AUTOMATING THE DEVELOPMENT PROCESS OF THERMOPLASTIC COMPOSITE SHEET RIBS USING KNOWLEDGE BASED ENGINEERING TECHNIQUES

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Abstract

Knowledge Based Engineering (KBE) tools can be used to increase the efficiency of the engineering process. In this paper it is shown how KBE tools can reduce the design lead-time of thermoplastic composite sheet ribs and the moulds needed to produce them. Design lead-time reductions of 60% to 90% have been achieved.

Introduction

In recent years composite materials have gained a strong foothold in the commercial aircraft structures market. Composite materials are being used because they are structurally efficient and because efficient manufacturing techniques can be used. These efficient manufacturing techniques can result in a reduction in recurring manufacturing time. An example of such an efficient manufacturing technique is the press forming of thermoplastic composite materials. This manufacturing technique can be used to create ribs for aircraft wings or movable control surfaces.
With the ability to manufacture these thermoplastic ribs efficiently the multi-rib concept for wing-like aircraft structures becomes attractive, because it mainly consist of ribs with few additional structural elements. This structural concept is especially attractive for lightly loaded structures, such as movables like elevators and rudders. In a multi-rib structure the rib's main functions are transferring the aerodynamic loads to the spars and preventing the skin from buckling. To perform these functions a large number of ribs is needed. These ribs are all geometrically unique when the movable is tapered. For each rib, therefore, the whole "development cycle" has to be run.
This development cycle consists of designing the rib, proving that it meets all the requirements by conducting several analyses and of preparing the production of the rib. Because the different ribs have the same characteristics this development process is ideally suited for automation. This automation will result in a significant reduction in design lead-time. For automation of the development process, tools will have to be developed. One methodology for developing such tools is the Knowledge Based Engineering (KBE) methodology. With this methodology knowledge is captured from the experts in the development process and this knowledge is used to create automation tools.

In this paper the development of KBE tools that speed up the development process of thermoplastic ribs will be discussed. The use of the resulting tools will be analyzed in an industrial environment, where they will be used to develop the ribs of an elevator and rudder of a large new business jet. The problem statement for this paper therefore is:

"Development time of thermoplastic ribs can be reduced significantly by using Knowledge Based Engineering tools throughout the development process."

Thermoplastic rib description

The thermoplastic composites sheet ribs discussed in this paper are press formed using thermoplastic fabric sheet material. The ribs described in this paper are build up from multiple layers of carbon fibre fabric in a Polyphenylene Sulfide (PPS) matrix. The main functions of a rib are: transfer of the aerodynamic loads to the spars, ensuring that the movable in which it is used retains its shape and ensuring that the skin it supports does not buckle. The rib is connected to the front and rear spar of the movable and to both upper and lower skins. For this connection flanges are integrated in the rib. An example of a thermoplastic rib can be seen in Figure 1

Figure 1 A carbon/PPS rib for an a movable

The thermoplastic rib is formed by pressing a blank between two moulds and trimming the resulting shape. In the case described in this paper, both moulds used in the pressing process are steel moulds. Other similarly shaped ribs can also be formed using a steel mould on one side and a rubber mould on the other [1]. Using only steel moulds limits the curvature of the flanges that can be formed. However it improves the surface finish of the ribs and enables the production of ribs with tighter shape tolerances. Examples of both a positive and a negative mould can be seen in Figure 2.

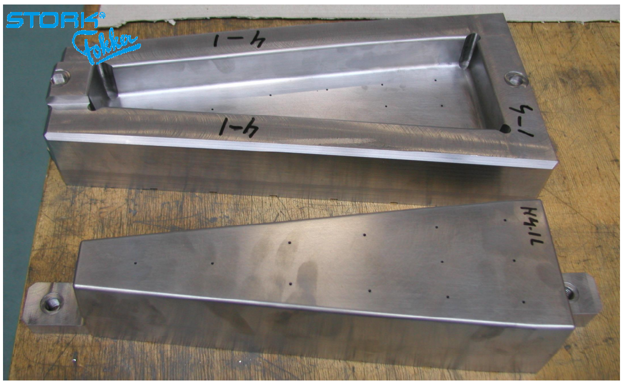

Figure 2 The mould set used to press a rib

Description of the MOKA methodology used for developing KBE tools

The development process of KBE tools described in this paper will follow the MOKA methodology[2]. This methodology describes the whole life cycle of a KBE tool as shown in Figure 3. The KBE lifecycle is highly iterative, which means that the steps are not always run in the sequence shown. For example "proof-of-concept" tools are sometimes Activated during the Capture phase to provide valuable feedback.

