Application of a Knowledge Engineering Process to Support Engineering Design Application Development

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Abstract. The design, analysis and optimization process of complex products can be supported by automation of repetitive and non-creative engineering tasks. The Design and Engineering Engine (DEE) is a useful concept to structure this automation. Within the DEE, a product is parametrically defined using Knowledge Based Engineering (KBE) techniques. To develop and successfully implement the concept of the DEE in industry, a Knowledge Engineering (KE) process is developed, integrating KBE techniques with Knowledge Management (KM). The KE process is applied to develop an application supporting the design and manufacturing of aircraft wiring harnesses, focussing on the assignment of electrical signals to connectors. The resulting engineering design application reduces the recurring time of the assignment process by 80%.

Keywords. Knowledge Based Engineering, DEE, Knowledge Engineering, agents, wiring harness.

1 Introduction

Today's prevailing aircraft configurations have seen no significant changes in the last 50 years. Product and process improvements were aimed at increasing performance and reducing cost [16]. However, the targets set by Vision 2020 aim at more affordable, safer and more environmentally friendly air transport [8]. Together with the globally increasing demand for air traffic [1], aircraft design requires a paradigm shift to exceed present design process efficiency and meet the demands.

A methodology that supports this paradigm shift is Knowledge Engineering (KE), providing a number of methods and tools that considerably improve the process of acquiring, using and implementing engineering knowledge.

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Knowledge is a vital component of engineering design and significant reductions in costs and product development time can be realized if engineering knowledge is reused. Where previously the geometric model took a central position, today design knowledge should have the focus: knowledge should be managed and engineered as a key business asset [6].

Computer systems enriched with logic and engineering knowledge support engineering by automating repetitive and time-consuming processes. This reuse of knowledge decreases the engineering resources required and relieves the engineers from non-value adding activities, making more time available to exploit their creativity and engineering skills. The Design and Engineering Engine (DEE) is a framework concept to structure this automation. Within the DEE, a product is parametrically defined using Knowledge Based Engineering (KBE) techniques. The analysis of a particular instantiation of this product model is performed by discipline analysis tools while a search engine provides a strategy to drive the design toward a feasible solution, satisfy functional and performance requirements within constraints.

To develop and successfully implement the concept of the DEE in industry, a KE process has been developed. The KE process integrates KBE techniques with Knowledge Management (KM) and ranges from engineering process analysis to training and support for deployed engineering design applications.

This paper is structured as follows. First, the aspect of Knowledge Management and knowledge are discussed in section 2. Second, a short background on the KBE methodology and the concept of a DEE is presented in section 3. In section 4 the structure of the Knowledge Engineering process is discussed, followed by the application of the process on wiring harness design in section 5. The paper is concluded with a discussion on the performed research and the next development steps.

2 Knowledge Management

Knowledge Management (KM) addresses the use of techniques and tools to make better use of the intellectual assets in an organization. KM concerns [14]:

- Identifying what knowledge is important to an organization
- Deciding what knowledge should be captured to provide appropriate solutions to real-world problems
- Capturing, representing and storing knowledge from domain experts and existing repositories for understanding and reuse

In order to describe the approach to Knowledge Management more clearly, the concepts of knowledge, Knowledge Acquisition and knowledge base will be explained.

2.1 Knowledge

Knowledge is defined as *(i)* the information, understanding and skills that you gain through education or experience, *(ii)* the state of knowing about a particular fact or situation [11]. Knowledge can also be considered as a dynamic concept, strongly linked to the context it is applied to. Knowledge can be thought of as a system, driving a process that takes data and information as input in order to generate decision or actions. This results in the following definition [14]:

$$\text{Knowledge is the } \begin{Bmatrix} \text{ability} \\ \text{skill} \\ \text{expertise} \end{Bmatrix} \text{ to } \begin{Bmatrix} \text{manipulate} \\ \text{transform} \\ \text{create} \end{Bmatrix} \begin{Bmatrix} \text{data} \\ \text{information} \\ \text{ideas} \end{Bmatrix} \text{ to } \begin{Bmatrix} \text{perform skilfully} \\ \text{make decisions} \\ \text{solve problems} \end{Bmatrix}$$

There are various classifications of knowledge. Two important dimensions with which to describe knowledge are: *(i)* Procedural knowledge versus conceptual knowledge; *(ii)* Basic, explicit knowledge versus deep, tacit knowledge.

