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IMPLEMENTATION OF A KNOWLEDGE-BASED ENGINEERING CONCEPT USING FEATURE-TECHNOLOGY AT AN AUTOMOTIVE OEM

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ABSTRACT
Feature Technology (FT) enables machining elements to carry both geometrical and technological information. Thus such features can improve the Product Development Process (PDP) by integrating Product Manufacturing Information (PMI) from the very beginning, avoiding redundant data storage and supporting the reuse of existing manufacturing knowledge.
This paper reports the efforts undertaken by a German automotive OEM to establish Knowledge-based Engineering (KBE) in the PDP of their engines. More specific, bores are modelled as User-defined Features (UDF) in the CAD system Pro/Engineer, capable of being exported into the OEM's production process planning tools. From there all necessary product, operation and resource information can be transferred directly into the OEM's working plan administrative system of the factories, due to the distinct feature definition and predisposed process description. In addition, a combination of CAD, CAPP and CAM libraries allows the storage of the manufacturing knowledge gathered during the actual production. For future product development projects these libraries may increase product design and production process planning celerity and reliability.

Keywords: Feature Technology, CAD, CAPP, CAM, PLM, Change Management

1 INTRODUCTION
In today's high level of global competition, manufacturers continuously strive for reducing costs while simultaneously increasing the quality of their products. Considerable effort "is expended in the automobile development value chain to constantly reduce throughput times in the development processes and to enhance the quality of digital product and process descriptions. Simultaneous Engineering in the product development and manufacturing planning" as well as "intensive cooperation between the various divisions within a company and with external partners are key factors for success in this context" [1].
To cope with these challenges it is necessary to constantly carry forward the transformation of traditional PDP to virtual PDP that lead to concrete enhancements in efficiency and quality. While previous endeavours more or less concentrated on single pillars of the virtual product development like the virtual car or the digital factory, the focus nowadays is put on the integration and connection of all areas, processes and IT systems involved [2].
Considering the PDP, the phases of product design and production are characterized by a fairly high degree of automation due to sophisticated software support. In between, however, the production process planning phase lacks methodical and systemical assistance, resulting in information redundancy, time delay and extra work for the personnel.
In order to improve the PDP the first objective must be to close this "automation gap" (Figure 1) by providing all partners involved with a coherent and consistent (3D-) data flow along the PDP and by standardization of working methods.
The second objective then is to facilitate the reuse of existing manufacturing knowledge in the sense of KBE [3], so that the product designers may incorporate standardization in their 3D models right from the start and to encourage production process planners to revert to already approved, "best practice" machining processes (Figure 1).

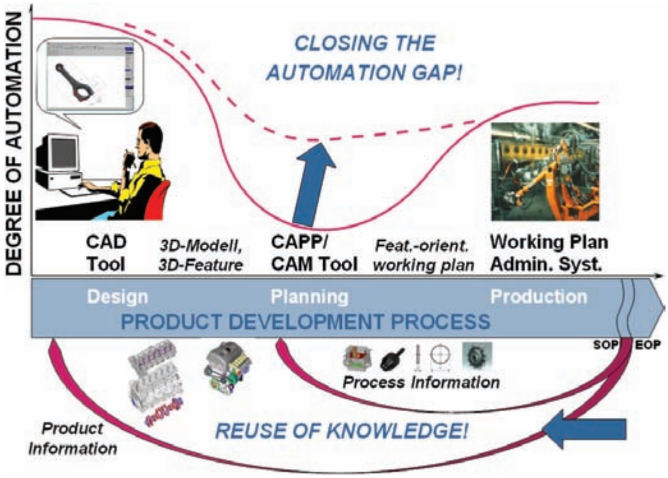

Figure 1. The two objectives of closing the automation gap and the reuse of knowledge

To meet these demanding objectives, four fields of action were identified:

- Developing a product designing method using FT
- Defining a process planning method based on product features
- Facilitating the reuse of manufacturing knowledge in the sense of KBE
- Implementing the KBE concept

The following chapters are structured accordingly, complemented by a summary, conclusions and future prospects.

