THE REALIZATION OF AN ENGINEERING ASSISTANCE SYSTEM FOR THE DEVELOPMENT OF NOISE-REDUCED ROTATING MACHINES

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Abstract

Today, product developer face the challenge taking not only the requirements for mechanical properties of a product into account, but also other requirements like the acoustical properties, for instance. If undesired acoustical product properties are identified product developer ask experts for counter-measures. They usually can find solutions for these acoustical issues by detailed analysis of data like sound emission measurements, noise and vibration measurements or validated multi-body simulation results. By aid of an engineering assistance system the knowledge of the expert can be provided to product developer in order to reapply these findings for new products or product variants already in early design phases of the product development process. This will help the product developer to guarantee the specified acoustical product properties already in the earlier phases. This contribution will give an insight in the realization of the engineering assistance system ALARM for the development of noise-reduced machines.

Keywords: Knowledge management, Early design phases, Product modelling, models, Design for X (DfX)

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1 INTRODUCTION

1.1 Motivation

In Germany, the market for wind energy in the recent years has grown rapidly, hence in November 2013, the German Government adapted the Renewable Energies Act (EEG) to the current situation: windy locations, especially close to the sea, need to expect a reduction of the subvention rates. Therefore, onshore locations for wind turbines (WT) become more lucrative. Thus, suitable onshore WT locations will become increasingly rare which necessarily leads to WT locations close to residential areas. Even at a very great distance from residential areas the WT have to satisfy strict noise emission and immission regulations (IEC, 2006). Hence, product developers of WT today have to face the challenge of taking not only the requirements for mechanical properties of a product into account but also other requirements like the acoustical properties, for instance. For this reason, the inter-European research project EUREKA-ALARM with partners from Belgium and Germany has been launched in 2012. The overall goal of EUREKA-ALARM is to develop an *engineering assistance system for the development of noise-reduced rotating machines* (EAS ALARM) using the example of a multi-megawatt WT. Product developers shall be assisted by context-sensitive allocation of design-relevant knowledge, so that optimization potentials in terms of the acoustic behaviour in early design phases of the product development process (PDP) are identified in order to reduce the risk of time- and money-consuming iterations like drop backs to conceptual phase.

1.2 Problem statement and objectives

In the field of acoustics product developers face the challenge that acoustical properties of a product are only revealed after manufacturing and assembly. Normally, simulations are done to reveal product properties in early design phases. However, assembled components are necessary to validate the acoustic simulations. Thus, acoustic simulation models in early design phases are often inaccurate and do not predict sufficiently the acoustical behaviour of the assembled product. In later design phases of the PDP, at best, measurements of manufactured and assembled components are available for product developers. These include, for example, sound emission measurements, noise and vibration measurements or validated multi-body simulation results. The cause for undesired acoustical product properties can normally be found by detailed analysis of the data and eliminated by modifications of product characteristics (e. g. stiffening of structures to influence eigenfrequencies), which is normally done by experts. A goal in this research project is to support product developers in early design phases of the PDP in designing new products or product variants with rotating components, so that specified acoustical product properties are already ensured at the beginning of series production. This contribution will give an insight into the realization of this engineering assistance system for the development of noise-reduced machines. Hence, the overall research question of this contribution is: *"What should an engineering assistance system look like in order to support product developers in designing a noise-reduced machine?"*.

1.3 Overview

The research clarification is explored in Section 1. Section 2 presents the state of the art in terms of wind turbine noise and noise-reduced design of machines in general. Section 3 gives an insight in the realization of an engineering assistance system regarding noise-reduced development of rotating machines. Section 4 gives an example for the use of the EAS ALARM and the benefits for product developers.

2 STATE OF THE ART

2.1 Wind turbine noise

WT emit two main types of noise: aerodynamic noise and mechanical noise (see Figure 1). The aerodynamic noise originates mainly from interactions of the natural atmosphere with the blades (see Figure 1a). Mechanical noise is mainly generated by the relative motion of mechanical components such as the gearbox or generator (Wagner et al., 1996). Although both noise types have almost similar levels, usually the mechanical noise leads to annoyance of residents (Pinder, 1992). The reason for this is the specific sound characteristics of mechanical noise: aerodynamic noise is often masked by natural noise such as rustling of forests whereas mechanical noise is audibled as a tone like a hum or a buzz (Wagner et al., 1996; Pinder, 1992). In order to take those sound characteristics into account during the approval process of WT, the IEC 61400-11 ed2.1 defines procedures to be used in the sound emission measurement of a WT (IEC, 2006). In case of tonal components in the overall spectrum of a sound emission measurement, the approval of the WT 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 countermeasures are expensive and WTs do not produce energy during the process of identification and elimination of tonalities.

