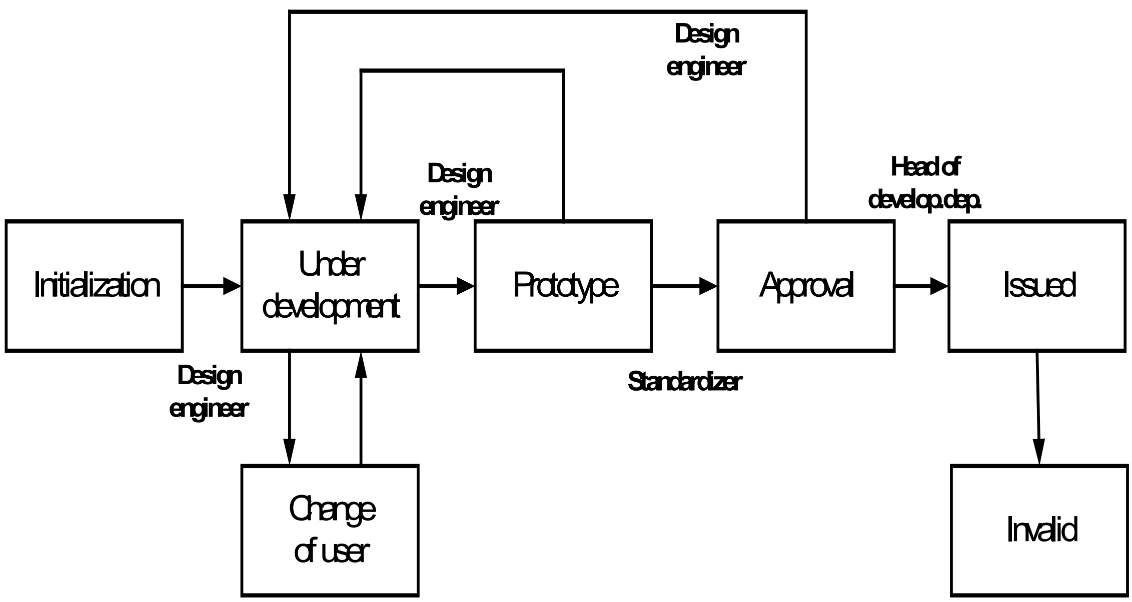


Figure 7. Document approval procedure (case from serial production)