2 PRODUCT DESIGNING METHOD WITH PRODUCT FEATURES

As indicated in the abstract, FT allows the integration of PMI in the 3D CAD model. Normally, PMI is attached to the product model, like in traditional blue prints. The presented approach, however, includes PMI in the product features themselves (i.e. a level deeper), which is necessary to harmonize the description of not only the product, but the according machining processes as well (e.g.: drilling a hole, not a crankcase).
The general idea now is to work with predefined product features in CAD for a full 3D solution, without extra work for the designers, but with the possibility to export all necessary information to the production process planning systems. Given the OEM’s multi-system environment there were some preconditions to consider:

- CAD: Pro/Engineer (PTC)
- Programming Environment: Pro/Toolkit (PTC), Visual Basic (Microsoft)
- Interface: PLM-XML-schema (Siemens PLM Software)
- CAPP: Process Designer (Siemens PLM Software)
- CAM: Machining Line Planner (Siemens PLM Software)

Concerning Pro/Engineer, the developed method shows the following core characteristics:

- Product features modelled as User-Defined Features (UDF) including PMI
- Fixed parameterization – editable parameter-values
- Relations/restrictions within the UDF to inhibit improper parameter value inputs
- Predefined parameter value sets (including locking mechanism) for standardization
- Product feature library in PDM[1] system (for the present)

[1] For a start this product feature library was directly applied to the according PDM system using a specialized file folder structure for easy handling and administration. One idea for improvement is to connect this library to a given application customized for standard and repeat parts with a more sophisticated search mechanism including a higher developed visualization function – and access to the OEM’s second CAD system: Catia V5.

The next step is a product and a cost-benefit analysis to determine the most appropriate product features to start with the new method. Which machining elements can be (easily) modelled as UDF? Which machining elements offer the presumably highest savings potential via standardization? For the OEM the answer to these questions is "bores", since they appear in high quantities in every part of a combustion engine and are relatively easy to parameterize. Having found a solution for bores, this solution can then be modified to fit other manufacturing elements (e.g. notches) in a second step. Figure 2 and Figure 3 show a typical bore as part model and as UDF, respectively, with geometric dimensioning, tolerancing (dimension, position), labelling and thread information (+ notation) and surface roughness information (+ symbol), all driven by a parameter table.

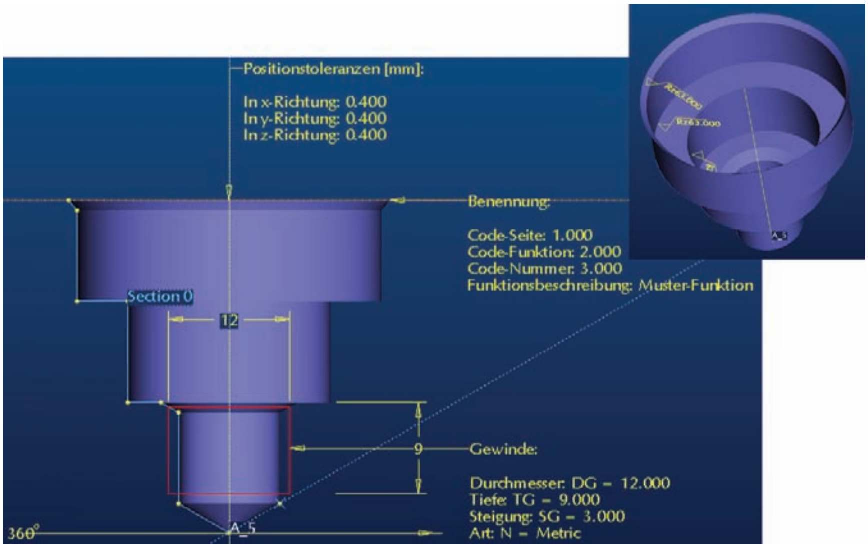

Figure 2. Left: bore part model with tolerancing (position), labeling and thread information (+ notation); Right: surface roughness information (+ symbol)