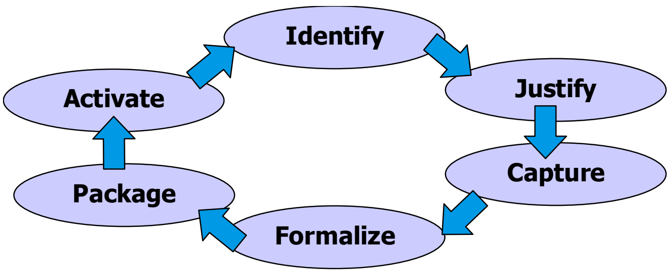

Figure 3 The MOKA cycle for the development of a KBE tool

Each step in the life cycle can be described as:

Identify: Using an existing business opportunity, the potential KBE applications and the resources needed to build them are identified.

Justify: For each potential KBE application, a go-ahead decision is made on the basis of expected benefits, development cost and available resources.

Capture: The knowledge needed for the KBE applications is gathered and

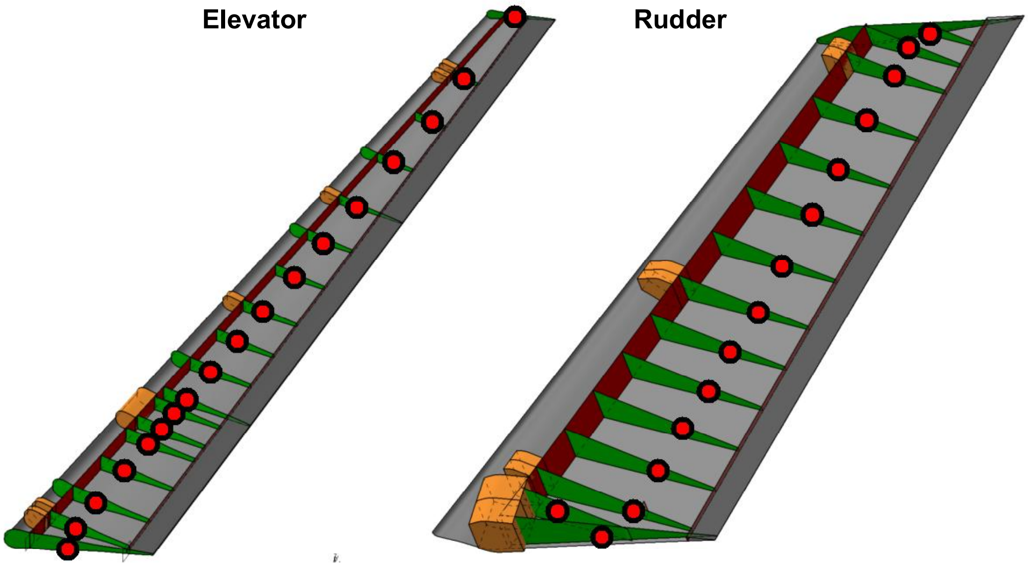

Figure 4 Elevator and rudder design concepts with the identification of carbon/PPS ribs used in these concepts

structured in order to get a solid knowledge base for the KBE application.

Formalize: The captured knowledge is rewritten in so-called formal format, which is easily understandable by the software engineers developing the KBE application.

Package: The software that makes up the actual KBE application is written based on the formal model created in the previous phase.

Activate: The software tools developed in the previous phase are put to work in daily practice.

In the sections below the contents of these steps will be described for the development of KBE tools for thermoplastic ribs.

