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DESIGN FOR NOISE REDUCTION – THE ARCHITECTURE OF AN ENGINEERING ASSISTANCE SYSTEM FOR THE DEVELOPMENT OF NOISE-REDUCED ROTATING SYSTEMS

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ABSTRACT

Despite detailed planning, conceptual and embodiment design important product properties like the acoustical behavior of complex machinery are only revealed in the later development phases (e. g. prototyping phase). If annoying acoustical behavior of machinery is identified in the later development phases, there will be the need to time- and money-consuming macro-iterations, which sometimes go back to the conceptual phase. This means a high financial risk especially for capital goods like wind turbines, because the operating license of wind turbines can be refused. In this paper, the demands and the basic architecture of a knowledge-based engineering (KBE) assistance system for the development of noise reduced rotating machines will be presented. It will assist the development engineers by context-sensitive allocation of design-relevant knowledge that enables them to identify components of complex machinery which are critical with respect to noise creation, noise transmission or noise radiation. With the aid of this assistance system, which is called ALARM, the risk of a drop back to the conceptual phase regarding undesirable acoustic product properties will be reduced.

Keywords: design for X, information management, knowledge management, wind energy, knowledge-based engineering

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1 ENERGY FROM WIND – SUCCESSES AND CHALLENGES

Due to the high complexity of modern machinery it occurs that despite detailed planning, conceptual and embodiment design important product properties like the acoustical behavior are only revealed in the later development phases (e. g. prototyping phase). However, this causes time- and money-consuming macro-iterations which sometimes go back to the conceptual phase and mean a high financial risk, especially for capital goods like wind turbines. This challenge will be faced by a collaborative research project called EUREKA-ALARM (EUREKA, 2012). ALARM is a German acronym for *Assistenzsystem für die Lärmreduzierte Auslegung Rotierender Maschinen*. EUREKA indicates an inter-European research project between partners from Belgium and Germany.

In this paper, the basic concept of a knowledge-based engineering (KBE) *assistance system for the development of noise reduced rotating machines* is presented. Among other issues, the development engineers shall be assisted by context-sensitive allocation of design-relevant knowledge that enables them to identify components which are critical with respect to e. g. noise transmission or noise radiation. The detection of components, which are responsible for noise creation, can be identified within a rotating machine by the radiated frequencies and the known rotational speeds. With the aid of the engineering assistance system (EAS) ALARM the risk of a drop back to the conceptual phase regarding undesirable acoustic product properties will be reduced. Hence a development process with less iteration will lead to an earlier start of series production and to reduced costs.

The potential of wind energy as a source for mechanical work is no modern-age knowledge. Hints that the first windmills were built in ancient Egypt are about 3000 years old. The first reliable source dates back to 644 AD as Burton (2011) explains. Since then wind energy has mainly been used as a drive for water pumps, grinding mills and sawmills. Despite the improvement of the steam engine's efficiency by James Watt the change from engines powered by wind and water to engines powered by fossil fuels was very slow. With the discovery of the electricity in the end of 19th century the first attempts were made to convert the wind energy into electrical energy as well.

According to Burton (2011) the breakthrough of wind turbines came in the late 1980s when first robust (but unfortunately non-profitable) prototypes with a rated power of up to 3 MW were installed. Yet, the first commercial success was revealed with "wind farms", consisting of several smaller turbines with a rated power of 60 kW. This is nowadays most pursued concept for on-shore and off-shore wind power production, whereas modern wind turbines can reach a rated power of 6.15 MW (2012, Repower 6M). Even 10 MW systems are being planned (AMSC SeaTitan™) as Wolf (2010) describes.