Procedural knowledge concerns processes, tasks and activities. It describes the conditions, under which specific tasks are performed, the order in which tasks are performed and the resources required to perform tasks. *Conceptual knowledge* concerns the description of concepts and their relation to other concepts. Hence, it addresses the ways in which objects are related to one another and their properties. An important form of conceptual knowledge concerns taxonomies, i.e. classes and class membership. Another type of conceptual knowledge addresses attributes of concepts.

Basic, *explicit knowledge* is the type of knowledge residing at the forefront of a specialist’s brain and is thought about in a deliberate and conscious way. It is concerned with basic tasks a domain expert performs, basic relationships between concepts, and basic properties of concepts. Deep, *tacit knowledge* is at the other extreme to basic, explicit knowledge. It is knowledge residing at one’s subconscious. It is often built on experiences rather than being taught. It often leads to automatic activities that seem to require no conscious thought. It is described in everyday words and phrases such as ‘gut feel’, ‘hunches’, ‘intuition’, ‘instinct’ and ‘inspiration’ [7].

The corporate advantages of captured and stored knowledge are numerous:

- Disseminated knowledge to other people within an organization to provide expertise
- Reduce the risk of knowledge loss in domains where only a small number of experts hold vital knowledge
- Reuse knowledge to enrich computer systems to perform tasks normally performed by human domain experts

Knowledge is captured through the application of knowledge acquisition techniques.

2.2 Knowledge Acquisition

Knowledge acquisition is the capturing and structuring of knowledge from humans and already existing repositories in order to enable knowledge reuse.

Although the benefits of capturing and using knowledge are manifest, it has long been recognized that knowledge is hard to acquire from domain experts. The difficulties stem from a number of factors. First, domain experts are not good at recalling and explaining everything they know. The tacit knowledge which operates at a subconscious level is hard, if not impossible, to explain. Second, domain experts have different experiences and opinions that require aggregating to provide a single coherent picture. Third, domain experts develop particular conceptualizations and mental shortcuts that are not easy to communicate. Fourth, domain experts use jargon and assume most other people understand the terminology being used.

To deal with such difficulties a number of techniques and tools have been developed that considerably improve the process of acquiring knowledge. A diversity of knowledge acquisition tools is presented in the Knowledge Acquisition Matrix, illustrated in Figure 1. The Knowledge Acquisition Matrix provides several tools in order to acquire the different types of knowledge.

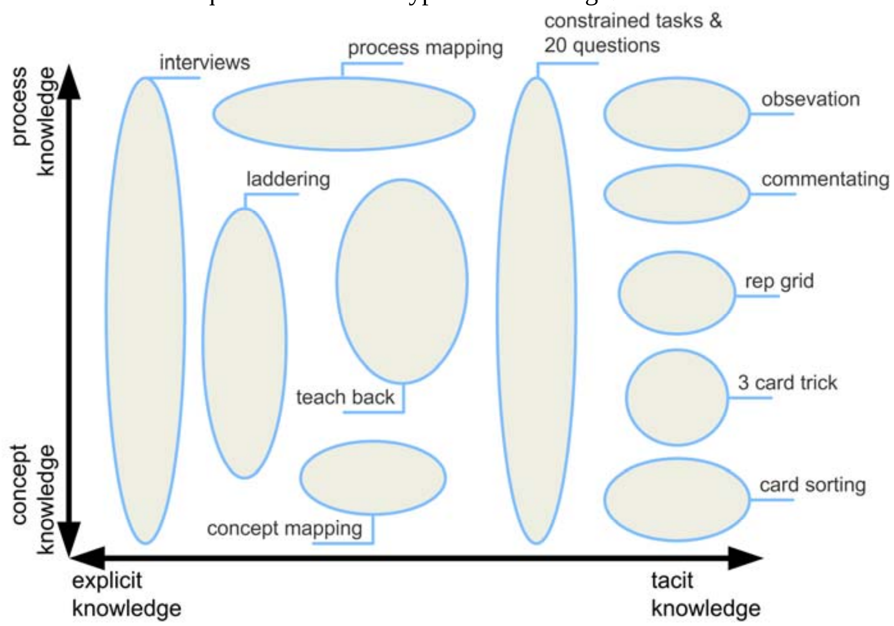

Figure 1: Knowledge Acquisition Matrix [7]

