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**Streamlining new product development (NPD) in aerospace through
knowledge based engineering (KBE)**

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Abstract. This paper analyses the potential of knowledge based engineering (KBE) methods and tools to streamline new product development (NPD) processes. In particular, design activities are investigated as a crucial context for technology implementation and process optimization in the aerospace industry. Based on a four-year collaboration with a leading company, the article shows the development of new processes and software tools which reduced sensibly the time and cost for designing key parts of aircraft engines, with indirect benefits on product quality. The paper can be a proof-of-concept for similar implementations in complex engineering sectors as the study combines discussion of technical aspects of modelling with strategic issues related to design and NPD performance. The process-based analysis and estimate of benefits achieved can help operation managers to better understand the uses and business value of KBE methods in process innovation and product development initiatives which address cross-functional and cross-organizational issues.

Keywords: aerospace; knowledge based engineering; new product development; process improvement; product design; six sigma; technology implementation.

1 Introduction

The rapidly evolving technologies, along with global economic trends and the information revolution pose new operational challenges to companies. Complex and extended supply chains are particularly impacted by the turbulence of markets and the growing expectations of customers. In such scenario, the performance of product design and development becomes a critical success factor and firms increasingly use tools (such as computer-aided design and simulation) to enhance product development time, quality, and design productivity as well as to reduce product and manufacturing costs (Leng and Vonderembse, 2006). Technology development and the pressures to reduce cost and time of design trigger indeed the

development of new approaches aimed to a more efficient product development (Danjou and Koehler, 2007).

During the early phases of new product development (NPD), and particularly for complex systems like automobiles and aircrafts, highly detailed information about the physical configuration of the product must be saved and updated as the design evolves. Besides, multiple representations of design are generated to take into account the varying needs of engineering specialists involved (Kugathasan and McMahon, 2001). In this perspective, the increased capability of computer technology can positively affect the management of engineering knowledge involved in design, analysis, and prototyping.

Among the methods introduced in the last years, knowledge based engineering (KBE) is a particularly interesting field to investigate. KBE systems are a special type of knowledge-based systems for efficiently capturing company's engineering knowledge and integrating the whole design process into a single computer model. Through KBE techniques, it is possible to organize data flows and architectures to effectively implement automated variant design solutions.

The aerospace industry is a particularly complex and technologically evolved setting where the adoption of KBE methods can be of great relevance. Several KBE implementations have been indeed realized with success in important organizations such as Boeing, British Aerospace, Textron Aerostructures, and also the US Airforce. Aerospace is a concentrated sector (with a very small number of system integrators), characterized by high performance and reliability requirements, huge development costs (e.g. Airbus's A380 exceeded \$10 billion), a very long product life cycle (Delfmann, Baum, Auerbach, and Albers, 2005) and a high level of customization. The product development process involves a large number of firms distributed across the world, designing products with millions of parts that must fit together with the closest of tolerances.

Design optimization and sharing of engineering knowledge are thus two issues at the top of the strategic and operational agenda in the aerospace. In such frame, this paper presents the development and application of KBE methods and tools aimed to streamline the design of aircraft engine's parts at a leading aerospace company. The design of engine components is showed as a highly knowledge-intensive and articulated process which can benefit from developments in terms of knowledge reuse and engineering automation. A process-based approach is used to estimate benefits associated with two separate KBE implementations made at the research site.

The article is organized as follows: section 2 discusses the main background; sections 3 introduces the company investigated and the research focus; sections 4 and 5 illustrate in details the two KBE applications realized and the benefits achieved; section 6 draws some conclusions and directions for future research.

2 Background

Tools such as computer aided design (CAD), computer aided engineering (CAE), and computer aided manufacturing (CAM) are increasingly important to improving the performance of NPD. A relevant challenge is the integration of such different systems as many modern engineering topics like concurrent engineering, rapid prototyping and virtual engineering put a great emphasis on the integration of CAD, CAM and CAE-related disciplines. Many organizations experience indeed difficulties in the handoff between the engineers that do design work with CAD tools and those responsible for undertaking CAE analysis (Deng, Britton, Lam, Tor and Ma, 2002).