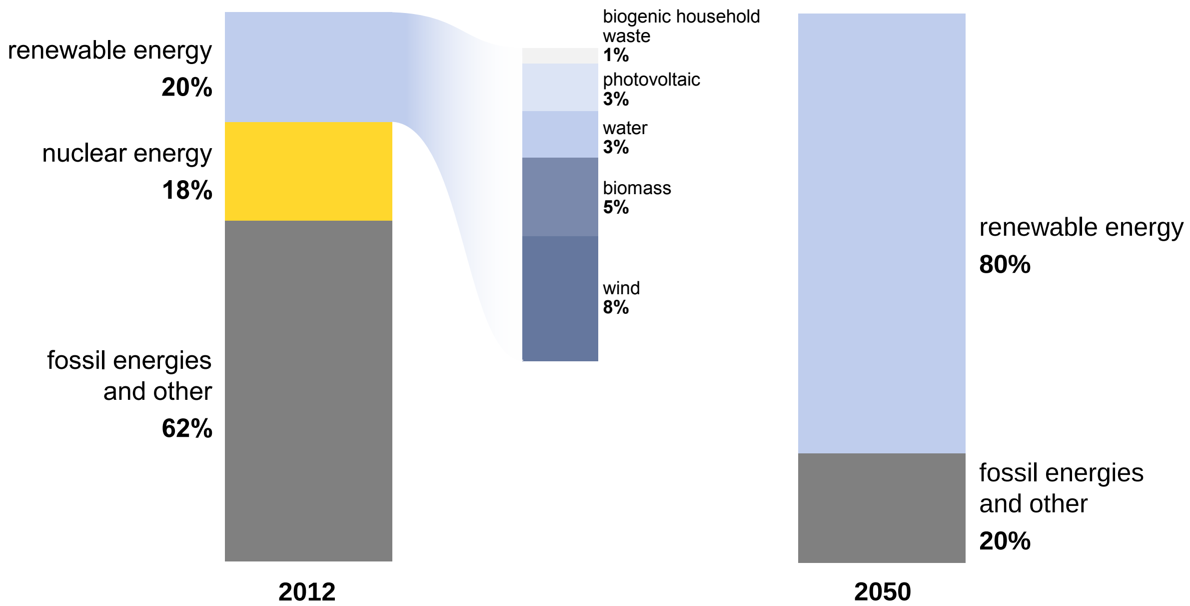

Figure 1. Meeting the energy demand in Germany based on (BMWi, 2012)

The incident of Fukushima in 11th March 2011 caused many industrial nations to reconsider their long-term nationwide energy production and supply concept. As for Germany the portion of renewable energy sources is to be increased from 20 % (2012) up to 80 % (2050) as shown in Figure 1 (BMWi, 2012). Wind energy is already the highest part of all renewable energy sources and it can be assumed, that this will at least not decrease during the years. Apart from that the outlined plan is almost the same for the Republic of Korea (Kim, 2011) and (Park, 2013). It can be assumed that the impact on environment by wind turbines will increase regarding visual (appearance, shadows) and acoustic (overall sound, noise, tonalities) issues. Hence, the developing companies will have to face the challenge of decreasing these impacts whereas the acoustical behavior especially regarding the mechanical components offers the most potential.

2 WIND TURBINES AND THEIR IMPACT ON ENVIRONMENT

2.1 Design of wind turbines and the project demonstrator

Within the last two decades wind turbines have passed through a substantial development. However, all leading wind turbine manufacturers prefer a mature architecture (Figure 2), consisting of a reinforced concrete foundation, a tubular tower, a nacelle with horizontal drive train, and three rotor blades. The drive train can either be realized direct-driven or with a multi-stage gear and is thereby the main distinctive feature of modern wind turbines. For power control two concepts are available and are described inter alia in Lee (2012): The stall concept uses rotor blades with a specific aerodynamic profile that causes the airflow to tear off at a certain wind speed. Nowadays, the pitch concept is used for most wind turbines that are put into operation. The blades can be rotated along their longitudinal axis while the wind turbine is working. Thus, for a same energy yield occurring loads on the blades are reduced, compared to stall-controlled turbines (Burton, 2011).
The demonstrator wind turbine of the EUREKA-ALARM project is a pitch-controlled system with a three stage planetary gearbox, a rated power of 3.200 kW, 114 m rotor diameter, 93 m hub height (type REpower 3.2M114) and is situated in northern Germany.