Dedicated software tools make the process of acquiring, storing and representing knowledge more efficient and less prone to errors. PCPACK [15] is the comprehensive of such tools. It is used for creating a knowledge base, a special database storing organizational knowledge and information representing the expertise of a particular domain [14]. To represent the expertise efficiently, the structure of the knowledge base is identical to the structures that underlie human expertise. Psychologists have found that this is based on four main components; concepts, attributes, values and relations. Furthermore, the appearance of the knowledge base is determined by the purpose of the knowledge. In the case of the development of a DEE based on KBE techniques, the structure will focus on representing the engineering process. The knowledge base will encompass both a current state and a future state, integrating the redesigned engineering process and software architecture for the application.

3 Knowledge Based Engineering

3.1 Knowledge Based Engineering Principles

La Rocca [12] defines KBE as a technology that is based on the use of dedicated software tools, i.e. KBE systems that are able to capture and reuse product and process engineering knowledge. The main objective of KBE is reducing time and cost of product development by means of the following:

- Automation of repetitive and non-creative design tasks
- Support of multidisciplinary integration from the conceptual phase of the design process

The KBE cornerstones are rule-based design, object-oriented modeling, and parametric CAD [13]. KBE has its roots in knowledge-based systems (KBS) applied in the field of engineering, hence the name. KBS is based on methods and techniques from artificial intelligence (AI). AI aims at creating intelligent entities [17]. KBE focuses on capturing rules of repetitive, non-creative human processes. Engineers have a product or object-oriented view of the world, which the object-oriented modeling approach supports. KBE found its first application as follow-up of CAD to enable designers to reuse models. CAD is based on geometrical primitives, KBE on knowledge primitives.

3.2 Design and Engineering Engine

A DEE is defined [13] as an advanced design environment that supports and accelerates the design process of complex products through the automation of non-creative and repetitive design activities. Figure 2 shows the DEE concept.

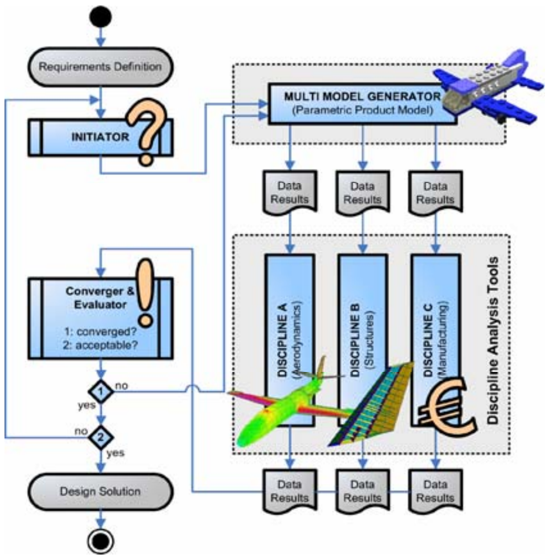

Figure 2: The Design and Engineering Engine (DEE)

The main components of the DEE are:

1) *Initiator*: Responsible for providing feasible initial values for the instantiation of the generative parametric product model.
2) *Multi-Model-Generator* (MMG): Responsible for instantiation of the product model and extracting different views on the model in the form of report files to facilitate the discipline specialist tools.
3) *Analysis* (Discipline Specialist) *tools*: Responsible for evaluating one or several aspects of the design in their domain or discipline (e.g. structural response, aerodynamic performance or manufacturability).
4) *Converger & Evaluator*: Responsible for checking convergence of the design solution and compliance of the product's properties with the design requirements and generation of a new design vector. These elements use loops in order to function.