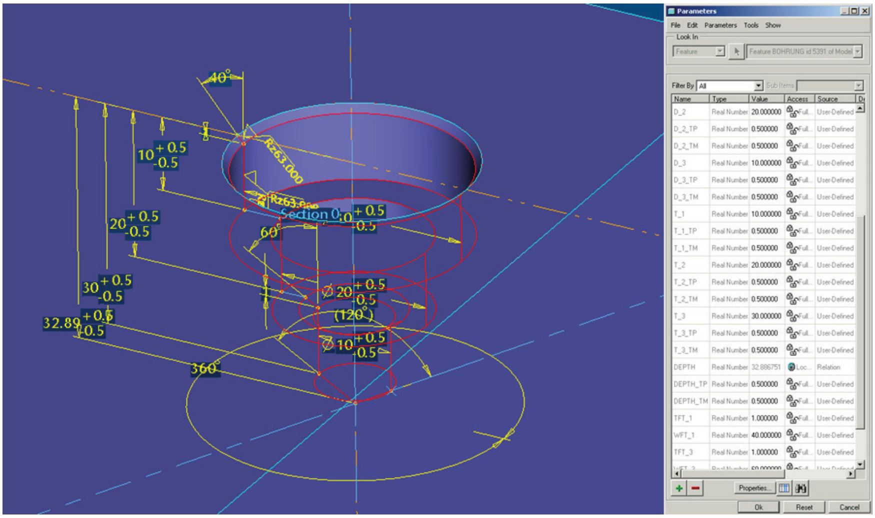

Figure 3. Left: bore UDF with geometric dimensioning, tolerancing (dimension) and surface roughness information (+ symbol); Right: parameter table

The fixed parameterization of a UDF does not delimit the designers' freedom per se, it only regulates the designing method. Still, there are several options to constrict the range of the values of the parameters. When initially defining a UDF, a so-called "External File for Restricted Parameters" can be read in. In this file "the value or range of values as well as the type of the restricted value parameter are assigned based on the name" [4]. The usage of multiple restriction files allows the customization of UDF for every purpose, namely from totally editable to completely fixed bores [5].
Working with such predefined UDF does not only ensure that all necessary information is incorporated in the 3D model; it also provides the opportunity for a well directed query of data, so that the feature information can be easily exported to a pending system, e.g. Process Designer. Like most of the available 3D-CAD tools, Pro/Engineer offers an Application Programming Interface (API): Pro/Toolkit allows the augmentation and customization of Pro/Engineers functionality to meet the specific user requirements by using the "C" programming language. More specifically, "important areas of enhancement include data exchange, user interface, regeneration, and interoperability" [6].
The UDF export program itself was written in Microsoft's Visual Basic (compiler) and can be initiated directly from Pro/Engineer. It parses the part model (or an assembly) for UDF bores, reads out the associated parameters and creates two XML files, one representing prototypes and the other instances for the bores in the CAM tool.
The main advantage of XML is that users are allowed to define their own tags, so they can create a custom-made, task-orientated data structure and classification. This adaptability of XML facilitates the data exchange between different information systems enormously.
In the case of the OEM the structure and classification of the XML files with the bores are adapted from PLM-XML, an open format developed by the UGS Corporation based upon standard W3C XML schemata [7]. In this manner the bores can be imported not only into Machining Line Planner, but also into Process Designer, due to their common data base. Consequently, the production process planners are not longer reliant on the fault-prone blue print, nor do they have to feed their CAPP and CAM tools with data manually[2], therefore avoiding another source of error.

3 PROCESS PLANNING METHOD BASED ON PRODUCT FEATURES

In the sense of concurrent engineering the two phases of product design and production process planning should overlap [8] to speed up the PDP. On this account, the rough production process planning is done long before the product design finally is approved, ideally supported by a CAPP system. Typical results are several case scenarios with different assignments of activities and resources (e.g. budget, factories and personnel), often even containing contract and order placing (e.g. machines). Usually the process description ends at the product level (at best), which might be sufficient for assembling, but not for machining. The detailed process planning on the level of machining elements such as bores starts adding value, as soon as the design of the new product reaches a reasonably steady state. A CAM tool is used to specify the machining processes or more precisely, the linkage of every product feature with the corresponding operations (i.e. drill, tap) and resources (i.e. tools, machines). Next, the single operations are allocated to the machines, where the CAM tool calculates the primary and secondary processing time and generates the tool path automatically. Furthermore it optimizes the cycle time by line balancing. Two other application areas of CAM tools are the collision (risk) analysis and the (non-machine-specific) NC code programming. Besides software complexity demanding simulation expert knowledge, the difficulty associated with CAM tools is that the latter require absolutely precise (and complete) input data to obtain a reliable outcome. In practice, some part of this data is unavailable at the time needed or totally missing; so planners are often forced into improvisation entailing barely usable and insignificant results characterized by pseudo-accuracy. Also it is quite time consuming to model an entire production line, which puts into question whether it is really necessary to simulate every single operation or only those relevant for validation purposes.
The aim in this field of action now is to develop a consistent working method that respects the special characteristics of the PDP, namely both flexibility in the beginning and accuracy in the end. Moreover, the process description shall amount to a directly linked-up, standardized working plan in the production.