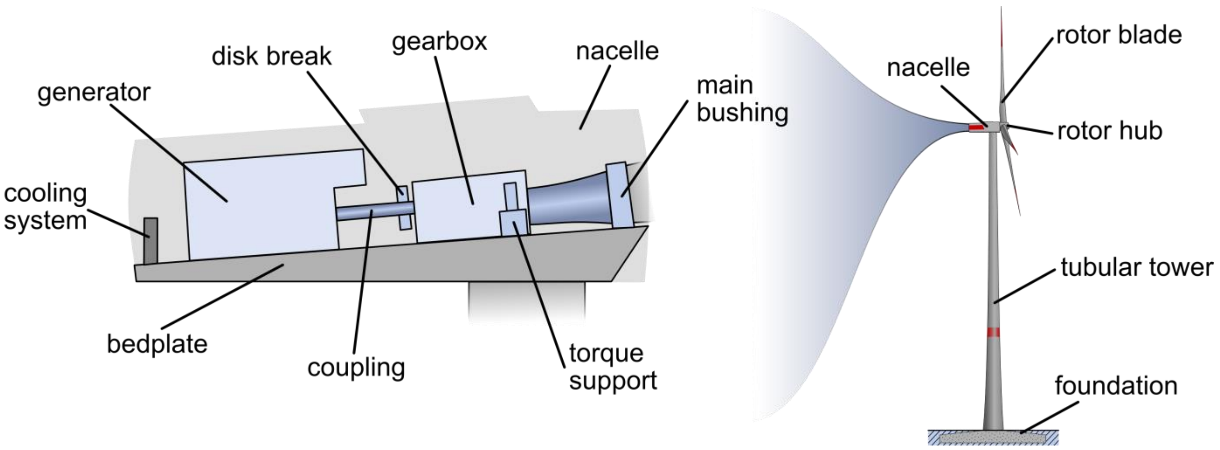

Figure 2. The general design of a wind turbine drivetrain with a multi-stage gear

2.2 Wind turbine noise emission, perception and measurement

Wind turbines emit two main types of noise: mechanical noise and aerodynamic noise. The former is mainly generated by the gearbox but also by the generator or the cooling system (Pedersen, 2004). The aerodynamic noise originates mainly from the flow of air around the blades, the sound pressure level (SPL) for instance, increases with the fifth power of tip speed. However, mechanical noise shows a dominant energy profile at frequencies below 1000 Hz and in addition to a broad noise spectrum discrete tone components (tonality, tone incorporation) can occur. Those tonalities are perceived as a hum or buzz and according to Pedersen (2004) they are known to be more annoying than "normal" noise. In order to take those tones into account during the approval process of wind turbines, the IEC 61400-11 ed2.1 defines the procedures to be used in the measurement, analysis and reporting of acoustic emissions of a wind turbine (IEC, 2006). In case of a single tonality the approval of the wind turbine can be refused by local authorities and thus cause an unprofitable period of maintenance. Different systems to eliminate or damp those tones have been developed such as tuned mass dampers.

However, those components are expensive and the wind turbine is disconnected from the electrical grid during the process of identification and elimination of tonalities. So both the system developer and the operator have substantial interests in avoiding tonalities already in early phases of the product development process (PDP). Within the EUREKA-ALARM research project an EAS should be conceived to assist the engineers in achieving a Right-First-Time solution. In the following the demands on such an EAS will be discussed.

3 ELICITATION OF DEMANDS ON AN ENGINEERING ASSISTANCE SYSTEM FOR NOISE-REDUCED DESIGN

The compilation of partners within the research project is similar to industrial development projects. Thereby the demands that have to be fulfilled by the EAS are of topical interest and take problems of development engineers into account. The term *demand* is used rather than *requirement* because it corresponds to the formulation of the EAS end user, that is, the development engineers of the wind turbine system, the gear or the torque support. The demands have been elicited by structured interviews, user stories and creativity methods. Central issues have been identified after analyzing the results:

- general communication structure of the EAS ALARM
- mapping the product development process and the flow of information
- relating acoustical behavior on gear test rig with acoustical behavior in-the-field test

All these demands will be formulated as software requirements specifications during the project progress in accordance to IEEE Standard 830-1984. Each issue will be described in the following sections in higher detail.

3.1 The general communication structure of the engineering assistance system ALARM

The development processes of all parts of modern machinery are usually different especially if some subsystems are purchased from suppliers. The suppliers have their individual development process based on the experience and knowledge about their offered products, e. g. planetary gear or damping torque support in a wind turbine. So every supplier sees the overall development process from his own point of view this means each supplier knows what kind of information and data is needed and at what time. Therefore, there cannot be only a single EAS, but every supplier will need an EAS that represents their product. On this account an EAS needs a user-defined front end and a computation kernel containing the core functionality, which will be the same for all companies, which use the EAS. This computation kernel will provide several fundamental algorithms (e. g. data mining algorithms) in order to carry out analysis of the specific product. For that purpose each partner uses an instance of the EAS with a description of his specific product structure. If specific results are necessary for analyses of other EAS users, they can be stated as “accessible” by a supplier and exchanged with the other companies. This ensures the security of the know-how of each company.