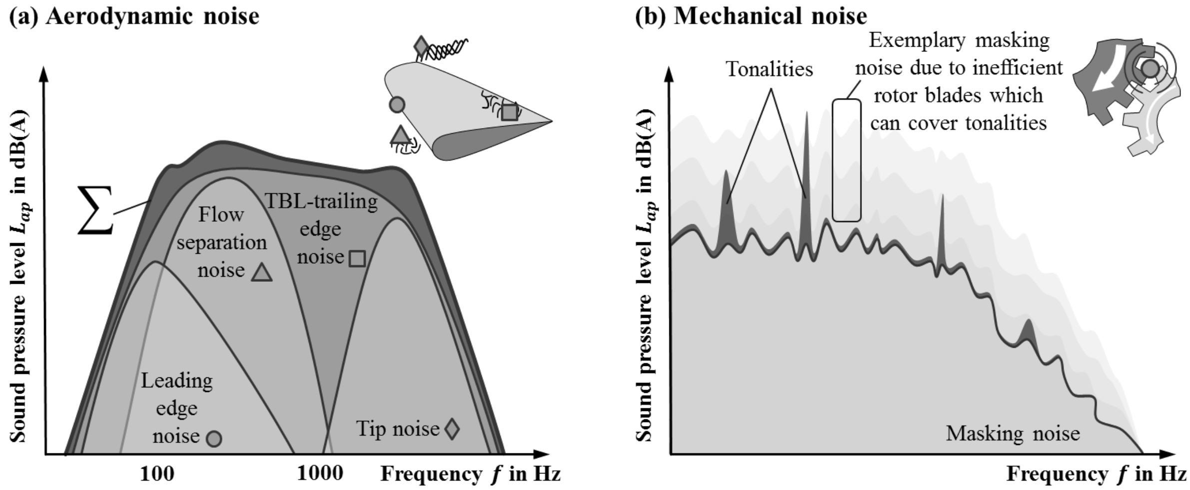

Figure 1. Aerodynamic noise (a) and mechanical noise (b) of wind turbines, according to Petitjean (2011)

Moreover, the efficiency of the rotor blades with respect to noise has increased in the last years. Hence, the masking noises of the rotor blades have been reduced and the audibility of tonal components has become more present (see Figure 1a and b). In case of WTs the development of a new platform variant, i.e. from 2MW to 3MW, takes approximately three to five years. Due to their dimensions systems like WT cannot be tested on a test rig en bloc, that is, the acoustical properties of WTs can then only be measured three to five years after the planning phase. Nevertheless, each single component is individually tested at each suppliers' test facility. But due to the different configuration, tonalities on the suppliers' test rig will not necessarily be tonalities on the WT, and vice versa. In order to reduce the risk of tonalities of a new WT platform variant and thus to annoyance of residents or the refusal of approval, data of previous platform variants need to be taken into account. The current state of the art is that product developers try to use data of pervious platform variants, but they are often not aware of which data of pervious platform variants is available and how it can be used to avoid tonalities. The EAS ALARM faces this challenge.

2.2 Noise-reduced design

There is several literature and standards describing methodologies for a noise-reduced design. Design catalogues, for instance, contain collections of known solutions and counter-measures to noise related issues (Dietz and Gummersbach, 1999; Gummersbach, 2001). Standards describe procedures and design processes to ensure low noise machinery and equipment (DIN, 2009; DIN, 2001; VDI 2014). In the following section the most important state of the art in terms of noise-reduced design is presented.

2.2.1 EN ISO 11688

The standard EN ISO 11688 (DIN, 2009; DIN, 2001) can help to analyse a prototype which has already been manufactured and assembled. Hence, this standard is used in later development phases like the prototype phase to identify, trace and eliminate issues regarding noise. It describes a procedure for the acoustical analysis of a prototype by doing measurements: (Gummersbach, 2001)

1. Classification of the noise generation, noise transmitting and noise radiating components
2. Identification of air-borne, fluid-borne and structure-borne noise sources
3. Tracing of air-borne, fluid-borne and structure-borne transfer paths

4. Identification of sound radiating surfaces
5. Determination of the biggest contribution on noise generation in noise sources, transfer path and radiating surfaces