[2] With the direct feature import, the feature recognition including laborious post-editing in CAM becomes obsolete – the strongest point of criticism within the OEM.

Again, there were some preconditions to consider due to the given multi-system environment:

- CAPP: Process Designer (Siemens PLM Software)
- Interface:
  - PLM-XML-schema
  - IDoc SAP standard data structure for electronic data interchange ("Intermediate Document")
- Working Plan Administrative System: SAP R/3 (SAP)

The key factor is the adequate granularity of the process description, where the minimum conditions are imposed by the measurement and test planning: The planner must be familiar with all necessary product information during the machining process; also, all test-relevant geometry attributes (e.g. of a bore) are operation-reliant (e.g. bore-diameter after pre-drilling, drilling and tapping). Hence, the working plan must have "intermediate state feature granularity" (Figure 4).

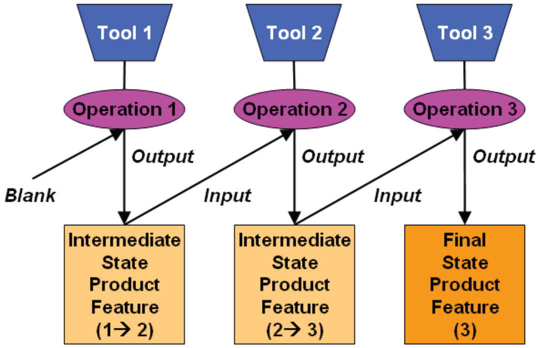

Figure 4. Intermediate state feature granularity

Another issue is the combination of the CAPP and CAM tools. This approach aims at describing the machining processes in the CAPP system, though with the same (intermediate state feature) granularity as in the CAM tool and therefore enabling feasible interaction of these two systems. Of course, the CAPP tool does not provide a mathematical verification, instead the planner resumes the liberty of entering estimated (empirical values reflecting expert knowledge!) and even fragmentary input values. At a later date the planner can proceed with his work and complete his entries. If a planner works with the CAM tool, he might reuse his simulation results by exporting the data objects (product features, operations, resources) and importing them in the CAPP tool. For future suchlike iterations these data objects retain their identification code and are updated automatically in the CAPP tool (Figure 5) – quite a benefit in consideration of operation details (feed, speed; also see Figure 6), for instance, after modifications in line balancing.

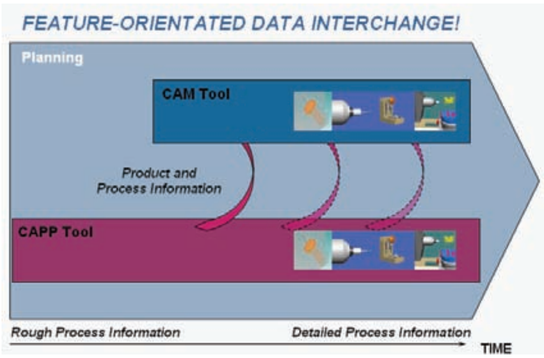

Figure 5. Repeated unidirectional data enrichment from CAM to CAPP

Whatever the planner decides to rely on – calculated (CAM) or empirical (CAPP) values – the result is a clear process description (Figure 6) in the CAPP tool with the right granularity for a link-up to the working plan administrative system of the production.