3.2 Mapping the product development process and the flow of information

The Original Equipment Manufacturer (OEM) of a wind turbine system engages the suppliers of the subsystems to develop and manufacture the according component (planetary gear, elastomer bearings, etc.). Every partner is a specialist with specific development processes but depends on data and information regarding other components. The exchanged information may be eigenfrequencies of other components or of the whole system and the excitation caused by the operation of the machinery. The different users of the EAS demand the possibility to model their internal development process and to assign design task specific internal and external information. Subsequently the different development process shall be mapped in order to support the exchange of design-relevant data and information among the partners as shown in Figure 3. The EAS will enable a very early exchange of relevant data and information on schedule and thus will help avoiding delays within the wind turbine development process.

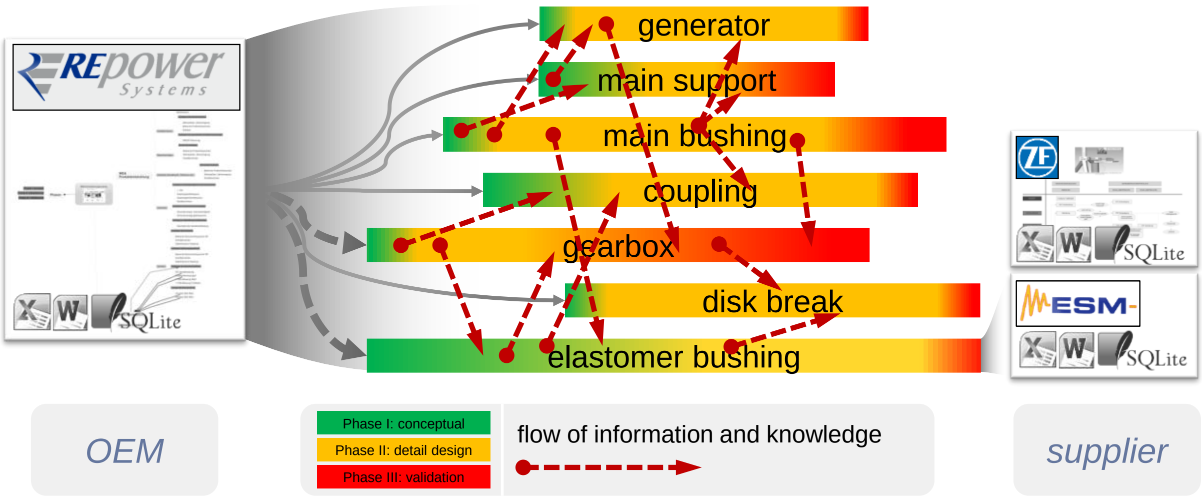

Figure 3. Flow of information in the product development process

3.3 Relating acoustical behavior on gear test rig with acoustical behavior in-the-field test

Due to their dimensions systems like wind turbines cannot be tested on a test rig en bloc, that is, the components are individually tested at each partner's test facility. Furthermore, there are detailed testing phases on the test rig an annual in-the-field validation period for the prototype of a new product series. This leads to a crucial problem as an example shows: The acoustical behavior of the planetary gear on the test rig and during the in-the-field test is different due to a different configuration. In the former case the gear is mounted on a stiff platform (on solid hall ground) whereas it is mounted on the bedplate inside the wind turbine nacelle (on the tower). The bedplate, with a much lower stiffness compared to the platform on the test rig, the nacelle, the tower and further components influence the acoustical behavior. In addition to the physical prototype testing virtual tests viz. simulations are performed both with the component models and a complete wind turbine model. However, the end user demands that the EAS can find a relation between the acoustical behavior of the multi-stage gear on the test rig and the acoustical behavior of the wind turbine prototype during the field test (Figure 4).