2.2.2 Information system for noise reduction measures

Gummersbach (2001) developed an information system for product developers which structures and allocates knowledge regarding noise reduction measures in form of counter-measures or proposals for design modifications like noise reduction design catalogues. This approach is based on the EN ISO 11688 (see Section 2.2.1) to ensure a systemized development of noise-reduced machines.
The procedure of Gummersbach (2001) involves three steps: It starts with the creation of a noise flow model based on the requirements specification for the machine in question. This model contains the design of the considered machine, i. e. each component (assembly and part) and their semantic constrains. These constrains show how the components influence each other. This is needed for the acoustical analysis according to EN ISO 11688, which is the second step of this approach. Before further investigations can be performed to identify noise mitigation measures, the classification in noise sources, transfer path and radiating structures needs to be done. In this third step, Gummersbach (2001) advices to define all components as noise sources which convert energy. All the others should initially be defined as noise transmitters. In the beginning, resonance- and flow-related effects can be neglected. By means of these findings product developers can investigate suitable noise mitigation measures for each class (noise generation, noise transmitting and noise radiating components) by the use of noise reduction design catalogues like Dietz and Gummersbach (1999), for instance. After considering technical and economic aspects, these findings can be used to modify the design.
The basis of the information system according to Gummersbach (2001) is the design and its acoustical analysis of the machine in question. Hence, product developers needs to know the structural design of the product in order to use this procedure. Therefore this procedure does not recycle the experience and knowledge of experts of other product variants, for instance. It also cannot use data like simulation findings or measurement results directly. Like the information system from Gummersbach (2001), the EAS ALARM is also supporting product developers in designing a noise-reduced machine. In contrast, the focus is not just on the design of the examined technical product, but on the application of appropriate methodologies or procedures of experts on structured data generated during the PDP. (Küstner et al., 2013)

3 THE REALIZATION OF ALARM

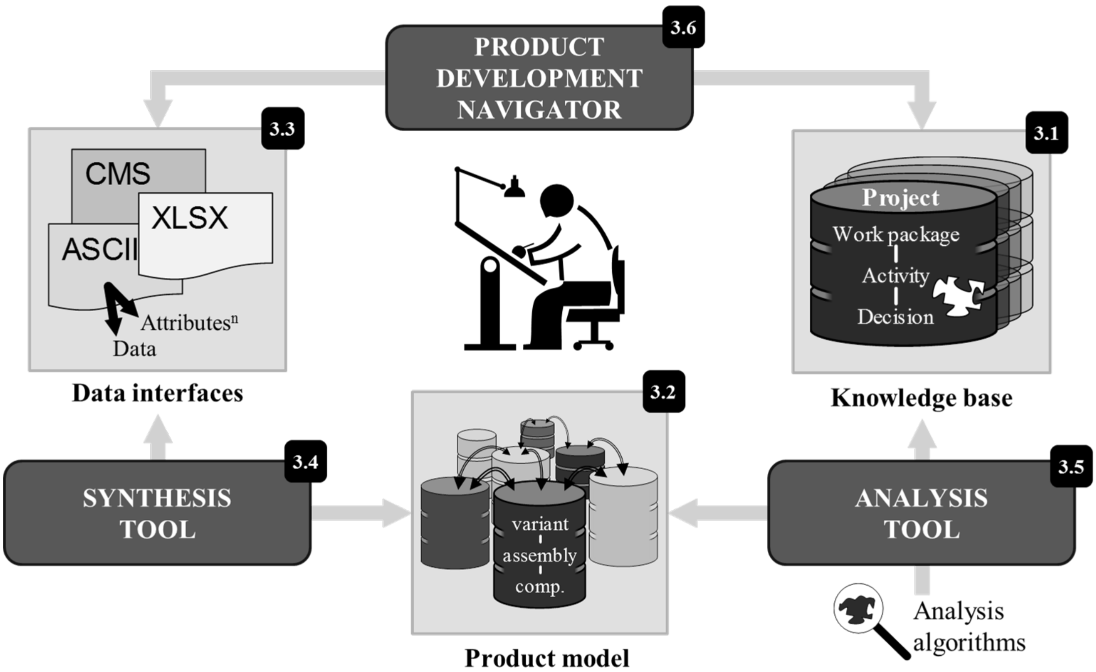

Figure 2. The overall concept of the engineering assistance system ALARM

The EAS ALARM is an engineering assistance system for the purpose of supporting product developers in designing noise-reduced machines by providing expert knowledge to analyse the acoustical behaviour of rotating machines by use of data. Figure 2 shows the overall concept of the EAS ALARM. After the elicitation of requirements on project partner side this overall concept has been developed. It consists of three main tools, which are responsible for the operating part of the EAS ALARM and three supports, which are connective links between the main tools. The three main components are the product development navigator (PDN), the synthesis and the analysis tool. The supports are the project-based knowledge base, the product data model and the data interfaces. Each tool and support will be described in the following sections in higher detail. The corresponding section to each tool or support is referenced in Figure 2.