The problem of knowledge creation, sharing and reuse is a particularly relevant issue in NPD processes which address both intra and inter-organizational perspectives. A study involving highly innovative aerospace composite products has showed the significant benefits

from knowledge sharing and embedding from effective cross-functionality in the NPD process (McAdam, O'Hare and Moffett, 2008).

Advances in information technology (IT) have facilitated integration of information flows and increased collaboration within companies and across supply chains. However, IT also removes “protective” barriers around assets and processes. Highly interconnected supply chains are thus more exposed to the risks of a strategic “disclosure”. At this proposal, it has been highlighted that the benefits of collaboration facilitated by IT integration must exceed the increase in risk due to IT security threats (Smith, Watson, Baker and Pokorski, 2007).

Concerning the integration of product design with other disciplines, the challenges associated with the CAD-CAM interface are well discussed in literature (Lee, 1999; Wheelwright and Clark, 1992) and the effective integration of CAD and CAE is highlighted as a way to streamline and accelerate product development (McMahon and Browne, 1999). Knowledge Based Engineering (KBE) can facilitate such integration through a set of software-based techniques that enable the capture and storage of engineering knowledge and its re-use in the form of automated or semi-automated applications. An experience-based method for the selection of suitable KBE design applications (Blount, Kneebone and Kingston, 1995) and a best practice guide of KBE implementations have been presented in literature (Cooper, Fan and Li, 1998).

In NPD settings, KBE can capture and store knowledge used by engineers during the design and evaluation phases of the development process, and generate software tools with the purpose to re-use that knowledge and standardize/automate routine tasks (Chapman and Pinfold, 1998; Kulon, Broomhead and Mynors, 2006). KBE can be thus particularly relevant in organizations whose products have a high degree of similarity and require a large number of design configurations, or where a large number of design processes are involved.

Unlike traditional CAD systems, which mostly contain geometric information for a single design, KBE aims to model the whole process of generating the design. In this sense, KBE combines engineering knowledge, methodologies, rules and best practices with process knowledge and practices, with the purpose to create comprehensive product models that describe how product designs are created or engineering analyses are undertaken. Once knowledge about the product is collected and stored, designers can generate and evaluate new designs quickly and easily by changing the model's specifications or modifying current parameters. This frees the engineers from repetitive and time-consuming tasks and calculations, resulting in more time available for value adding design activities.

The application of knowledge-based systems in an industrial environment has been studied to propose object-based knowledge integration supporting the early stages of product development (Lee, Lau and Yu, 2005). In particular, KBE applications have been realized in different industrial and organizational contexts. A feature-based CAD-CAE integration model has been proposed in the design of injection-moulded parts (Deng, Britton, Lam, Tor and Ma, 2002). Prior studies have focused on successful KBE applications in the automotive industry (Chapman and Pinfold, 2001), in the integration of the hot forging design process (Kulon, Mynors and Broomhead, 2006), in the wheel and brake industry (Liening and Blount, 1998), and for estimation of weight and cost of a composite structure at the conceptual stage of design (Choi, 2009; Choi, Kelly and Raju, 2007). A previous work in the aerospace has been focused on the application of KBE to optimize the design of low pressure turbines (Corallo, Laubacher, Margherita and Turrisi, 2009).

3 Research site and focus

This paper is based on a four-year collaborative research with an Italian aerospace company, Avio s.p.a., a leader in the design, production, and maintenance of aerospace propulsion

subsystems and components. The company participates in military programs such as Eurofighter Typhoon and F-35 Joint Strike Fighter, and civil partnerships with companies like General Electric, Pratt & Whitney, Rolls Royce, and Volvo.

The research is based on a detailed case study of technology implementation (Orlikowski and Baroudi, 1991; Yin, 1994). The approach used to assess the benefits associated with the introduction of the new design process and tool is the Activity Based Performance Measurement (ABPM), a methodology based on mapping activities before and after introduction of the new technology, and thus measuring benefits by comparing key activities before and after the implementation (Laubacher, Kothari, Malone and Subirana, 2006).

Two of the co-authors participated as members of the team that developed the KBE applications described in the following sections. A direct participant observation allowed thus to collect and analyse the most of data which are synthesized in this article. Besides, several interviews have been made with persons in different departments at Avio, such as “Product Engineering” and “Research and Development”. The roles of the interview subjects included Design Engineer, CAE Department Manager, CAE Coordinator, Structural CAE Analyst, Thermal CAE Analyst, and Aerodynamic CAE Analyst. After the initial findings were developed, managers and engineers at Avio were then consulted for validation.