The definition of the product is based on selection or creation of High Level Primitives (HLPs). HLPs are functional building blocks, containing an a priori definition of a family of design solutions. These functional blocks are encompassed sets of rules that use sets of parameters to initiate objects that represent the product under consideration. The object oriented approach of the HLPs allows capability modules (CMs) to specify the representation of the product as desired by various engineering disciplines.

4 The Approach to Knowledge Engineering

Knowledge Engineering (KE) is the engineering discipline integrating KM and KBE techniques by developing computer systems that conduct engineering processes normally requiring human expertise. It addresses the management of corporate knowledge and the creation of design applications that automate repetitive or time-consuming processes by reusing this knowledge. To successfully implement the concept of the DEE as a suitable framework to structure this automation, a KE process has been developed. It consists of six fundamental phases, as illustrated in Figure 3:

1) The first phase concerns an engineering *process analysis*, aimed to identify process improvement opportunities by applying lean principles to the field of knowledge engineering. The deliverable is a value map, addressing key opportunities for the application of KBE techniques.
2) The second phase addresses the *knowledge acquisition*; relevant expert knowledge is captured and validated. The deliverable is a knowledge base, a knowledge repository containing a formal description of knowledge associated with the concerned process.
3) The third phase focuses on the *knowledge structuring*. The formalized engineering process is analyzed and redesigned, incorporating computer automation strategies. The deliverable is a redesigned engineering process, and forms a blueprint for the DEE.
4) The fourth phase, *knowledge application*, concerns the software engineering of the DEE components based on the formal model, using KBE principles. The deliverable is a set of stand-alone KBE software modules with full capability to execute the engineering process, requiring a fraction of the formerly addressed engineering resources.
5) The fifth phase addresses the *integration of the KBE modules* into a framework to form the DEE. It includes the development of communication interfaces and the deployment. The deliverable is an engineering design application based on the concept of the DEE, offering engineering services.
6) The last phase concerns *support*, *maintenance*, *and training* related to the deployed design application. The main deliverable is a training and maintenance program to train engineers as operators of the application and ensure the knowledge base is up-to-date.

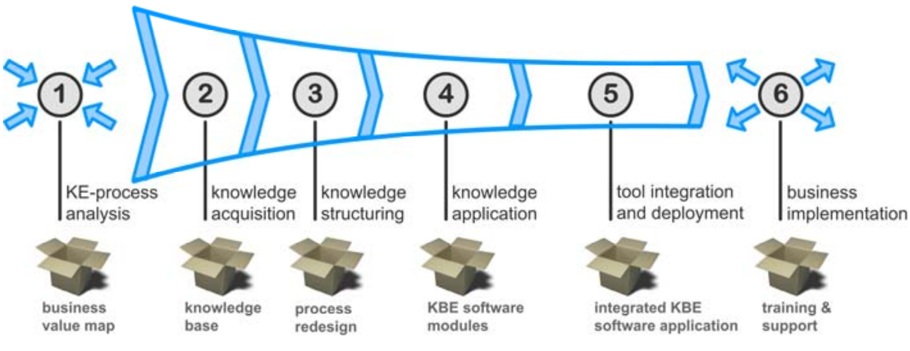

Figure 3: Knowledge Engineering process

In the next section, the specific phases of the KE process are discussed in more detail as performed during the development of a DEE supporting the design process for aircraft wiring harnesses.

5 Wiring harness Design Application

Electric aircraft wiring harnesses can be comprised of hundreds of cables and ten thousands of wires, providing connectivity between all the mission and vehicle systems ensuring sufficient redundancy and reliability. Electrical wiring design is often performed in parallel with structural design. Consequently, the wiring harness design is subject to changes in the aircraft structure that occur with subsequent design iterations, requiring time consuming rework for any harnesses affected [18]. The routing for all wires is determined manually and strongly dependent on personal knowledge and experience. Besides, the electric wiring design is governed by numerous regulatory and functional design rules. The repetitive, time consuming and rule-based nature makes aircraft wiring design a key opportunity to develop design applications based on the concept of the DEE and applying the KE process.
The development of the application is performed in close corporation with a main, international player on the aircraft electric wiring market, regarding both design and manufacturing.