3.1 Distributed, project-based knowledge base

In the beginning of the research project EUREKA-ALARM, several structured interviews of product developers and experts have been carried out. The aim of these interviews was to identify, how product developers prevent or solve noise-related issues during the development of rotating machines: Normally product developers and experts work collaboratively. They discuss and analyse existing data (e. g. sound measurements or simulations results) in order to gain a deeper understanding of the acoustical behaviour. Based on the considered data decisions are made, which have an influence on the product characteristics and on the ongoing PDP.
The procedures to prevent and solve noise-related issues are usually unique for each *event* in the PDP. An event is defined as a modification on the product, which has an influence on acoustic product properties, for instance, if the rotor blade department releases a new rotor design. After an event has occurred one or more procedures to prevent noise-related issues need to be executed. All procedures, which need to be executed, can be bundled in a *project*. The procedures in a project are called *work package*. That is, a work package describes the procedure of experts during data acquisition, data analysis and decision making, i. e. it defines a sequence of *activities* and *decisions* (Figure 3).

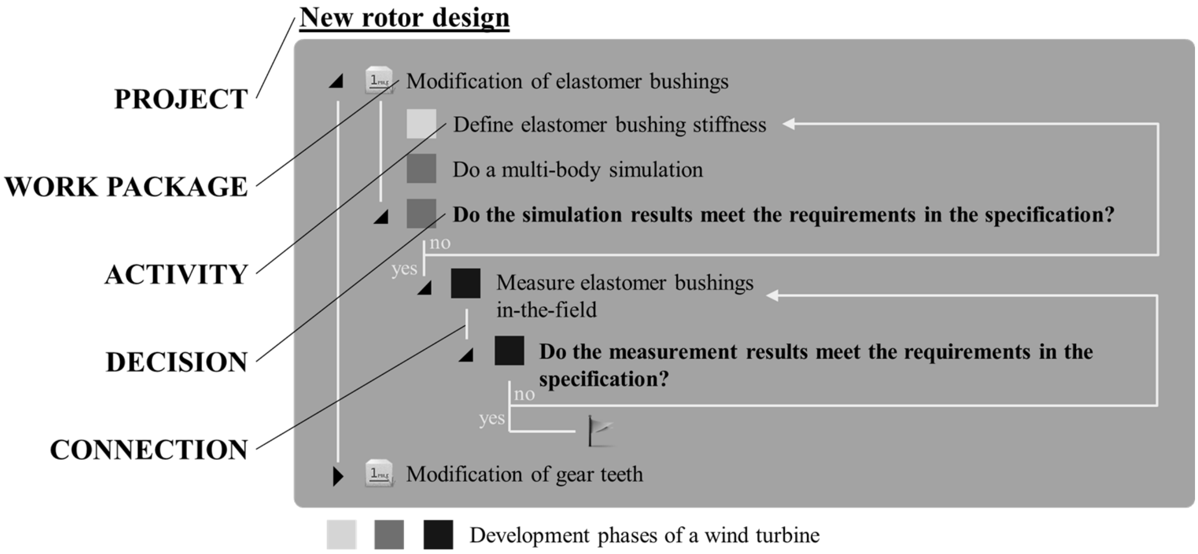

Figure 3. Example for the separation in projects, work packages, activities, decisions and connection

Activities are related to data acquisition or analysis. Decisions are made based on the acquired data and analytical findings. Each work package, activity and decision has a description. This description is a wiki-like storage, where experts can write an advice or describe a procedure about what has to be done. Product developers need to read this description before starting with a work package or activity or making a decision. The order and structure of projects, work packages, activities and decisions is formalized as object-orientated knowledge representation. Although the description is a part of the knowledge base and necessary and valuable for product developers, it is not processed by problem-solving component of the EAS ALARM (see Section 3.6). It is used to explain the procedure the experts have defined. For further information about projects, work packages, activities and decisions see Küstner and Wartzack (2014).