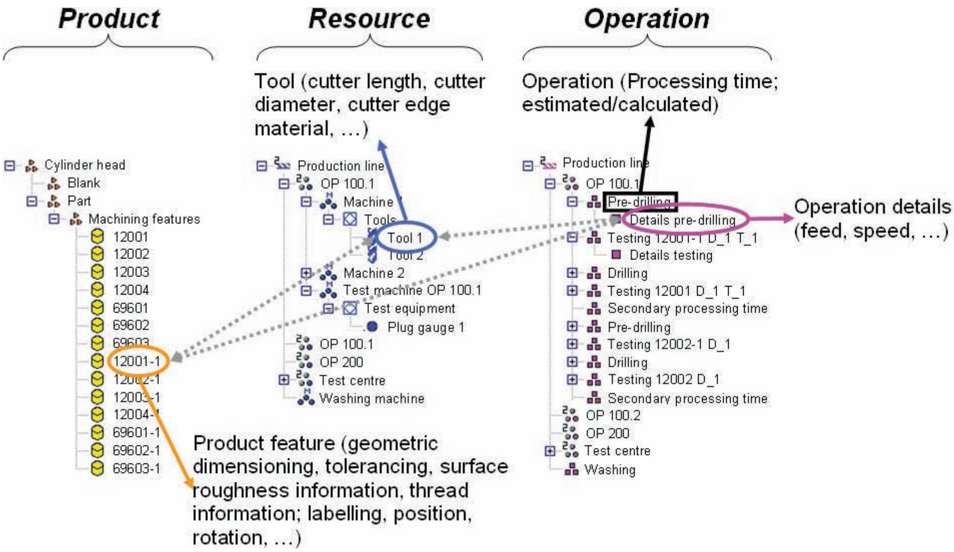

Figure 6. Production process description in the CAPP tool with input data from the CAM tool

For the working plan transfer, the PLM-XML-schema (Siemens PLM Software) of the CAPP tool is processed to SAP R/3 via an integrator interface (Figure 7). This layout not only allows bidirectional data interchange, but also the easy connection of other systems (e.g. tool data management system) to the working plan administrative system:

- Data import and export from and into non-SAP applications → XML
- Data import and export from and into SAP → IDoc
- Data routing, mapping and transformation → Integrator interface

Figure 7. Working plan transfer from the production process planning tools to the working plan administrative system (and backwards)

With the combination of the direct product feature transfer from CAD to CAPP/CAM and this new advance of describing machining processes, the first objective – closing the automation gap – is achieved.

4 KBE CONCEPT

The two challenges faced with every KBE concept are the acquisition of the adequate information out of the production and the backflow of this information to the intended users. As trivial as it may seem the proper process description in the planning phase and the process documentation in the production phase are absolutely mandatory for a KBE to work. Having this condition fulfilled with intermediate state feature granularity in both the production process planning systems and the working plan administrative system, this section proposes an approach offering three different "knowledge" libraries for comprehensive and optimal information backflow with respect to all persons involved in the PDP:

- Product feature library
- Process library
- Rule library

The product feature library is attached to the CAD system, hence intended to be used by the product designer for his part design. It contains the bore UDF including full PMI as previously shown in Figure 2 and Figure 3. With multiple parameter restriction files it is possible to enclose fully editable and totally fixed parameter values in the UDF, thus permitting freedom of construction or facilitating standardization. Howsoever, the designers get perfectly customized product features, especially made for their own and specific purposes and applicable of being transferred to the planners' CAPP and CAM tools.

When considering a library for best practice processes, one can think of a template-based and a rule-based solution. A template-based library is used to retain the process information of particular manufacturing processes. In such a manner already gathered manufacturing experience can be stored in a process library in a CAPP tool (granularity!) as process (meaning product feature + operation + resource information) master copies serving for future planning projects, assuring reliable, well-proven outcomes and short start-up times. A rule-based library, however, is advantageous for planning basically new product features, operations and resources in accordance with more or less sophisticated rules. These rules reflect the state-of-the-art of the production and are typically stored in a CAM tool. Reverting to this rule library, the planner is offered a manufacturing strategy (e.g. pre-drilling yes/no) depending on the geometry of the product feature (e.g. the diameter-depth ratio of a bore).

The KBE concept (Figure 8) is introduced as follows: Starting with the production, actual machining processes are analysed and filtered according to their suitability for standardization and best practice. The corresponding product features are then designed as UDF in Pro/Engineer (parameter restriction!) and stored in the product feature library. Likewise special process templates for the process library in the CAPP tool are extracted from the working plan administrative system, as well as general rules for the rule library in the CAM system. Again, this separation in three libraries for different usage cases proves to be advantageous for both practical application and personnel acceptance reasons [9]. The designers avail themselves of the UDF in their library for the part design, so that all relevant product feature information (including PMI) is embedded in the 3D model and can be exported to the planner while avoiding any loss or redundancy. In turn, the planners can revert to already field-tested process solutions by using the process library and the rule library. As a result, their process description is optimized for a quick and safe commencement of production.