5.1 Process Analysis

The first phase of the Knowledge Engineering process aims at identifying general process efficiency improvement opportunities regarding the design of aircraft wiring harnesses. The process analysis is mainly aimed at knowledge-intensive processes and to products belonging to a larger product family, ensuring a large applicability of the application.

During the analysis of the engineering design process the flow of information and required expert knowledge is monitored. The analysis focuses on three main process properties:

- Required engineering resources
- Repetitiveness of engineering activity within product family
- Complexity of applicable expert knowledge

The deliverable of the process analysis phase is a *value map,* providing identified process improvement opportunities, involving the concept of the DEE.

For the wiring harness design process, one of the key opportunities involves the assignment of signals at production breaks, where connectors connect the different wiring harnesses (Figure 4). Each wiring harness connector can include up to 150 slots, called pins, to accommodate a signal. The pins can vary in size, as do the signals to be assigned.

Figure 4: Connectors applied at a production break for electric wiring harness

For each production break the signals are assigned to a pin and associated connector, one by one. This process of pin assignment is repetitive and time-consuming due to several reasons:

- Separation of signals across multiple wiring harness segments or cables is enforced by numerous opposing design rules and regulations, for example redundancy of flight controls, electromagnetic compatibility or heat dissipation of power cables.
- The increasingly vast quantity of signals to be assigned.
- Rework caused by changes in the input data, for example governed by design iterations for the aircraft structural design.

The development of the DEE hence the subsequent process phases focus on the pin assignment process as the key identified opportunity.

5.2 Knowledge Acquisition

In the knowledge acquisition phase expert knowledge involved in the engineering process is formalized and captured. The knowledge acquisition phase is the first step in the development of the actual design application, and forms the foundation for the subsequent phases of the KE process. The quality of the formalized and captured knowledge will largely determine the success rate of KE process hence the resulting DEE as design application. To guarantee a successful result, the acquisition process is performed in close cooperation with the domain experts. The domain experts are important for two main reasons:

- Identification of relevant knowledge rules
- Validation of quality and completeness of the captured knowledge

Using the different knowledge acquisition techniques, a so-called informal model of the engineering activity is constructed, providing an informal but detailed description of the pin assignment process. It mainly encompasses a detailed activity diagram, describing the complete process. The informal model is part of the knowledge base.

The iterative knowledge acquisition process of identifying, capturing and validating the expert knowledge is supported by PCPACK. A separate ontology is developed, specifically built to suit the wiring harness domain. The ontology forms a Domain Specific modeling Language (DSL) and support the communication between engineers by unambiguously representing the (simplified) real-world problem: each element or concept in the problem domain is represented by an element in the model. The most important knowledge components captured in the informal model are the set of design rules and best practices, many of which are opposing. Some examples of applicable design rules are:

- The ratio of occupied pins over available pins has a settable maximum (design requirement)
- Signals are grouped among connectors to fulfill separation requirements (authority regulations)
- Per connector, signals should be centered and grouped together (manufacturing requirements)

The informal model functions as a detailed engineering handbook, decreasing the knowledge level required to perform the pin assignment processes.

5.3 Knowledge Structuring

After the formalization and validation of the domain expert knowledge, the pin assignment process is analyzed. The result is a redesign of the process, called the formal model and composes the second main item in the knowledge base. It takes the informal model as fundamental input, to ensure the governing functions are sustained.

The formal model provides the outline and the process for the improved engineering process, incorporating the software automation of repetitive tasks. Therefore, during this stage of knowledge structuring the configuration of the DEE and the associated KBE modules are defined. Although inheriting the functions of the original process, the redesigned process might consist of entirely different sub-processes or activities. For example, when the objective is to assign 10 signals across 90 available pins fulfilling all requirements, a human engineer will require a vast amount of time to explore most if not all possibilities. Applying commercial of-the-shelf optimization software results in a much more efficient exploration of the solution space, solving the problem concurrently for all signals thus increasing the reduction in recurring process time.