The knowledge base is to be created by experts, provided as project templates and stored centrally in the intranet (e. g. oracle database). Product developers can download these project templates as file-based databases (e. g. sqlite-files). On this account, we talk about distributed knowledge bases. Interviewed product developers stated that, beside sharing, there should be a supervised feedback loop from product developers to experts. That is, if product developers have ideas for improving a project template, it first need to be send to experts for review and evaluation before it can be shared with other product developers (see Figure 4). Due to this, a supervised knowledge exchange between experts and product developers can take place. For further information about the distributed, project-based knowledge base see Küstner and Wartzack (2014).

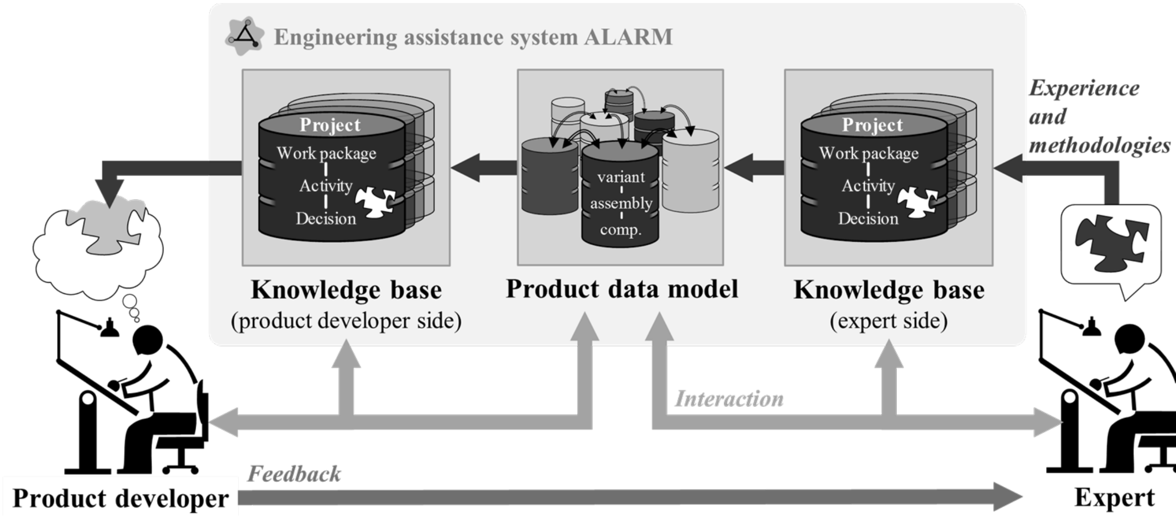

Figure 4. The exchange of knowledge between product developers and experts via distributed, project-based knowledge base

3.2 Product data model

Product developers' activities during the PDP are based on and result in huge amount of data, which are measurements or simulation results, for instance. The EAS ALARM requires storage for this data to ensure a supervised exchange (e. g. measurement, simulation data and project templates) between product developers, to ensure a uniform structure for all data and to have a full overview of which data for each product or component is available. For further analysis, each data set requires detailed metadata to describe under which circumstances the data has been elicited. For instance, if we want to compare the acoustical behaviour (accelerometer measurements) of a gearbox in-the-field and on the test rig, the torque and speed (operating point) need to be known for both data sets (e. g. "torque = 0.75 kN", "speed = 20 mms^{-1}"). The torque and speed are necessary information (metadata) to describe this kind of data set and to link similar data sets. Therefore, the metadata must not be in the data set (e. g. in the spread sheet or matlab file), but stored as an inducible *attribute* of the data set. Every type of data set has a different amount of attributes, for some data sets the metadata consists of up to 20 attributes.

Usually, companies set up product data management (PDM) systems to manage, revise, archive and distribute their product portfolio, product structure and the related data in form of documents. Commonly used PDM-systems do not have the flexibility to store data and metadata of different kinds out-of-the-box. Companies normally order these features from the PDM software provider. The EAS ALARM is conceived as a cross partner tool and almost every project partner uses a different PDM-system which makes the customization very expensive. Moreover, purchased parts are usually not mapped in a sufficient level of detail in common PDM-systems. Thus, the acoustic product properties of purchased parts are hardly provided and exactly they often affect the acoustical behaviour of the product. For this reason the EAS ALARM must provide a server-based database, which represents the product structure by its own.