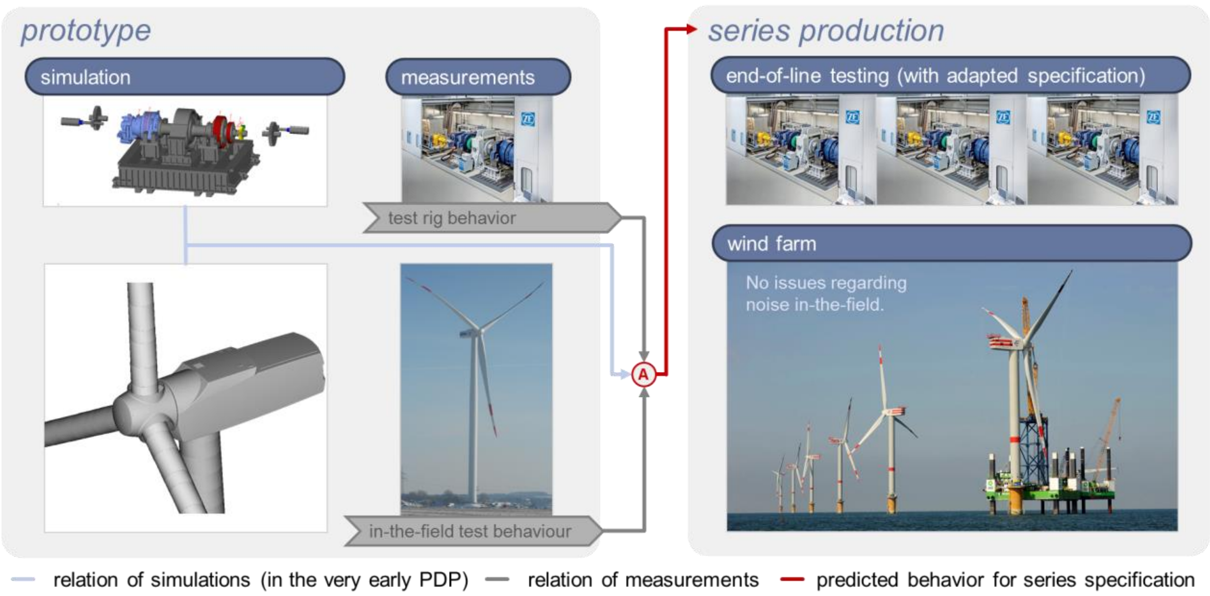

Figure 4. From prototype to series production
(picture: ZF.com and REpower Systems SE)

4 CONCEIVING AN ENGINEERING ASSISTANCE SYSTEM FOR THE DEVELOPMENT OF NOISE-REDUCED ROTATING SYSTEMS

4.1 General architecture of a knowledge-based system

According to Spur and Kause (1997) knowledge-based systems are software systems in particular, which map a part of the knowledge of one certain discipline in their field of application. The "source" of this mapped knowledge is usually adapted gradually. The basis of all knowledge is information, which can have different structure depending on the task of the knowledge-based system. Sources for information are, for instance, experts, knowledge engineers or specific training of artificial intelligence (AI) algorithms. Spur (1997) calls computer vision, image processing, processing of natural language in smartphones and assistance systems as an example.

The basic structure of these systems is shown in Figure 5. Available knowledge can be brought into the *knowledge base* by the *knowledge acquisition tool* in order to be linked up to existing knowledge. Furthermore, it also provides the ability to manage and maintain the knowledge base. There is a distinction between *direct*, *indirect* and *automatic* knowledge acquisition. In the direct knowledge acquisition an expert as knowledge carrier brings his knowledge in the knowledge-based system by himself. This method is more expensive and prone to errors because experts often lack the expertise to formalize their own knowledge so that it can be processed computer-aided. The indirect knowledge acquisition uses a third person who has the skills to elicit the knowledge from an expert unadulterated on the one hand and to formalize it for the knowledge acquisition tool on the other hand. Within the automatic knowledge acquisition, knowledge is identified with machine learning algorithms independently by the knowledge acquisition tool (Spur, 1997).

The core of the knowledge-based system is the *knowledge base*. It stores the knowledge of a certain domain persistently in a suitable form of knowledge representation for reuse. The problem-solving tool uses the stored domain knowledge. On this account the problem-solving tool is that tool which classifies the whole knowledge-based system to a certain specialized field because the problem-solving tool provides itself a kind of special knowledge by means of how to handle the knowledge in the knowledge base.