Identifying the opportunities for developing KBE tools and justifying this development

At the start of any KBE project the elements that will be incorporated in the project need to be identified and the use of the resources required for such a project need to be justified. Before deciding to automate the design of the rib and its moulds such an identification effort was undertaken for a project in which the movables for a large business jet are developed. A KBE application can automate certain steps in the development process. However knowledge needs to be available about these steps. Developing a KBE application also costs a considerable amount of resources. For the KBE application to be come a success it has to be used frequently. Therefore the concept designs of the movables were evaluated for often occurring parts. As can be seen in Figure 4 the design concepts contain a lot of ribs because they are of the multi-rib structural concept. In total, 35 carbon/PPS ribs are encountered. Therefore, automating part of the development process of these ribs was identified as an opportunity for automation using the KBE methodology.

The development process of a carbon/PPS rib contains three major elements: designing the rib itself, structurally analyzing the rib to ensure it remains intact during operation and designing the moulds needed to manufacture the rib. These three elements of the development process were identified as candidates for automation. This paper will focus on the rib and mould design elements of the development process.

To justify the development of KBE applications the return on investment of these tools needs to be estimated. In this project the applications had to become profitable within the project of developing a rudder and elevator for a large business jet. To determine the return on investment the resources needed to develop the KBE application and the resources saved by such an application need to be estimated. Such an estimation can be based on previous development projects of both the ribs themselves and of other KBE tools. In Table 1 the normalized estimates used in the justification phase are shown. Assumptions for this justification were that there are 35 ribs and that the design lead-time reduction achieved by using KBE tools is 60%.

Table 1 Normalized KBE tool justification table with normalized values for the estimated hours

	Rib design	Mould design
Regular design 1 unit	1	1
Total time	35	35
Automated design 1 unit	0.4	0.4
Total time	14	14
KBE application development	6	3.5
Return on investment	1.75	2

As can be seen the expected return on investment for both rib and rib mould design is greater than 1 meaning that the development of KBE tools for these activities is justified. It also has to be stated that the development of a mould design tool is only feasible when there is a rib design tool. Therefore the conclusion at the end of the justification phase was that a KBE application for both the rib and tooling design should be developed.

Capturing the design knowledge and storing this knowledge

In the Capture phase the knowledge needed for developing the KBE tools is captured by, for instance, interviews with experts. To use this knowledge in a KBE tool it has to be formalized. This means representing the knowledge rules in a manner, which is understandable for the software engineer developing the KBE tool. The Capture and Formalize steps are highly iterative and also interact with the next step in the KBE life cycle the Package step. What this means in practice and how the Capturing and Formalization phases for both the rib and mould design tools were executed will be discussed in this section.

To capture the knowledge needed for a KBE tool one first has to determine if this knowledge is available. Part of this assessment has already been done in the Justification phase when an inventory is made of the knowledge sources available. In case of the rib design the knowledge sources available consisted of previous designs of similar ribs and of experts experienced in designing these ribs. In case of the rib moulds no previous experience was available. This meant that, in principle, the required knowledge for developing the mould design tool was not available at the start of the project. This implied that the knowledge had to be created during the development process of the Rib Mould Design KBE Tool. Therefore the development cycle of this tool was different to that of the Rib Design KBE Tool.

For the Rib Design KBE Tool previous rib designs were analyzed and design experts were consulted to determine the knowledge rules governing the design of a rib. This knowledge was stored in a knowledge base. Using specialized software in the form of PCPack [3] knowledge diagrams were created. In addition to these diagrams test designs were created. These test designs proved especially helpful to identify areas where there was a lack of knowledge and also to identify where the extracted knowledge rules contradicted each other. Using the test designs and the diagrams the knowledge sources, in this case usually experts, could be consulted to fill the identified knowledge voids. A diagram of the rib design process used for consulting the knowledge experts is shown on the left side of Figure 5.