The main goal underlying the research was to reduce the time, and thus the costs, for designing specific parts of aircraft engines. Product design is a very strategic process for Avio and the company is strongly engaged in adopting improvement methods. Among these, Six Sigma is used to minimize variability in design and manufacturing activities. In particular, *Define-Measure-Analyze-Improve-Control* (DMAIC) methods are normally adopted for projects aimed at improving existing business processes (Tennant, 2001). The Six Sigma approach of the company, and thus the analysis and improvement effort at the basis of the

work done, leverages a statistical process control which is one of ten “dimensions” of a lean production system, as studied in literature (Shah and Ward, 2006).

In particular, the focus of improvement has been placed on two critical components of an aircraft engine, which also represent two core capabilities and areas of specialization of Avio: a) the low pressure turbine; and b) the gearbox. Figure 1 shows an illustrative view of the last generation engine of General Electric, the *GENxTM*, with the indication of the two subsystems.

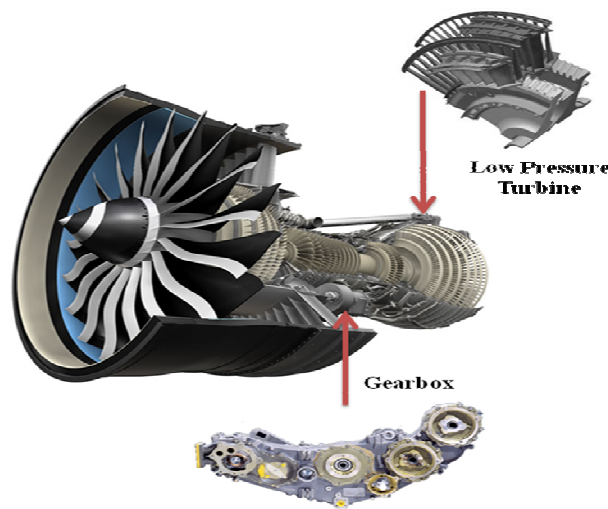


Figure 1 General Electric *GENxTM* (source: Internet) and areas of specialization of Avio

Next section analyses in details how KBE has been used to optimize the performance of product design, with specific reference to the components mentioned. The tools described here, i.e. the *CTX Vane Creator* and the *Gear Generator*, are two of eight KBE applications developed to enhance NPD activities at Avio. Combined, these applications required about 30 months (600 workdays) of software development time. There were very limited costs associated with software distribution or hardware/software upgrades. The tools could indeed be installed on the company IT infrastructure and accessed from the server by design engineers.

4 KBE application#1: Low pressure turbine and the CTX Vane Creator

The first application was realized within the design and production of the low pressure turbine (LPT), a major subsystem placed at the rear of turbofan engines. In particular, it was developed a new process model and a tool, the “CTX Vane Creator”, with the purpose to streamline the CAD-CAE handoff during the design of the vane, a part that directs the air flow air around the LPT.

The development of a turbine begins with the design engineers receiving a set of requirements. The first task is the definition of a *cross section*, which is a bi-dimensional representation of the whole turbine and is the starting geometry for defining the aerodynamic components of the turbine. The aerodynamic team defines a set of *corner points* within the *cross section* and, based on such points, the team models the *flow path*, i.e. the path followed by the gas inside the turbine, and the *airfoils*, which are profiles of static turbine blades.

After an initial design for the LPT vane’s airfoil is developed by engineers using CAD tools, it is passed on to CAE engineers who undertake an aeromechanical assessment. This involves testing the structural, aerodynamic, and thermodynamic properties of the system. If the output of this assessment is not satisfactory, the design is sent back to design engineers, who revise the model and resubmit it to the CAE group for another round of testing. This process is repeated until an acceptable configuration is obtained. At this point, the design engineer “freezes” the airfoil model and moves on to detailed design work.