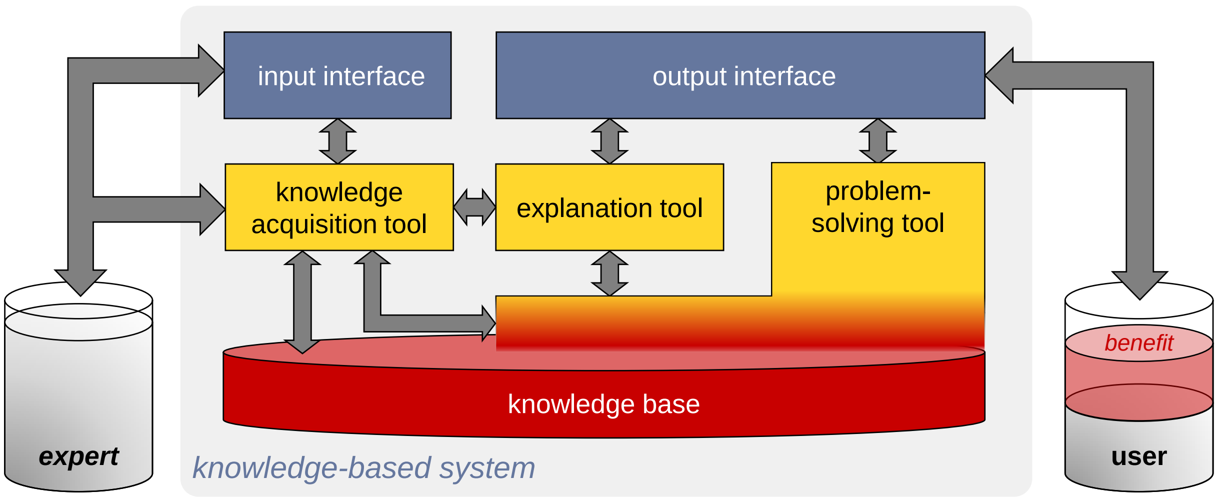

Figure 5. General architecture of a knowledge-based system based on Spur (1997) and Rude (1998)

The problem-solving has generally two steps: at first the sequencing control and afterwards the inference engine is activated. The sequencing control identifies the needed knowledge for the current problem in the knowledge base and sets an exact order in which the inference engine has to process the knowledge to deductions. The inference engine derives logic statements from the knowledge. The statements correspond to new facts, i. e. the facts are formulated indeed explicitly, but they have already existed implicitly in the knowledge base (Spur ,1997) and (Rude, 1998). It should be noted that there is no possibility to create "new knowledge" because this is produced via creative approaches applying existing knowledge. However, creativity as an activity is reserved for intelligent living beings only (Holm-Hadulla, 2010).

The *input and output interface* is used for the communication between the knowledge-based system and the user (e. g. an engineer) as well as for an expert during the indirect knowledge acquisition. The user has the ability to enter a problem in order to get a response from the problem-solving tool. The response does not have to be a solution for the problem directly; it also can be guidance to solve the problem. The *explanation tool* tries to improve the understanding of the conclusion, which was drawn by the problem-solving tool (Spur ,1997).
By use of knowledge-based systems users get the possibility to work on previously unsolvable problems by accessing the stacked knowledge in the knowledge base and by falling back on the ability of the problem-solving tool which enlarges the users' scope (Puppe, 1990).

4.2 The engineering assistance system ALARM

The concept of the EAS ALARM is based on the engineering design assistance system *mfk*. In contrast to this assistance system the EAS ALARM doesn't map the design methodology to assist the product developer regarding manufacturability, conceptual design, mechatronic product development or multi-criteria analysis of alternative product concepts (Wartzack, 1999) and (Wartzack, 2000). It will support the engineer in designing a noise-reduced machine. Therefore, the focus is not directly on the design of the examined technical product, but on the application of appropriate methodologies to structured development data. The results will help the engineer to develop new ideas and to gain a deeper understanding of the examined technical product with respect to the acoustic behavior and assist in this way with the noise-reduced product development.