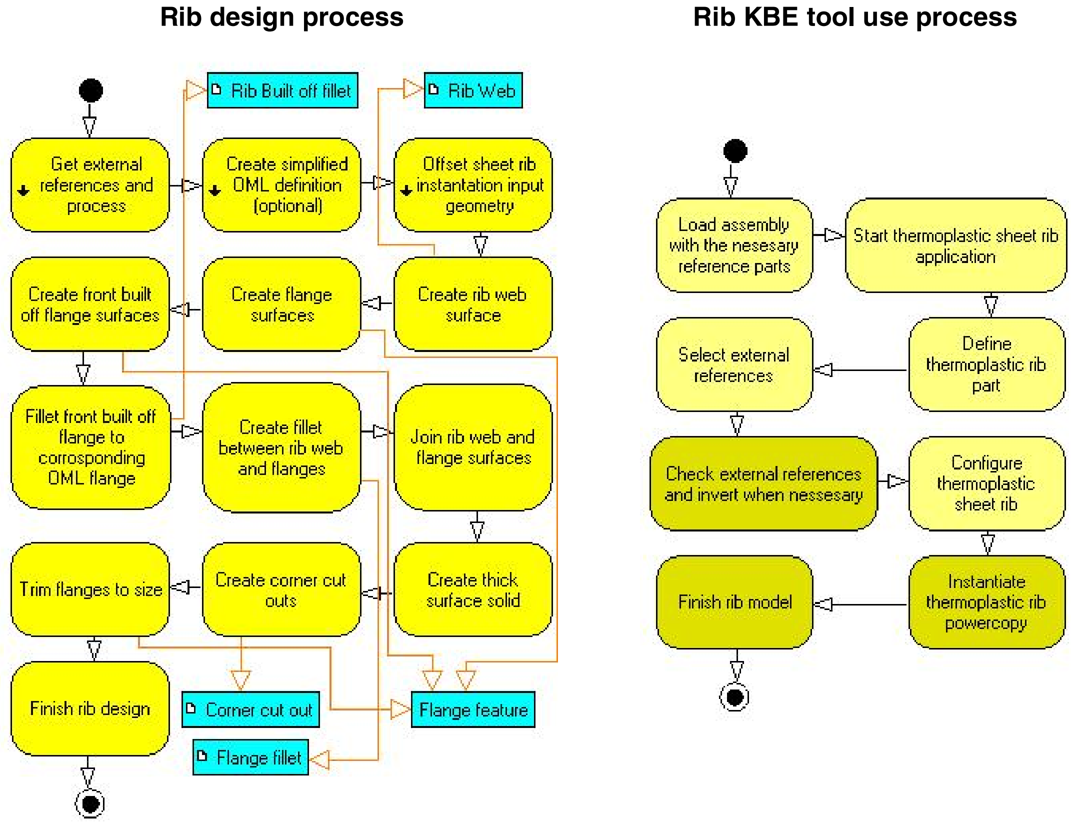

Figure 5 The rib design process captured from knowledge sources and the process using the rib design KBE tool to create a rib design

Since the knowledge engineer and the software developer creating the KBE tool were one and the same person a Formalization phase as described in MOKA was not conducted. Instead the Rib Design KBE tool was developed in conjunction with the Capture phase. In fact beta versions of the tool were used to create the test designs. A project where the Formalization phase is more explicitly conducted is discussed in [5]. Besides capturing the rib design knowledge in diagrams also the knowledge about how to use the KBE tool and the processes behind it were stored in diagrams. In this way the rib design knowledge was captured and the rules contained in resulting tool were stored. The diagrams and their annotations describing the different diagram elements in more detail form the rib and rib mould design knowledge base. The process of using the rib KBE tool to design a rib is shown on the right side of Figure 5.

For the Rib Mould Design KBE Tool another approach was used; in this case the development of the KBE tool followed the knowledge developed by the experts. This is a risky strategy; several times the development of the KBE tool was halted because knowledge to further develop the KBE application was not available. Furthermore because knowledge was being the developed, knowledge rules implemented in the KBE tools were not mature and therefore subject to change. To counter this the KBE tool was developed modularly as will be described in the next section. Furthermore an attempt was made to identify immature knowledge rules beforehand and to make these knowledge rules easily adjustable in the KBE tool. Being able to quickly implement knowledge rules and to produce test design with these rules proved vital for the development of the KBE tool and also for the development of the knowledge rules themselves, because the "real life" effects of these knowledge rules could be quickly assessed. Using the test designs the knowledge development process could also be directed.