In the CAD system, a continually updated version of the design of turbine’s components, known as the *master model*, is saved to allow engineers and discipline specialists to share geometric information according to the level of detail they need. A great quantity of data, including geometric definitions and information about manufacturing, is thus saved throughout the development process. The *master model* serves as the basis for simpler models, known as *context models*, which contain only the information needed to undertake

specific engineering analyses. *Context models* are thus used by CAE analysts who need information concerning only the shape of components and any additional information provided could be counterproductive.

Before the KBE implementation, CAD engineers had to undertake a number of tasks to prepare a *context model* to be passed on for testing by CAE engineers: 1) simplification of geometry to eliminate objects in the *master model* that are not relevant for CAE analysis; 2) splitting of vane surfaces in smaller parts (a complex operation to be repeated for each airfoil in the vane); 3) subdivision of the vane into several distinct solids; 4) alignment of the lowest part of the vane with the base; 5) conversion into a neutral file format, called Parasolid, that can be handled by CAE software.

The KBE process and tool introduced, the CTX Vane Creator, provides a user-friendly wizard to reduce the number and complexity of tasks mentioned, thus reducing the time needed and the possibility of mistakes. In addition, the implementation of the tool allowed to effectively formalize and standardize a set of activities that were previously undertaken in a variety of ways. When using the CTX Vane Creator, the CAD designer need only to select entities in the model and insert a small number of inputs through a Graphical User Interface (see figure 2). All of the tedious geometric operations, which previously had to be done by the CAD designer, are now done automatically by the tool.

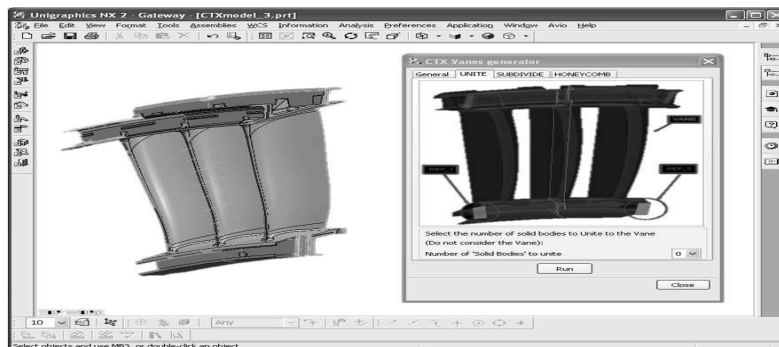


Figure 2 GUI of the CTX Vane Creator

The comparison between the pre and post-implementation scenarios allowed to assess the benefits of the CTX Vane Creator. Based on interviews with managers and engineers at Avio, the research team identified a set of indicators of process optimization. Three metrics were defined to measure the reduction in process complexity: a) number of activities; 2) number of activities, join and split; 3) control flow complexity (measuring the number of decisions in the control flow). The team also considered two metrics for time reduction: 1) overall design time (time required for the creation of one single *context model*; and 2) annual time (time required in a year for preparing the *context models* for all the LPT's vanes). Table 1 shows the values of complexity and time metrics before and after the KBE implementation, along with the percentage change. The annual time is calculated considering an average number of 13 vanes per year and, for each vane, an average of 10 "iterations" CAD/CAE (thus resulting in 130 different *context models* per year).

Table 1 Complexity and time metrics before vs. after the introduction of KBE

Type of metric	Metric	Before KBE	After KBE	Change
Complexity metrics	N. of activities	12	1	-92%
	N. of activities, join, split	17	1	-94%
	Control flow complexity	8	6	-25%
Time metrics	Overall design time (minutes)	30	2	-93%
	Annual time (days)	8,1	0,5	-93%

The KBE-enabled automation reduced thus the time required to prepare *context models* by 93 percent. The development, test and training for the CTX Vane Creator required about 21 workdays and this means that the tool generated a direct annual return on investment of about 36 percent (7,6 days of CAD engineer time saved yearly versus an "investment" of 21 days of software engineer time). Since the tool reduced the time for routine tasks, engineers had more time for critical design activities such as structural and aeromechanical analyses under

different boundary conditions (i.e. different values of pressures, temperatures, etc.) and the exploration of new product features and/or configurations.

5 KBE application#2: Gearshaft and the Gear Generator

In the aircraft engine, another key component is the gearbox, a complex system typically made by four parts: 1) the housing, i.e. a non-rotating component which is the central part aimed to fix all other components; 2) the gearshaft, i.e. the round and toothed device enabling the conversion of engine speed into torque; 3) the bearings, i.e. the devices allowing constrained relative motion between two or more parts; and 4) the set of nozzles, nuts, bolts and seals.