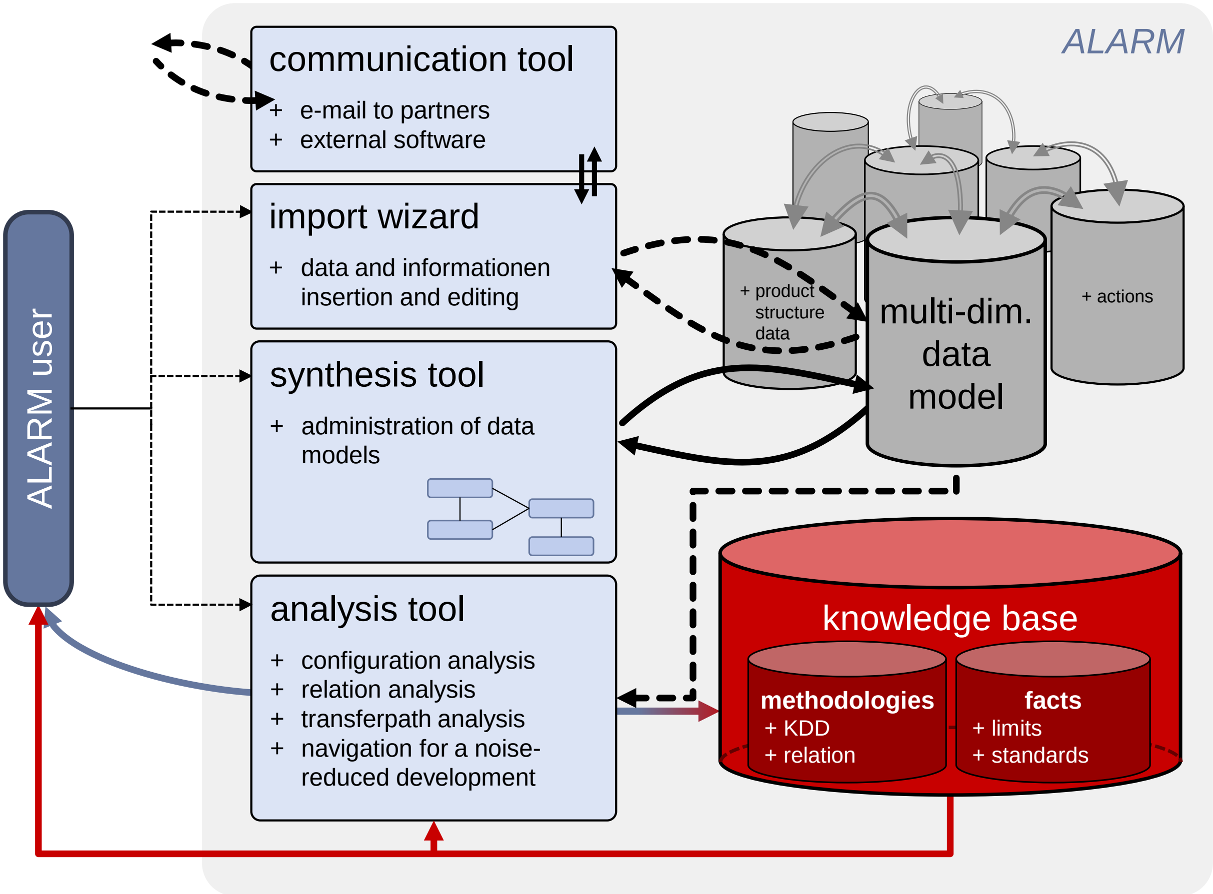

Figure 6. Specific architecture of the engineering assistance system ALARM

The EAS ALARM is subdivided in seven main components (Figure 6). A *multi-dimensional data model* maps all data incurred to an object-oriented structure. The data model is called multi-dimensional because it is not only one big data model, but it consists of many different small data models, which are connected and linked to each other. As an example, the product structure data model and the action data model should be mentioned. The product structure data model will reflect the technical system, which consists of assemblies and parts. The action data model stores all actions for a noise-reduced development of an assembly or a part. The connection of both models arises from the fact that the actions for a noise-reduced development is always assigned to the assemblies or the parts.

The *synthesis tool* allows the ALARM user to create and delete data models. Speaking of the creation does not mean the content of a data model, but the structural architecture. Moreover, structural changes can be introduced in the multi-dimensional data model. In addition, the synthesis tool can implement connections between the data models in which not every data model compulsorily needs a connection to another data model, i. e. there can be independent data models as well, which do not have any connection to other data models at all.

The *import wizard* is the tool to import data and information into the multidimensional data model. On the one hand the data and information can be stored directly in a data model, on the other hand there can be a link to data and information in files (e. g. spread sheets, documents, etc.) of an existing folder structure of the underlying operation system, i. e. there will be a link to the individual file and folder organization structure of an engineer in the product development team. Furthermore, the data and information can also be provided by partners participating in the project, where the *communication tool* provides the necessary interface. The import wizard ensures independently and automatically the consistency of the linked data, which are not directly stored in a data model.

The *knowledge base* offers all available methodologies and facts, which are used in the project EUREKA-ALARM for analysis purposes. The concept of the knowledge base provides for modular extensions either by programming or by adding results at runtime. In contrast to the multi-dimensional data model, the methodologies like knowledge discovery in databases (KDD) or norms cannot be implemented at runtime; they have to be implemented before, see Röhner (2011) and Breitsprecher (2012). The analytical findings are also stored in the knowledge base for reuse that is to apply the acquired knowledge later on new data in the multi-dimensional database on the one hand and for further computations (e. g. visualization purposes) on the other. For instance, the analytical findings, which represent a part of the handled knowledge within the EAS ALARM, can be a report with values, formulas, surrogate models (e. g. response surfaces or trained neuronal networks), a structured guideline or an interactive diagram. Another type of handled knowledge within the EAS will be the product development process of the considered product from which the ALARM user is awaiting a noise-reduced behavior by the aid of the EAS ALARM. This knowledge will be inserted during runtime. Thus, every ALARM user has the possibility to implement confidential knowledge in the EAS ALARM without the possibility for other EAS ALARM instances at other partners having access.