Due to availability and experience, the selected optimizer to solve the pin assignment process is ILOG’s Cplex [5]. The KBE system selected to develop the MMG is GDL from Genworks [10]. GDL is a new generation KBE system that combines the power and flexibility of the older ICAD system with new web technology. Its object oriented programming language is based on the standard ANSI Common Lisp. It allows both the manipulation of parametric geometric primitives as well as the construction of HLPs.

Within the concept of the DEE, GDL will perform the functions of the *Initiator* and the *MMG*; Cplex represents the mathematical analysis tool as well as the *Converger & Evaluator*, as represented in Figure 5. Since, the pin assignment problem is uni-disciplinary (mathematical discipline), no integration of multiple discipline-specific solutions is required before evaluation. Hence, Cplex will function as a general optimizer, not exclusively as a discipline specific optimizer.

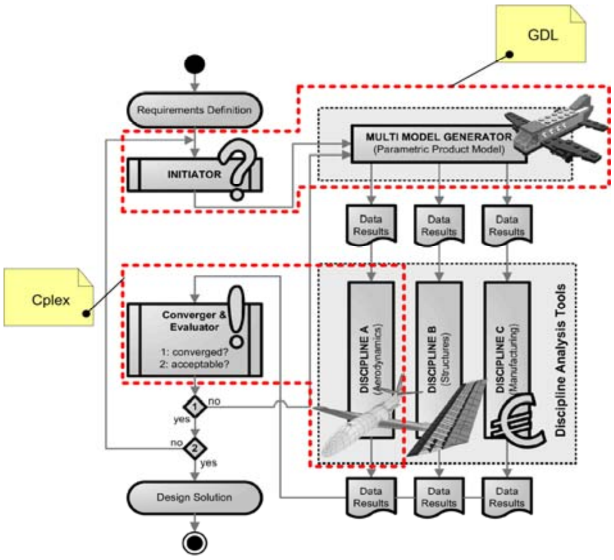

Figure 5: DEE consisting of GDL and Cplex

During the knowledge structuring phase, a large amount of specific domain knowledge is crunched into the formal model, reflecting deep insight into the domain and a focus on the key concepts [9]. The formal model is considered a collaboration between the domain experts and the developers of the design application, so-called knowledge engineers. Since the development of the KBE modules is iterative, the collaboration must continue throughout the knowledge application and knowledge integration phases as well.

5.4 Knowledge Application

The knowledge application phase addresses the development of the KBE software modules composing the DEE, according to the redesigned pin assignment process as stated in the formal model. The deliverable is a set of stand-alone KBE software modules, providing the full capability of the DEE. Since Cplex is available as a commercial of-the-shelf optimization, the knowledge application phase involves the development of the MMG, encompassing the HLPs and the CMs.

The HLPs are composed of mostly conceptual knowledge and represent the building blocks that allow combining and assembling to instantiate a member of the product family. By applying the parameter values generated by the initiator to the HLPs, the MMG is capable of producing an instantiation of this generative product model. For the pin assignment process, the initial or default solution generated by the initiator is empty: no signals are assigned, with the exception of manually pre-assigned signals. Although the pre-assigned signals are incorporated into the final solution, they will be left out of scope during the problem analysis, as are the associated pins.

The CMs are responsible for extracting different views on the product model, forming report files to facilitate the discipline specialist tools. The CMs are mainly composed of procedural knowledge. For the pin assignment process, the only incorporated discipline is mathematics. The related CMs extract a mathematical model of the connectors composing the production break, defining the supply of pins as well as the demand generated by the signals per separation code. The CMs define the objective function (minimize the number of pins occupied by a signal) and generates all constraints derived from the applicable design rules. The output is a report file, specifying a Linear Programming (LP) problem modeled after the instantiated pin assignment problem. This LP problem can be analyzed and solved by Cplex efficiently.

The development of the KBE software modules is performed iteratively and can be considered domain driven. After each iteration cycle, the formal model is adjusted to ensure the model accurately represents the structure and process of the DEE.

5.5 Knowledge Integration

To empower automatic (mathematical) analysis of the pin assignment problem a multi-agent task environment is used. The environment integrates the KBE software modules into a framework and provides communication between the KBE modules through software agents [4].