During the life cycle of a product the factories might improve the production. Provided that the process documentation is well maintained (process transparency and comparability!), by means of analysis these improvements should lead to new standard product features and more sophisticated best practice processes. Naturally, not every actual product feature or machining process is meant to become standard or best practice, so some kind of approval process with a committee for updating the three libraries must be established. The members of this committee should represent all three phases of the PDP and it is recommended that these members also assume the responsibility for the library administration themselves. In any case, the synchronization of the three libraries and the consistency with one another must be warranted (Figure 8, magenta).

For updating the feature libraries, several case scenarios must be considered: If a machining process gets enhanced, while the relevant machining element remains the same, only the process library in CAPP tool and/or the rule library in the CAM tool must be updated, depending on whether the process enhancement can be described as a rule (Figure 8, mint). If a new process affects the geometry of its machining element, the designers too must be taken into consideration. If necessary, all three libraries have to be adapted (Figure 8, orange).

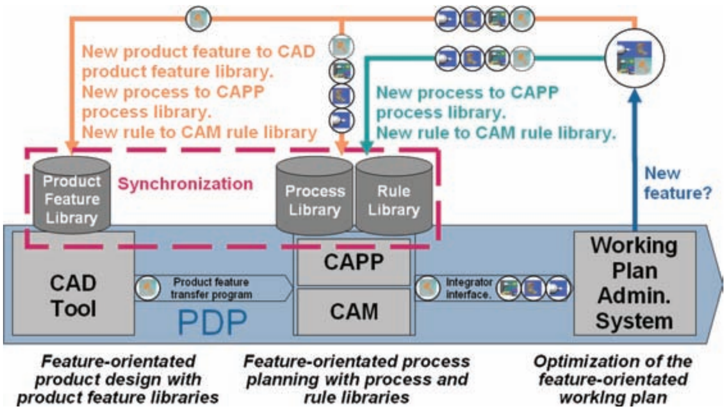

Figure 8. KBE concept

It is most likely that the committee will have some heated arguments whether to appoint a product feature to standard and a process to best practice, respectively, or not. On behalf of design for manufacturing the final say should have the production side. Recurring to the improvement of the PDP, the second objective – facilitating the reuse of existing manufacturing knowledge in the sense of KBE – is achieved.

5 IMPLEMENTATION OF THE KBE CONCEPT

Implementation can be described as "bringing a new concept into a given context" [10] or also as "mutual adaptation of concept and context". There are three kinds of implementation [10]:

- Personal implementation: The acceptance of change by the affected people
- Organizational implementation: The adaptation of new self-organizing principles to given formal structuring principles
- Technical implementation: The warranty of compatibility of new software with the existing system environment

From experience, the personal implementation is the very crucial one for a KBE concept to work, thus addressed in the following. So how can "acceptance" be described?
The acceptance of a change is explained largely by four factors [10]:

- Awareness
- Competence } Ability to change
- Willingness
- Directiveness } Readiness to change

Loosely correlating to these factors there are five types of instruments of personal implementation [10]:

- Instruments of communication
- Instruments of qualification
- Instruments of motivation } Interventional instruments
- Instruments of organization
- Diagnostic Instruments

Interventional instruments are used to affect the concept and the context. More precisely, they provoke the favoured change in awareness, competence, willingness and directiveness in a direct or an indirect way. On the other hand, diagnostic instruments are used to assess the need for action, that is to say how much of awareness, competence, willingness and directiveness is missing and where, so that the subsequent intervention hits the spot.
To complete this overview, the two extreme scenarios must be mentioned: context and concept substitution. To avoid such radical cures, the so-called context and concept flexibilization regards

some adaptability on both sides from the outset. It is recommended to sensitize the affected people to the need for change, whereas the concept itself should include some extra savings clauses and degrees of freedom to be prepared for the expected resistances. In correspondence, Figure 9 describes personal implementation as the adjustment of the optimal and the acceptable concept.