The *analysis tool* combines the available methodologies, facts and previously computed analytical findings from the knowledge base in a suitable way and applies them on the data and information in the multi-dimensional data model. The data and information is processed for each type of analysis in its respective manner. The results can either be presented directly to the engineer or stored in the knowledge base for reuse like mentioned before. A possible scenario for the reuse of analytical findings is given in the next subsection 4.3.

The *ALARM user* cannot control all components of the EAS. He controls the import wizard as well as the synthesis and analysis tool. Not all analytical findings are a direct solution, thus the user has to be able to interpret the analytical findings which are given by the EAS. Hence, the EAS ALARM assists the user, but it cannot replace him. On this account the ALARM users are engineers, who are familiar with the topic of the technical acoustic.

4.3 One application scenario for the engineering assistance system ALARM

During the prototype phase of a multi-stage gear for wind turbines, for instance, many operational data is collected. However, the data often does not contribute to the improvement of new and further developments of the product completely. This is not the engineers' fault, because the engineer often cannot see the use of the data. Even if a benefit is identified, the engineers will not have the ability to identify all patterns, relationships and trends within the large amount of data (Ester, 2000). For example, the operational data that is the acoustical behavior of a multi-stage gear on the test rig and in-the-field is different (see subsection 3.3). One task for the EAS ALARM is to compute a surrogate model on basis of two datasets which will be stored in the multi-dimensional database. One dataset represents the behavior on the test rig and the other represents the behavior of the multi-stage gear on the wind turbine in-the-field test. The source of the dataset can either be a simulation in an early product development phase or measurements in later (Figure 4). With the aid of the computed

surrogate model, which is stored as an analytical finding in the knowledge base, the engineer that is the ALARM user has now the ability to predict the behavior of the multi-stage gear on the wind turbine. If the behavior can be predicted, the engineer will be able to define requirements for tests on the test rig which will eliminate the acoustical issues on the wind turbine for series production. Hence, time- and money consuming iterations while putting wind turbines into operation are avoided.
The research question for this scenario is the development of a methodology to create a surrogate model which can predict the acoustical behavior of a system during lifetime based on two characteristic datasets for the operation on a test facility on the one hand and the normal operation of the system on the other. With the aid of the EAS ALARM the engineer gets support in finding the right decisions during and before the prototype phases regarding the series production.

5 CONCLUSION AND OUTLOOK

Wind energy plays a central role within the Post-Fukushima and long-term nationwide energy production concept of first world nations like Germany and South Korea. On the other hand wind turbines and wind farms have a certain impact on the environment either visual (appearance, shadows) or acoustic (overall sound, noise, tonalities). These acoustic properties are only revealed in later product development phases (e. g. prototyping phase). The research project EUREKA-ALARM has the purpose to develop an engineering assistance system (EAS) ALARM enables the design engineers to identify components which are critical with respect to noise transmission or noise radiation. With the aid of the EAS ALARM the risk of drop-backs to early design phases regarding undesirable acoustic product properties will be reduced. Hence a development process with less iteration will lead to an earlier start of series production and to reduced costs.
Very important issues within the development of the EAS ALARM are the demands of its end users. These have been elicited via structured interviews, user stories and creativity methods. Afterwards these demands have been analyzed and central issues have been identified. Based on these demands a software specification in accordance to IEEE Standard 830-1984 will be worked out. Within this paper a specific architecture for the EAS ALARM is proposed. The central components are a synthesis, an analysis and a communication tool. Furthermore a knowledge base stores methods (e. g. for KDD-analyses),facts (e. g. Campbell diagrams) and analytical findings. In order to manage the data a multi-dimensional data model maps all data incurred to an object-oriented structure.
The next steps include the development of a suitable KDD-process. The core idea is that the EAS ALARM can perform an automatic acquisition of design-relevant knowledge independently from the end user. The basis of this knowledge acquisition process is data derived from former wind turbine developments or from test rig measurements of a wind turbine prototype (including the components) that is being developed. In any case the KDD-process shall induce regressionmodels for example to predict the acoustical behavior of a wind turbine, an expected Campbell diagram or a frequency spectrum for the whole system or components (multi-stage gear, hydraulic torque support). Based on these predictions the engineer shall define end-of-line testing specifications (limits) for standard gear test runs during the series production more precisely and earlier. In this way the chance that the assembled series wind turbine meets the official noise emission requirements is increased and money-consuming iterations are avoided.

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