The product data model has three levels at which the data can be attached: *variant-level*, *assembly-level* and *component-level*. The component-level stores data related to a component, e. g. known eigenfrequencies of a gearbox in WT. If measurements are done for a single product (assembly), they will be stored in the assembly-level. For instance, if we upload a condition monitoring system (CMS) measurement of a WT it is only valid for this single WT (assembly). Computer-aided engineering (CAE) tools, like multi-body simulations (MBS) normally use nominal geometry of an assembly. So each CAE result, if validated, is valid for a variety of assemblies with the same design, so the results are valid for a variant.

3.3 Data interfaces

Since all data related to the acoustical behaviour of a product need to be stored in the product data model to be analysed or exchanged, an accuracy classification before the import of the data in the EAS ALARM is crucial to guarantee correct analysis results. If the data is used as an input for analysis, the outputs precision is influenced by inputs quality. In the domain of acoustics, data of different reliability and precision is produced. We distinguish between three accuracy levels depending on the source of the data. *Estimates* have a small accuracy. These are empirical values of experienced product developers or experts, for instance. *CAE* and *calculation results* have a medium accuracy. *Measurements* have a high accuracy, because they give feedback how a product really behaves. *Facts* have the highest accuracy, like data sets, which describe the product structure of a partner.
Each data set gets its accuracy classification from its data source. For instance, if a data set describes a complex acoustical spectrum, the data source will either be a simulation result or a measurement, which indicates a medium or high accuracy respectively. During import, the metadata (attributes) is separated from data.

3.4 Product data synthesis tool

The synthesis tool is a link between the *data interface* and the *product data model*. It builds and maintains the product data model and imports or exports data sets. Before data can be imported, the structure of the product data model is to be created. For this, a data set is necessary, which describes the product structure. Usually this kind of data set can be exported from business operation management software or PDM-systems and then processed by the synthesis tool via data interfaces.

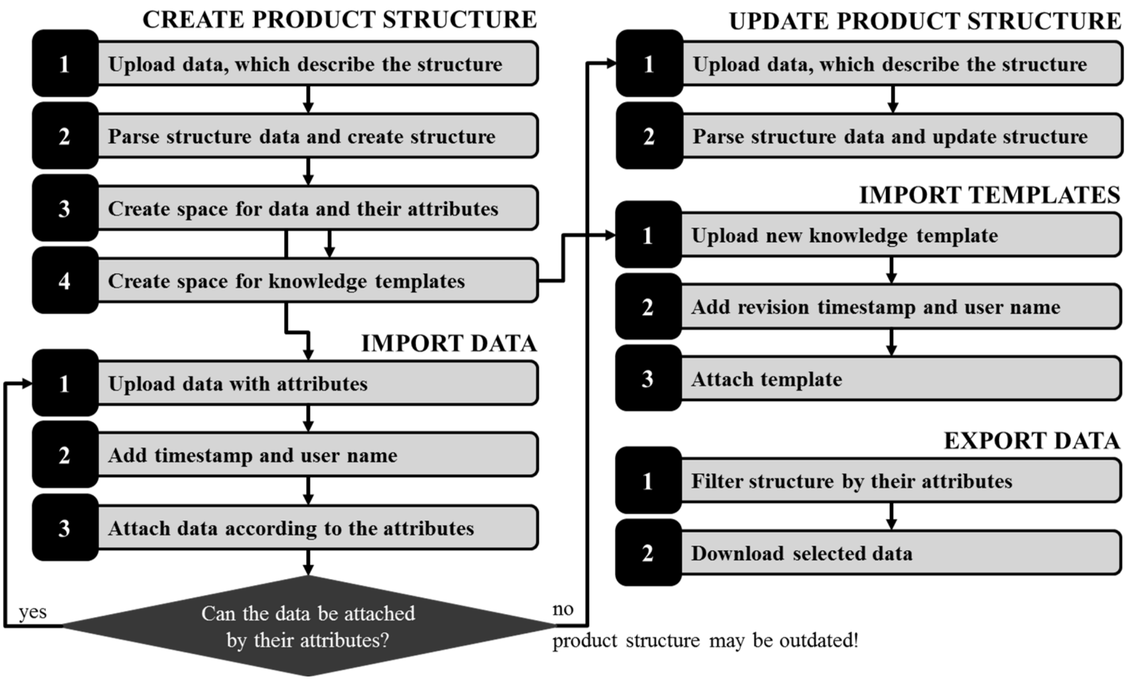

Figure 5. Procedure to create and update the product data model

After the product data model has been created data sets can be processed. The processing includes a plausibility test and the comparison of attributes identified by the data interfaces and attributes, which are related to the variants, assembly or component in the product data model. In case of an inconsistency, the ALARM user is asked to solve the conflict. If the attributes of a data set describe a variant, assembly or component, which is not in the product structure, the product data model may be outdated and needs to be updated. The procedure to create and update the product data model and the import and export is shown in Figure 5. Finally, if all tests are passed, the data set is attached to the product data model described by attributes.