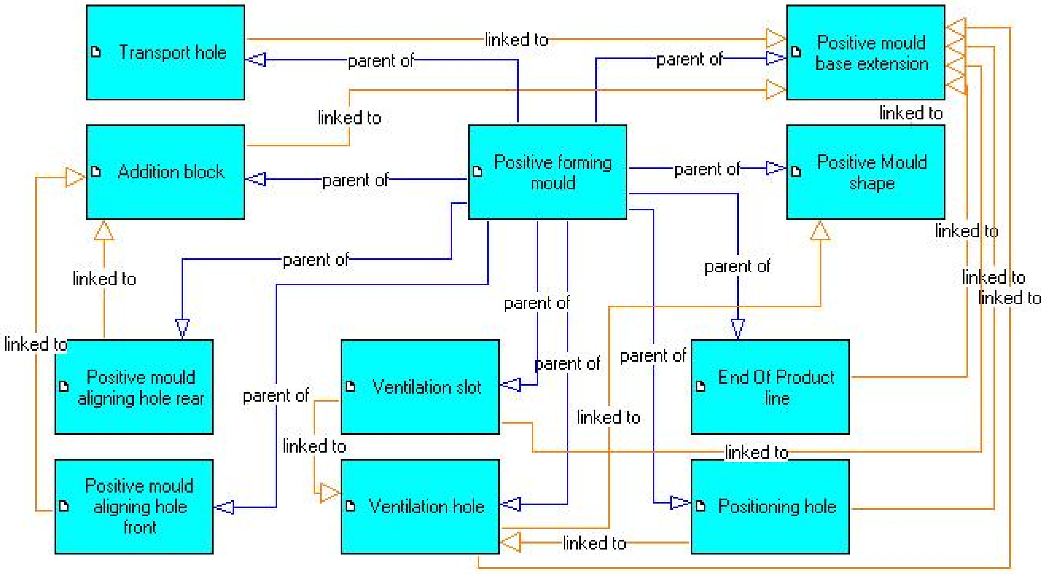

Figure 6 The positive rib mould structure mould showing the different elements of the mould and the relation between them

During the Rib Mould Design KBE Tool development process the moulds proved to be much more complex than anticipated and therefore the associated KBE tool is more complex than the Rib Design KBE Tool. Besides storing knowledge about the design processes used to design the moulds, it was therefore important to store the structure of the moulds themselves in diagrams. In such a diagram the elements of a mould and the relation between its elements is described. In the KBE tool development process each next step usually meant adding an element to this structure. The structure diagram of the positive forming mould can be seen in Figure 6.

Because the Rib Mould Design KBE Tool was developed over a larger period of time and was subject to knowledge about design steps becoming available it follows these design steps much more closely than the Rib Design KBE Tool does. This was also the case in the capturing process; knowledge was captured for each subsequent design step instead of capturing all knowledge for the tool at once. This resulted in a smoother knowledge capturing process because the un-clear points in the knowledge rules were isolated to a single design step and could therefore easily be resolved. The knowledge for the Rib Design KBE Tool was sometimes so integrated that it was difficult to identify the critical knowledge rule that needed to be clarified.

Packaging the acquired knowledge in KBE tools and using them in everyday practice

The next step of the KBE cycle is the Packaging step. “Packaging” means: using the acquired knowledge from the previous step to create the actual KBE software tool. This software tool is put into action in the Activate step. Both the Packaging and the Activation steps will be discussed in this section.

Before creating the KBE applications first the software platform on which it will be created has to be chosen. In this case both Rib Design KBE Tool and Rib Mould Design KBE Tool use the Visual Basic interface of Catia V5. Catia V5 is chosen because it is the CAD software package used in the project. The Visual Basic interface was chosen because it allows relatively simple programming of the software modules, while still allowing the programmer to use all the modelling options necessary. It also provides satisfactory performance. Programming code was used only where necessary, in other words where the standard functionality of Catia did not suffice. What this means is that the software mostly controls the combination of features pre-modelled in Catia and changes the parameters controlling the dimensions of these features. The pre-modelled features are so-called PowerCopies, which model a number of CAD elements based on a set of input geometry and parameters. In the applications developed the tool user, through user interface forms, sets these parameters values. However default values, based on the input from experts, are given for these parameters. A diagram showing how a PowerCopy is used is shown in Figure 7.