The design of the multi-agent task environment is inspired by the issues posed by earlier generation design support frameworks experienced addressing the automation of Multi-disciplinary Design and Optimization (MDO) problems often as a top-down execution of a string of individual discipline analysis tools. These execution strings are executed from start to finish: when errors in a particular discipline analysis tool emerge, the highly coupled nature of an execution string often leaves no other possibility than to re-execute all or parts of the tool chain. Besides, these support frameworks are often created an implicit way and need severe adapting when a new MDO problem or product family is addressed [2].

To overcome the identified obstacles a multi-agent task environment is developed that addresses the aforementioned problems in a structured and consistent way: decoupling the knowledge of the product from the process and able to handle a family of design problems. The framework should prevent waste of CPU resources when partial re-execution of discipline analysis tools is required. Moreover, instead of upfront fixing the tool chain definition, the problem is communicated to the framework and each agent and tool combination is using its communication skills and knowledge of the problem to request information through a specified, but not tool and address specific, call [2, 3, 4].

Considering the pin assignment problem, the resulting DEE functions as a stand-alone design application and has not yet been connected to the company's other engineering software tools. GDL and associated agent have been deployed at the company on-site, whereas the Cplex-agent is executed remotely as engineering service, on request. The software architecture of the application is illustrated in Figure 6.

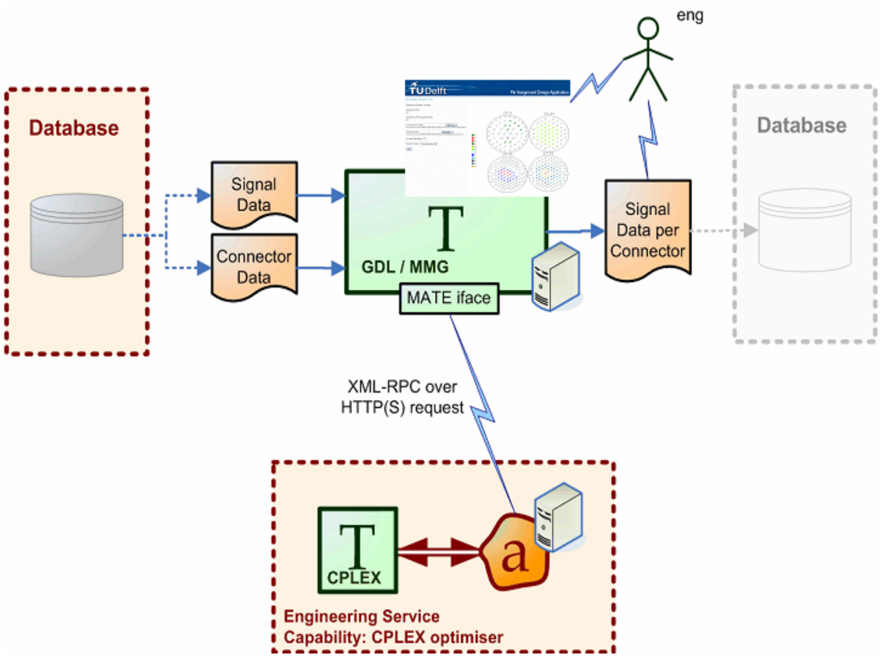

Figure 6: Software architecture of the pin assignment design application

A Graphical User Interface (GUI) is designed to enable interaction with engineers. The GUI allows the engineers to specify the input data (problem description) and provides identified best practices as execution options, such as grouping of signals. The GUI also enables the engineers to manually adapt the solution as provided by the DEE through incorporated selection functionality and provides different types of report files to accommodate manufacturing as well as design engineers. The GUI illustrates the front view of the set of connectors composing the production break of the wiring harness. The different signal types are color-coded by separation code, to enable easy verification by the engineers.

The efficiency improvement gained by the design application is two-dimensional; reduction of time-to-market and reduction of product development cost for all products within the family. The recurring time for the pin assignment process for all production breaks per aircraft is reduced from approximately several hrs to a couple of minutes. Taking into account the manual processing of the solution data into the main engineering database, the gross recurring time is approximately a half hour: a recurring time reduction around 80% is obtained.