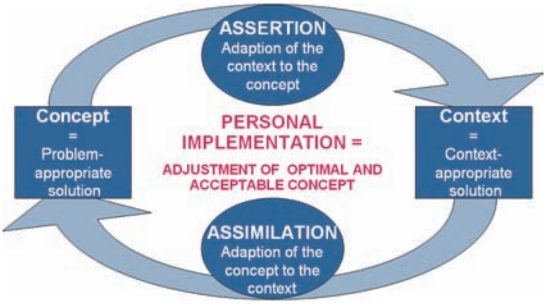

Figure 9. Personal implementation: adjustment of optimal and acceptable concept [10]

A common direction to implement change was described by Kurt Lewin:
1. Unfreeze
2. Change
3. Refreeze

Based on this approach Reiß, Rosenstiel and Lanz developed a more detailed change process model (including some guidelines for the change process management), but – the essential difference – from the affected people's point of view. There are seven stages for people undergoing a change (Figure 10):
1. Shock
2. Denial
3. Realization
4. Acceptance
5. Trial
6. Understanding
7. Integration

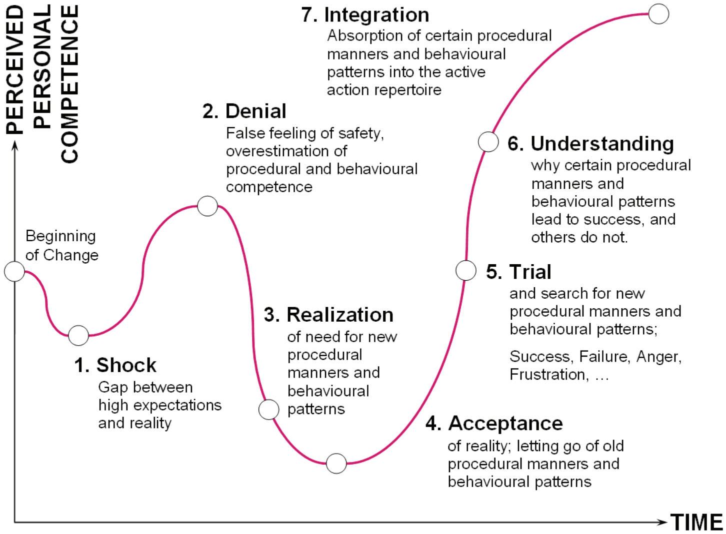

Figure 10. Change process from the affected people's point of view [10]

Applied to the implementation of a KBE concept, it is now possible to educe the following table using the seven stages of a change process as abscissa and the five types of instruments of personal implementation as ordinate (Figure 11). This framework facilitates the coordinated use of various instruments depending on the people's reaction to the change, all in accordance with the regular project management (milestones!). Obviously, the choice of instruments may differ from project to project.

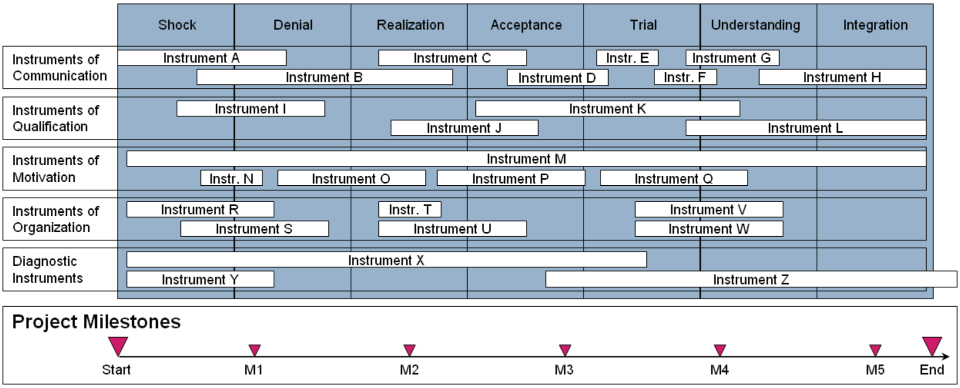

Figure 11. Change process management for personal implementation (schema)

Looking at the personal implementation of the KBE concept there were several challenges concerning personnel issues, indeed distinguishable (from each other) according to the four factors of acceptance:

In the beginning, communicating a new concept is relatively easy, because people have the tendency to remain indifferent as long as they are not both directly and immediately affected. The harder task is to enlist them in active collaboration. For this reason it is necessary to clarify their individual responsibilities and to sensitize them to their process partner's needs. Best if they can take advantage of the new concept, because the argument of the optimization of the overall process is not very convincing, particularly not when some change in methods results in extra work for the single employee.