Depending on their role, gearshafts can be accessory or power gearshafts while gears can have different shapes classified as helical, spur and spiral bevel. Before the KBE implementation, the gear design process in Avio involved the use of several software tools, and in particular NX (a commercial CAD/CAM/CAE software suite) and Patran (an environment for finite elements analysis). The information exchange between these two platforms was allowed by files exchange in Parasolid format.

The process executed for modelling a gearshaft varies according to the type of gear. In particular, the procedure for designing a spiral bevel gear takes in input several data (e.g. number of teeth and longitudinal section of the gearshaft) defined in a preliminary design phase. These inputs are then computed to obtain detailed geometric data used as input for the successive design steps. These are: 1) creation of the gear model in Parasolid format using Patran; 2) import of the Parasolid model into the NX CAD environment (with a twofold output represented by the gear and its envelope); and 3) gearshaft modelling, made in the NX CAD environment based on the inputs of the initial design phase.

Such procedure presented different problems: a) the generation of the model within Patran is complex and the geometry obtained is not precise; b) an external tool (i.e. Patran) is required; b) the operation of “blending” gear and shaft may fail; c) the overall modelling technique is not properly standardised; d) the estimation of gearshaft’s volume is not accurate; e) there’s a lack of fit of geometries generated; f) it’s difficult to use control structures. A major shortcoming of such problems was the relatively long time needed for obtaining robust models ready for manufacturing.

Four critical variables were identified as key indicators to monitor and improve: 1) modelling time for the shaft; 2) modelling time for the gear; 3) total modelling time; and 4) percentage of gear time over total time. In particular, the average value measured for 2) was about 4 hours for a helical gear, 3,5 hours for a spur and 6 hours for a spiral bevel. The high impact of the time for modelling the gear on total modelling time was demonstrated by the value of 4), comprised between 80% and 85% (according to the type of gear).

Four main reasons were identified for this poor performance in the pre-KBE scenario: 1) method, i.e. the lack of a standardized procedure applied to execute the process; 2) software, i.e. time lost due to the use of different tools which are not integrated; 3) skills, i.e. operator’s experience and knowledge of the product; 4) environment, i.e. process interruption due to external factors (a residual factor with an estimated impact of about 5%).

The effort was thus aimed to define a new process/method and operationalize such method in a software tool for the automatic modelling of gears within the CAD environment. Providing the design operator with an intuitive design tool endowed with a user-friendly interface and a comprehensive user manual could indeed solve the skills’ gap issue. The process defined is showed in figure 3.