3.5 Product data analysis tool

After the product data synthesis step, analyses can be performed in order to analyse the acoustical behaviour of the product. The product data analysis tools are links between the *distributed, project-based knowledge base* and the *product data model*. The knowledge-base defines, how the data in the product data model is analysed. Each implemented analysis algorithm expects different data types, e. g. eigenfrequencies, excitations, complex spectrums, which are attached to the product data model. The analysis tools handles the different analysis algorithms. In Küstner et al. (2013) four analysis methods have been conceived for the EUREKA-ALARM research project, which are currently being implemented:

- configuration analysis to identify configurations having conspicuous behaviour,
- visual relation analysis between test rig measurements, in-the-field measurements and noise emission measurements,
- transfer path analysis to identify noise sources or emitters, which have an high excitation level or vibration level, respectively,
- an interactive data visualization to let engineers dive into all the kind of available and processed data.

3.6 Product development navigator

The product development navigation tool (PDN) is a link between the *data interfaces* and the *knowledge-base*. The PDN provides the administration dialog of the distributed, project-based knowledge base and navigation dialogue for product developers. Thus, it controls and guides the whole workflow of experts and product developers during the use of the assistance system. The PDN is the tool, which controls all input and output of data sets on the one hand, and the creation and modification of the knowledge-base by adding and removing projects, work packages, activities and decisions on the other. According to Rude (1998) the administration dialog of the EAS ALARM is the acquisition tool as well as the input interface. The navigation dialog is the problem-solving tool, the explanation tool and the output interface.
The PDN is the main window of the graphical user interface (GUI) of the EAS ALARM which the product developers and experts are working with (see Figure 6). Via the GUI, the EAS ALARM users can also access all implemented analysis tools, the product data model viewer (product data model) and the data import tool (data interfaces).

4 THE USE OF THE EAS ALARM AND THE BENEFIT FOR PRODUCT DEVELOPERS

The EAS ALARM is used by experts and product developers, both use the same application. After executing the assistance system, the GUI of the PDN is displayed. On the left hand side all available project templates are displayed (see Figure 6). The project templates represent knowledge bases, which are provided by experts. They describe procedures to prevent or solve noise-related issues after an event in the PDP has occurred. The EAS ALARM users can either edit or execute project templates via an administration dialogue or navigation dialogue respectively. Each project template can be executed independently several times in order to apply it on different data sets.
The administration dialogue is the knowledge acquisition component of the assistance system, where project templates are created or maintained. At first, EAS ALARM users (usually experts) need to add or delete work packages and their activities and decisions. Afterwards connections between activities and decisions need to be added. The sequence of activities and decisions and their connections represent the workflow of an expert. An activity has always one descendant, a decision can have many descendants, which are followed up based on a condition. For instance, if the question for the decision is “Does the elastomer bushing stiffness fulfil the requirements?”, there may be two options (connections which originate from the decision): “Yes” and “No”. Each condition refers to a different activity or decision. Conditions can also refer to activities or decisions which have been executed

before. Thus, design loops can be realized. Each work package, activity or decision has a detailed description to explain in detail what is to do. Finally the type of data, which is required by a decision or generated by an activity, needs to be specified.
If a project template is executed, the navigation dialogue is displayed. After reading the description of the first activity, EAS ALARM users start with the data acquisition. Data either can be downloaded from the product data model or imported from disk and uploaded to the product data model later. Afterwards the acquired data can be process by analysis tools. Each activity is finished by the definition of a result data set (e. g. “Axial stiffness of elastomer bushings =” *50* Nmm^{-2}), which is a conclusion the users have to draw based on analytical findings and the description of the activity. Decisions are made based on result data sets of activities, which have been finalized before and the experts’ description of the decision.
A work package is finalized, if all activities are finished and all decisions are made. Based on all analytical findings and the work packages description, EAS ALARM users need to derive modifications for the product properties to prevent or solve a noise related issue.
If product developers use the EAS ALARM, the following benefits are generated:

- A structured database with all data related to noise in a central database leads to an uniform database for all EAS ALARM users and thus to comparable analytical findings.
- Generated data and analytical findings are shared with other product developers.
- Looking for data in the product model is fast and saves time.
- Due to the concept of the EAS ALARM, knowledge transfer from experts to product developers is guaranteed.
- Feedback from product developers to experts is supervised.
- Design procedures for noise reduction are standardized.