The matter of competence normally is dealt with considerable training, coaching and supporting efforts in varying intensity depending on the ongoing (product development) project phase. Trainers and coaches from within the company, who are familiar with internal workflows, strengths and weaknesses might benefit from their authenticity, whereas external personnel may have advantages in terms of authority.
Additionally it is advisable to appoint some "early adopters" as key users, so that they can act as direct contact persons for those who lag behind.

The golden rule of willingness is to motivate people through participation [10]. Those who were engaged in the development of a concept normally do not meet the implementation "of their own work" with refusal, but there are always others who will get the impression of "not being asked" and who might react with disaffirmation. Up to a certain limit people can be ordered to apply a new concept, but this is only reasonable for a start. Shortly after that it can be seen clearly whether a person really is willing to adopt a change or not. In accordance, the employees should be handled individually. At this point it is essential to stay the course, constantly encouraging cooperation. Of course, motivation can be positive (e.g. gratification, reward) and negative (e.g. punishment, isolation) and sometimes it takes a mixture of both not to jeopardize the whole implementation. But again, neither the context nor the concept substitution is a satisfactory result.

Being aware to run, able to run and willing to run, but not knowing when and whereto run, leads to frustration. This is where the organization is challenged.

After a positive[3] decision has been made to implement the new concept, all managers have to be brought into line. People can be remarkably short-sighted, when it comes to questions of responsibility (e.g. "My (department's) work used to be fine – why changing it?") and resources (e.g. personnel, time, money for training and coaching, but also for further methodical and systemical improvements), especially if they do not profit (fast) (enough) from the new concept themselves. Here again it is necessary to explain the reasons for the implementation, to point out the overall advantages of the concept and to clarify the process partners´ needs. If this is not convincing after all, "individual deals" among the persons in charge might help. However, such differences should be settled when actually starting the implementation so as not to affect it adversely, because backing from the managers will be needed for sustainability.

For the OEM, the implementation of the KBE concept is still ongoing. There are discussions of the kinds headquarters vs. factories, factory vs. factory, PDP vs. sub process improvement, product design vs. process planning vs. production, manufacturing vs. assembling, machining process planning vs. test and measurement planning, drive line vs. chassis, person vs. person, etc. But the applicability of the concept itself is repeatedly confirmed.

6 SUMMARY, CONCLUSIONS, FUTURE PROSPECTS

The aim of improving the PDP led us to two objectives: Closing the automation gap between the product design and the production phase and facilitating the reuse of existing manufacturing knowledge. The first one was achieved by developing a product designing method using FT and by defining a process planning method based on product features. The work on the second one resulted in a library-based KBE concept and an implementation framework for the latter.
As far as known, the investigated OEM is the only company in the automotive industry to have 3D product features including all relevant PMI completely transferred from the product designing to the production process planning systems using different software providers for CAD and CAPP/CAM, respectively. Furthermore, the OEM is the first one with a direct link-up of the process description from the planning phase to the working plan administrative system of the actual production. (3D-) data can flow coherently and consistently along the PDP – and backwards: By documenting product and process information with "intermediate state feature granularity", the OEM obtains comprehensive transparency and broad comparability. The analysis of this information is followed by the definition of standardized product features and best practice machining processes that can be stored in three different libraries respecting the role allocation of the designers and the planners. For the next PDP, design for manufacturing is enabled.
As a matter of principle, such a KBE concept is only reasonable for recurring, easily parameterizable product features and relatively "steady" machining processes. Other downsides are the rather short list (only bores) of supported product features and the primary specialization in concrete software tools with hardly any "standard" interfaces (C-program for product feature transfer). Accordingly, future research and developments should address the following issues:
CAD:

- Augmentation of product feature types (e.g. notches)
- Enhancement of product feature library (e.g. search mechanism)
- Expansion towards the OEM's second CAD system Catia V5 (including synchronization with Pro/Engineer)
- Product feature transfer with a more "standard" converter instead of the C-program (for both Pro/Engineer and Catia V5) (e.g. within a JT converter)

CAPP/CAM:

- Enhancement of process feature library and rule library
- Automated synchronization process for all libraries
- Refinement of approval process for new product features and according machining processes

[3] A positive decision does not imply that everyone wants the implementation. Nevertheless, they have to abide by the decision.

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