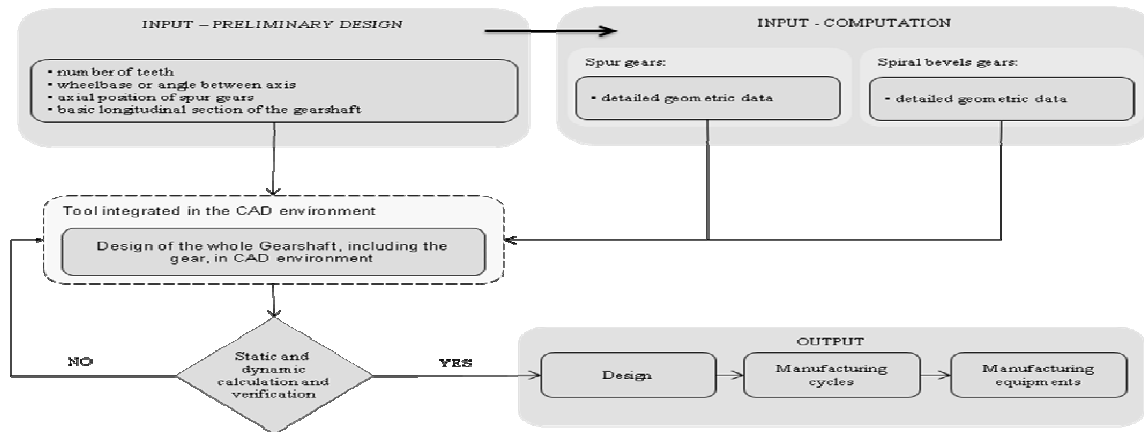


Figure 3 New process for obtaining a gearshaft model

The new process is characterized by the complete design of the gearshaft, including the gear, in a unique CAD environment. It is no more needed to model the gear in Patran and then to import it in the NX environment. For all the types of gear, the design within the NX environment is completely automated and the shaft design step is standardized. The new process has been enabled by a purposeful software tool, called *Gear Generator*, developed by means of both the Matlab and the CAD environment APIs' and which has been fully integrated into the CAD platform. The *Gear Generator* is divided in two interfaced "macro-modules": 1) NX module, responsible for user input collection, gear compartment generation (cutting surface) and generation/management of associated gear objects; and 2) Matlab module, embedded into a *dll* ("dynamic-link library"), which processes the input passed by the NX module in order to generate a set of points representing the cutting surface.

The NX macro-module includes four parts: 1) Graphical User Interface (GUI); 2) Input Validation; 3) Geometry Creation; and 4) Gear Objects Management. The GUI is the main module through which the user interacts with the application. It collects user's inputs and moves them to Input Validation, which checks the correctness of data and sends them to the Matlab macro-module. Geometry Creation takes the set of points ("point cloud") generated by

the Matlab and creates the cutting surface calculating the curves passing through these points and then the surface passing through the curves. Gear Objects Management is responsible for the creation and management of *gear objects*, i.e. NX user-defined objects (UDO) that can be linked or associated with NX objects. The GUI allows the user to create a new gear from the scratch or by inheriting all the parameters from an already existing model (“Inherit from selected” function, as showed in figure 4). The GUI provides different tabs for the three kinds of gear and requires diverse input parameters to be set. As showed in figure 4, the user is required to insert key geometric data such as number of teeth, face width, absolute position and orientation related to the schema model of the shaft, and mesh accuracy.

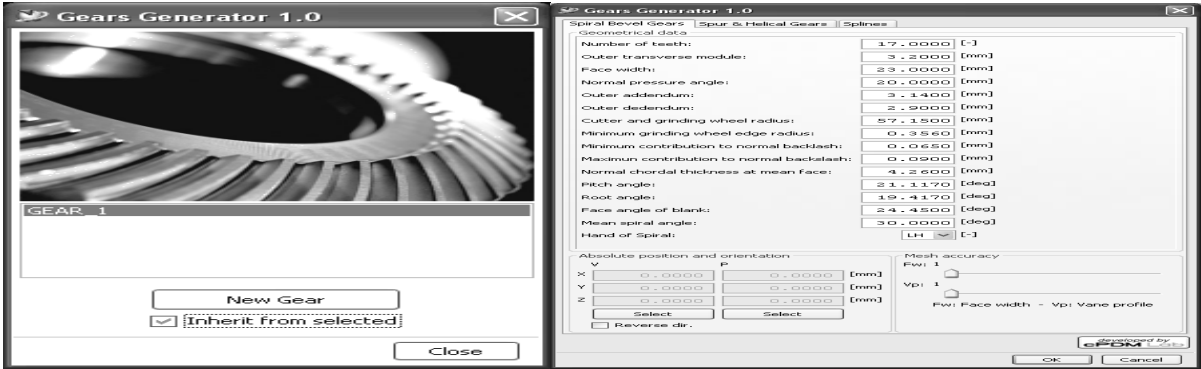


Figure 4 Tab of Gear Generator for creating a spiral bevel gear

Using the new procedure and tool, a gear is modelled directly on the shaft by simulating the manufacturing procedure and cutting geometry followed by a hobbing machine. Furthermore, the tool uses a (more) precise mathematical approximation. The modelling time for the gearshaft, modelling time for the gear, total modelling time, and percentage of gear time over total time have been measured for the new process and compared with the pre-KBE scenario. In particular, the time for modelling the gear has been reduced to about 0,05 hours (3 minutes), resulting in a ratio of gear time on total time now comprised between 2 and 3%.