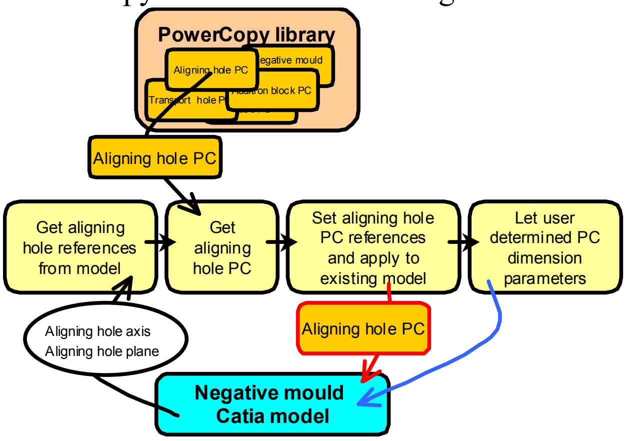

Figure 7 The process of applying an Aligning Hole PowerCopy to an existing Catia model of a partially built negative mould part

In this project the Packaging step has a high degree of interaction with the Capturing and Formalizing steps described in the previous sections. This was because prototype tools were used to verify the knowledge captured and also to help with the capturing of new knowledge. When using this approach it is important to keep the software developed modular. In this way software tool elements representing newly acquired knowledge rules can be easily plugged in. This modular approach was especially important for the development of the Rib Mould Design KBE Tool, because this tool was developed in conjunction with the development of the knowledge rules for designing the rib moulds. The modules developed for this tool tend to resemble the elements of the mould structure as represented in Figure 6. The evolution of the Rib Mould Design KBE Tool is depicted in Figure 8 where mould instantiations of subsequent prototype tools are shown.

Once the developed tool is mature it can be put into use in daily practice. However, a finished tool itself is not sufficient to guarantee successful use of the tool. The users of the tool should be supported in every possible way. This