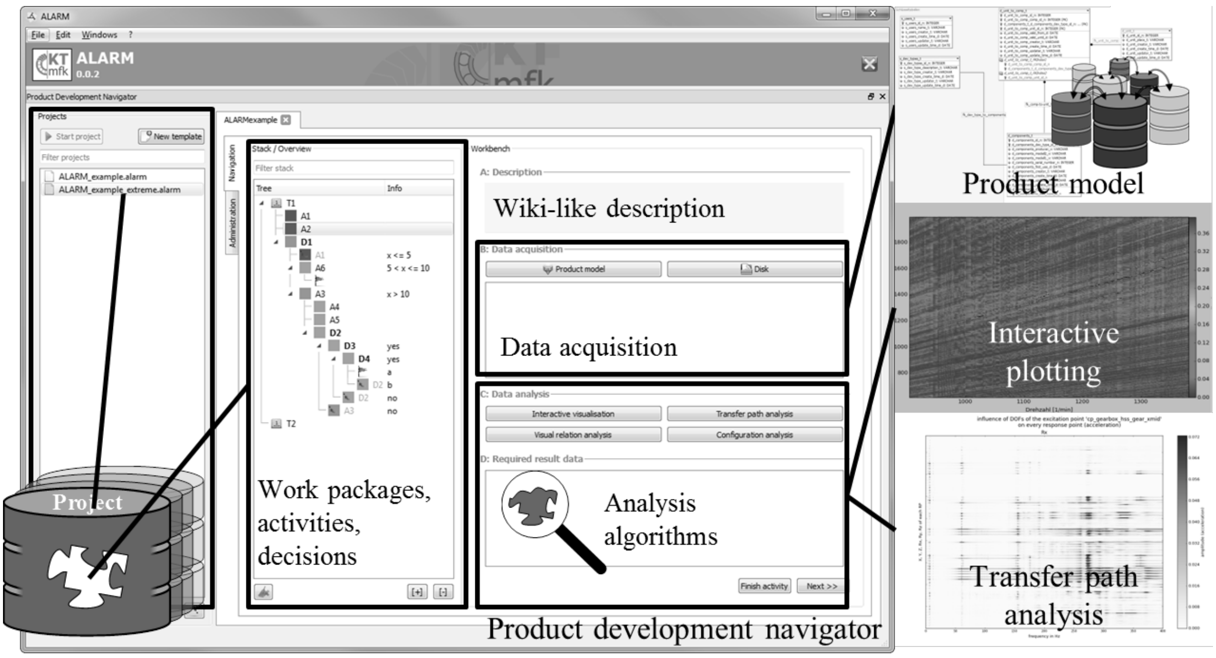

Figure 6. An outline of the graphical user interface of the EAS ALARM (left: product development navigator, upper right corner: product model, middle right: interactive plotting, lower right corner: transfer path analysis)

5 CONCLUSION AND OUTLOOK

This paper presented a new approach and concept of an engineering assistance system for the purpose of supporting product developers in designing noise-reduced rotating machines. It provides expert knowledge to analyse the acoustical behaviour of rotating machines by use of data. The EAS ALARM consists of six components which are responsible for storing experts’ knowledge in a knowledge base, storing data related to the product in question, ensuring the accuracy of used data, controlling data exchange between product developers, providing data analysis algorithms and finally navigating product developers during data analyses. With aid of experts' knowledge and the analytical findings product developers get a deeper understating of the acoustical behaviour to draw the right conclusion for modifications of product characteristics. Hence, product developers are supported in reducing risks for noise related issues like tonalities.

The EAS ALARM demonstrator, which is an implementation of the approach presented in this paper, is currently tested at an associated partner. Product developers and experts give feedback via *user stories* in order to improve the concept and implementation. After the feedbacks have been implemented, the approach and the demonstrator will be validated by using the EAS ALARM demonstrator on issues of another rotating machine. In case of missing features in future applications, the EAS ALARM is extensible, i. e. other analysis algorithms can easily be implemented as well as other data interfaces.

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