The benefits achieved can be discussed at three levels: 1) reduced modelling time; 2) decreased modelling costs; 3) increased design robustness and product quality. The *Gear Generator* introduced a semi-automatic procedure which allows a faster modelling. Working hours were reduced both in the modelling of new gears and for gears already designed (when the CAD model is not available). As detailed in table 2, the time for modelling has been reduced on average by 60% for helical gears, 61% for spur gears and 71% for spiral bevel gears. This has had relevant effects on the production economics of Avio. Considering the last two years, Avio has modelled (and produced) an average of 53 gears per year, divided as follows: 38 spur gears, 10 spiral bevel gears and 5 helical gears. Assuming an average hourly (gross) cost of a senior engineer of 43 Euros, the KBE implementation determines cost savings of about 7.000 Euros per year.

Table 2 Economic benefits enabled by the Gear Generator

Gear type	Average hours per unit - old process (a)	Average hours per unit - new process (b)	Average benefit per unit (c=a-b)	% Reduction	Manpower savings per unit (d= 43*c)	Number of gears per year (e)	Savings per year (f=d*e)
Helical	5,00	2,02	2,98	-60%	€ 128,14	5	€ 640,70
Spur	4,00	1,55	2,45	-61%	€ 105,35	38	€ 4.003,30
Spiral bevel	7,00	2,05	4,95	-71%	€ 212,85	10	€ 2.128,50
							€ 6.772,50

Seven thousands Euros are not a huge saving *per se*, but if similar benefits can be obtained for the design of all the (many) parts of the engine, the overall result can be significant. Beside “hard” benefits, the KBE implementation has also allowed an increased design robustness and product quality. The procedure is now completely automated as it does not require modelling work but just data input. Moreover, the process is completely integrated within the CAD environment and a comprehensive support manual is provided to the user. As a consequence,

the only risk of mistakes is represented by a wrong execution of the procedure by the operator, resulting in a sensible increase of robust models at a first design stage.

6 Conclusions

The management of physical and/or technical functions related to development, production, and manufacturing are relevant areas to be addressed in the perspective of operations management (U.S. Department of Education). This involves the responsibility of ensuring that business operations are efficient and effective, and increasing the content of value-added activities in any process of the company.

In such endeavour, KBE methods and tools can have a significant role as they enable optimization of product development along multiple dimensions. The use of KBE allows to integrate the design process into a single framework and to guide the designer throughout the design. The ultimate goal is to reduce development cycle time and costs and achieve other advantages such as simultaneous modifications and consistent maintenance of design and analysis models. KBE enables the capture and storage of tacit knowledge inside the organization and its effective re-use by means of integrated applications. Knowledge based designs provide all information regarding the shape, function and manufacturing of the product for all the phases of the product life cycle.

Time savings allowed by technology-enabled improvements in NPD activities can be used by the company management in different ways. Besides reducing overall NPD costs by using fewer engineering hours for design, time savings can be “reinvested” to design products with more features or enhanced quality. In most settings, the second choice is more common. In a case study in the NPD group of a global electronics firm (Laubacher and Papandrea, 2007), the benefits associated with the introduction of advanced simulation tools were increased by one-third through the investment of the resulting time savings in added product features.

This paper has presented the application of KBE methods to reduce time and costs in the design of aircraft engine's parts. The design processes have been improved with the introduction of more standardized procedures and integrated software which also allowed to enhance the skills of the operator and his/her knowledge of the product. In the design of the low pressure turbine, the time for modelling the vane has been reduced by more than 90% whereas a reduction of more than 60%, with a yearly saving of about seven thousands Euros, was obtained in the design of the gearbox.

Because of the long cycle times in the aerospace, it was not possible to estimate the financial benefits associated with enhanced product quality at Avio. However, since many civil engines are sold to airlines on a "power-by-the-hour" basis, where manufacturers retain ownership of the aircraft's power plant and rent functionality to customers, improvements in engine quality can lead to reductions in maintenance costs. Since maintenance is one of the largest costs for manufacturers, any reduction in those costs goes directly to the engine maker's bottom line.

A possible limitation of the study stays in the fact that the applications showed are strictly dependent from the CAD and CAE systems used. Next research will be thus addressed to render the method independent from the technology platform used for design and engineering analysis. Besides, future research will use this case as a proof-of-concept to extend the application of KBE tools to other organizational contexts and other companies as well. Insights from this case study can be indeed re-used to estimate the business value generated by KBE applications in other NPD settings.

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