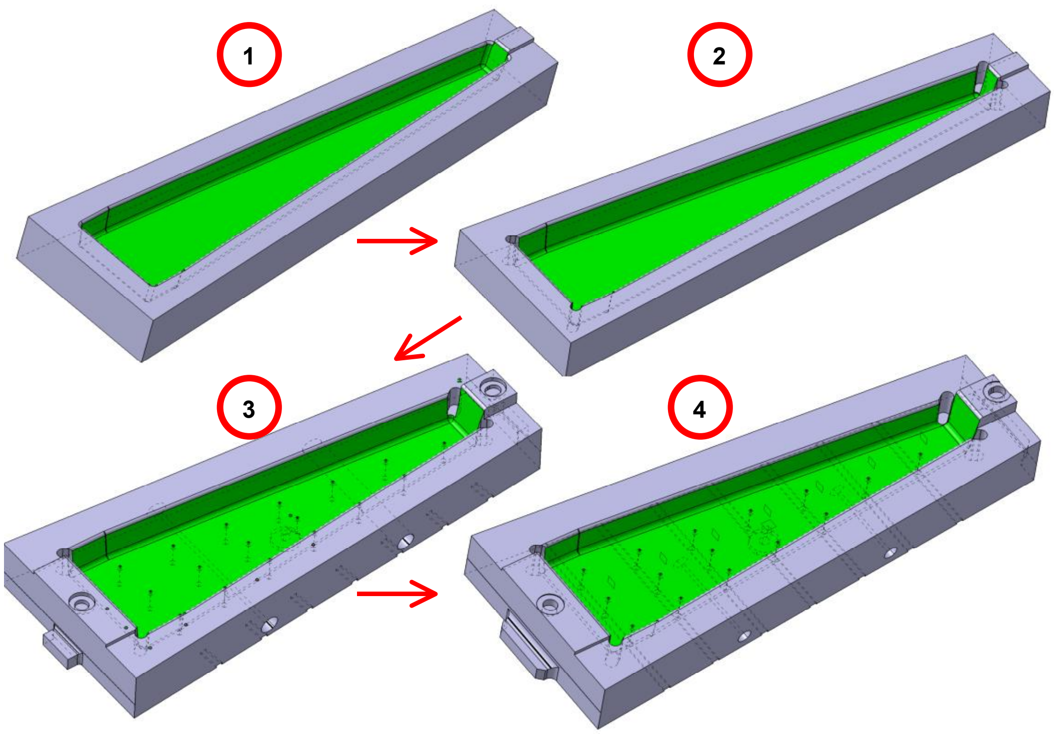

Figure 8 The development of the Rib Mould Design KBE Tool shown by 3 prototype design results of negative moulds (1-3) and a design result from the final tool (4)

means that they must receive proper training. In case the users are the same people that were using the prototype tools and supplying the knowledge rules the training of using the tools is easy. One should however in this case take care to have a training plan in place to train new users of the tool. Besides training, a manual is also necessary as a reference and to explain the different functions of the tool. Finally the activities performed by the tool also need to be transparent so they can be evaluated by existing and new users. This is especially useful when the tools are used in different projects and the existing users and tool developers are not available. In this project, the activities of the tool are made transparent by the diagrams in the rib and rib moulds knowledge base, together with the comments made in the software code.

The KBE tools developed were the Rib Design KBE Tool and the Rib Mould Design KBE Tool. The tools were kept separate because these two activities are conducted at different departments within the company. The Rib Design KBE Tool is capable of designing a thermoplastic composites sheet rib, while Rib Mould Design KBE Tool is capable of designing a positive and a negative mould for this rib. The result is a fully parametric CAD model, which has no link to the KBE tool that created it. This means that the rib or mould designer can easily change dimensions or the design itself just as he would be able to do with any rib or mould designed without a KBE tool. The resulting rib and mould designs are discussed in the next section.

Models created by the KBE tools and time reductions achieved

The KBE tools developed are being used to create models of ribs and rib moulds in a business jet development project. Although this