5.6 Business Implementation

The final phase of the KE process covers training, support and maintenance regarding the deployed design application. After the deployment and integration of the application within the company's engineering process, engineers will be trained and educated in order to utilize the full potential of the design application.

Furthermore, the knowledge base will be maintained and additional knowledge included, enabling the DEE to solve assignment problems for other product families, for example another series of connectors.

For the pin assignment design application, the business implementation phase is no yet performed and will be the subject of a subsequent paper.

6 Concluding Remarks

A time reduction of approximately 80% is obtained, reducing the recurring time from several hours back to a couple of minutes. Further reductions can be obtained up to an estimated 95%, if the automatic coupling with the organizational main engineering database is established.

Since the formal model describes the structure and process of the pin assignment application, engineers are not only capable of operating the design application; they will also gain better understanding of the process that is applied in order to obtain the results.

Since the formal model encompasses the structured conceptual knowledge within the application, it can be concluded that it contains an accurate diagrammatic model of the MMG. Besides, the DSL makes the source code of the DEE more transparent, since all programmed objects will have an equivalent object in the actual problem domain. This straightforward mapping between the software application and the problem domain enables the exploration of automatic model-driven generation of source code directly from the knowledge base. The decoupling of domain knowledge and platform dependent problem knowledge remains a major challenge within the Knowledge Engineering process.

References

[1] Advisory Council for Aeronautics Research in Europe (ACARE). Strategic research agenda, vol 1+2 and executive summary. 2002. Available at: http://www.acare4europe.com.

[2] Berends JPTJ. Development of a Multi-Agent Task Environment for a Design and Engineering Engine. M.Sc. Thesis, Delft University of Technology, Faculty of Aerospace Engineering, Delft, The Netherlands, 2005.

[3] Berends JPTJ, van Tooren MJL. Design of a Multi-Agent Task Environment Framework to support Multidisciplinary Design and Optimisation. 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2007-0969, Reno, NV, USA, 2007.

[4] Berends JPTJ, van Tooren MJL, Schut EJ. Design and Implementation of a New Generation Mulit-Agent Task Environment Framework. 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Schaumburg, IL, USA, 2008.

[5] Cplex Interactive Optimizer, Software package, version 10.2.0. Gentilly France: ILOG, 2006.

[6] Drucker P. Management challenges for the 21st century. Oxford United Kingdom: Butterworth-Heinemann, 2001.

[7] Emberey CL, Milton NR, Berends JPTJ, van Tooren MJL, van der Elst SWG, Vermeulen B. Application of Knowledge Engineering Methodologies to Support Engineering Design Application Development in Aerospace. 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO), AIAA-2007-7708, Belfast, Ireland, 2007.

[8] European Commission. European aviation: a vision for 2020, Belgium, 2001. Available at: http://www.cleansky.eu.

[9] Evans E. Domain-Driven Design. Boston USA: Addison Wesley, 2004.

[10] GDL, Software package, version 1.5.5.7, Genworks International, Birmingham, MI, USA, 2007.

[11] Hornby AS. Oxford Advanced Learner's Dictionary, 6th edition, Oxford University Press, 2000

[12] La Rocca G. PhD. thesis, Delft Univeristy of Technology, Delft, Netherlands (to be published)

[13] La Rocca G, van Tooren MJL. Enabling distributed multi-disciplinary design of complex products: a knowledge based engineering approach. J. Design Research, vol 5, No. 3, pp.333-352.

[14] Milton N. Knowledge technologies. Monza Italy: Polimetrica, 2008.

[15] PCPACK, Software package, version 1.4.4R, Release 5. Epistemics, Nottingham, United Kingdom, 2006.

[16] Pratt PD. History of flight vehicle structures 1903-1990. Journal of Aircraft, vol 5, No 41, 2004.

[17] Russel S, Norvig P. Artificial intelligence: a modern approach. Second edition. Prentice Hall, 2003.

[18] Van der Velden C, Bil C, Yu X, Smith A. An intelligent system for automatic layout routing in aerospace design. Innovations Syst Softw Eng No 3, pp 117–128, 2007.