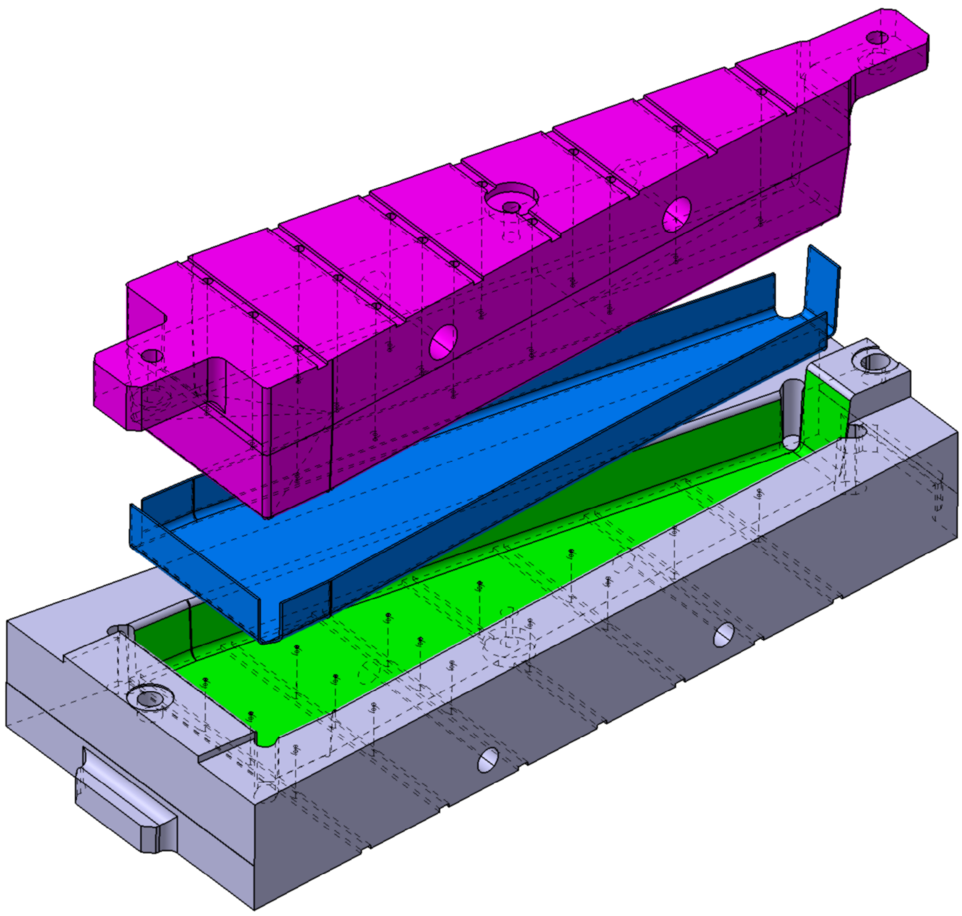

Figure 9 The final rib desing including the positive and negative mould used to manufacture it

project is still ongoing the results up to now will be discussed in this section.

The set of models that results from the developed KBE tool is shown in Figure 9. The resulting models are a solid model of the rib, as well as solid models of the positive and negative moulds used to produce this rib. For the rib model a considerable effort is still required to finish it, by adding annotations and dimensions. Therefore, the development time reduction achieved for the rib design process is not as significant as for the mould design process where the annotations and dimensions are not required. The mould design is usually finished by adding some additional features to the model like chamfering the sharp edges. Both rib and mould models need to go through the same check and approve procedure as models created without KBE tools. However this process is speeded up because the models that need to be checked are similarly structured.

The table presented in the justification phase was filled in again with the real hours achieved in the project to quantify the results. The results are shown in Table 2. In this table the regular design times have been halved with respect to the justification phase. This is because half the modelling time estimated in the justification phase is not related to the actual modelling of the parts themselves. The KBE tools will not operate in this area and therefore it will be kept out of the analysis. In the table the number of ribs created with the KBE tool is still set at 35. However because the project in which the tools are used is still in progress the final number of ribs still uncertain, although it is expected to be less than 35. For the rib design process the time reduction of 60% estimated in the justification phase is being achieved. For the mould design process the achieved time reduction is 90%. As can be seen, the reductions for the mould design are more spectacular than anticipated in the Justification phase. However tool development time was also longer that expected. As can be seen the reduction of the actual modelling hours and the increase in the development hours for the mould design application have resulted in a decrease of the return on investment. However this is still above 1 so the development of KBE tools has been profitable within this single project.

Table 2 Normalized KBE tool results table with normalized values for the estimated hours

	Rib design	Mould design
Regular design time estimated in justification phase	1	
Regular design 1 unit	0.5	0.5
Total time	17.5	17.5
Automated design 1 unit	0.2	0.05
Total time	7	1.75
KBE application development	5	12.5
Return on investment	1.46	1.23

Conclusions

It has been shown that using Knowledge Based Engineering tools can reduce the development time of thermoplastic ribs significantly. Development lead-time reductions of 60% to 90% have been achieved. This reduction in development time more than compensates for the resources needed for the development of these KBE tools. Therefore the development of KBE tools has been profitable within a single project. Moreover the KBE tools can now also be used in other projects, reducing development lead-time in these projects at minimal extra cost.

When starting to introduce KBE tools in a company, it is best to start with simple tools like the rib design tools because they can achieve results without requiring big investments. They also achieve results quickly, and can therefore be used to promote the idea of using KBE tools in the development process.

Besides reducing development time, the development of KBE tools has also contributed to the recognition of design problems early in the development phase. This recognition is achieved because, in the knowledge capture phase, design experts are forced to think about the design process in detail before the actual development process starts.

By storing all the knowledge rules used in the KBE tools in a knowledge base, the rules used for designing thermoplastic sheet ribs and the rules for designing the moulds needed to produce them are stored. Because the knowledge base is easily accessible these rules are made available and usable in future projects even when the KBE tools might not be used.

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