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PREDICTING THE BEHAVIOR OF SOLUTION ALTERNATIVES WITHIN PRODUCT IMPROVEMENT PROCESSES

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ABSTRACT

Nowadays an increasing number of industrial products are equipped with sensors, allowing a complete monitoring of the product and its working conditions during the use phase. The data generated by such sensors is mainly used for maintenance purposes. The evaluation of that data can offer valuable input for the improvement of existing product generations.

The presented approach offers a methodology to identify improvement potentials and to support decisions within product improvement processes. This approach is based on prescriptive decision theory and uses feedback data in addition to product-specific characteristics and properties. A prediction of future product solution alternatives behavior is realized on the basis of object-oriented Bayesian Networks. The validation of the proposed solution has been demonstrated on the basis of decision processes for the improvement of centrifugal pumps.

Keywords: product improvement, decision making, prediction, knowledge management

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1 INTRODUCTION

Current industrial products are mature products but have to meet the requirements of several stakeholders. These requirements can be very diverse and change throughout product life. Therefore these products are almost always subject to periodical improvements driven by customers, competitors, users, service providers, new legislative regulations, or technologies.

The increasing use of embedded sensors, condition monitoring systems, and IT-supported maintenance reports leads to a high availability of digital information about current product generations. Nevertheless this information is used for maintenance, repair and overhaul events mainly, to improve the lifetime of a product (Kara et al., 2005; Van Houten and Kimura, 2000).

Current product design research activities mainly address methods and tools for the development of new products (Pahl et al., 2007). The improvement of existing products has been regarded scarcely. The use of product use feedback information for the improvement of future product generations has also been addressed by few research activities (Kiritsis, 2011; Abramovici and Lindner, 2011; Takata et al., 2004). An overview on how product use information can be used is provided by Goh et al. (2009).

Due to the lack of appropriate methods and tools, the improvement of existing products in current industrial practice is chiefly made individually, subjectively, and not systematically. This often leads to suboptimal or over-engineered products.

Numerous available product use information and progresses in knowledge based methods offer new opportunities to optimize the improvement process of industrial products. Therefore the solution proposed in this paper adapts and extends existing general methods and offers a framework for the product improvement process by exploiting available product use information.

2 METHODICAL APPROACH

2.1 Product improvement process

The drivers for product improvements are product failures, deviations in product performance compared to the expectations, new similarly better or cheaper competitive products, new emerging technologies which could substitute current ones, as well as new relevant laws and regulations which affect existing products.

The product improvement process should follow all or some of the same stages as within the process of new product development, including requirement analysis, functional, principle, and embodiment design. Compared to the development process of new products the product improvement process occurs within very strong boundaries and constraints. The product specifications (requirement lists) as well as the basic functional, principle, and embodiment product structures can be taken from the current product generation and are mostly already set.

The requirement analysis is the initial step of a product improvement process. The existing product specification is extended to fit new requirements arising from the drivers for a product improvement. Existing requirements can be changed or cancelled.

Within the functional, principle, and embodiment design existing structures are taken. The product developer can only modify, substitute, extend, or cancel a few items within these structures. These changes require a lot of difficult decisions.

Based on classical prescriptive decision theory the decision process can be performed cyclic, allowing step backwards at any point. The following stages have to be performed (Abramovici et al., 2012):

- *Problem analysis*: Identify the problems and the reasons for the problems. Define the specification.
- *Generation of solution alternatives*: Generate alternatives that have different focuses so that the alternatives cannot replace each other.
- *Evaluation of the solution alternatives*: Evaluate the solution alternatives based on the requirements in the specification.
- *Decision*: Select the most suitable solution alternative.

2.2 Considered Data and Products

Due to the high variety of products and accessible feedback, an initial definition of considered products and feedback is required. Products can be subdivided into the area of consumer goods and industrial goods. Consumer goods indeed have a very short expected lifetime. Very often, the only feedback the provider has access to is highly subjective customer feedback or objective guarantee and warranty cases (Abramovici et al., 2011). Subjective feedback needs to be rendered objectively to further process and provide only such information to the product developer that is true at the moment but may change during product development (Schulte, 2007).

Industrial products create a stronger bond between the provider and the customer, due to new industrial product service systems. It is assumed that these products are improved periodically, and that they are equipped with embedded micro-sensors capturing structured and objective use information (e.g. operational temperature, rotation speed) mainly for condition monitoring purposes (Abramovici et al., 2011). A further assumption is the availability of large sets of product use data for analysis tasks. Hence, feedback is available and much more effective.

The objective feedback can be collected automatically or manually and subdivided into the following groups:

- Technical product data (e.g. power, load)
- Environmental data (e.g. temperature, humidity)
- Operation data (e.g. use time, use intensity)
- Service data (e.g. failure, maintenance)
- Product user data (e.g. use habits, use of specific functions)
- Data about the use (e.g. maintainability, usability)
- Customer data (e.g. surveys, warranty cases)

This data can further be used to analyze the use of an industrial product.

2.3 Related research approaches

State of the art research approaches that consider feedback for the improvement of existing products either address only specific feedback data sources (feedback from product-embedded information devices (Kiritsis, 2011; Rostad et al., 2005; Abramovici et al., 2013), specific feedback data receivers (e.g. feedback for quality improvement (Edler, 2001; Teti et al., 2010), or subjective feedback from customers (Schulte, 2007). Approaches that deliver a holistic approach and address the acquisition, management, processing, and visualization of PUI in product improvement are currently only scarcely considered.

The consideration of product use information for the behavior of products is frequently addressed in the field of condition monitoring or maintenance. Single approaches exist which do classify such product use information and lead this information to the product development (Goh et al., 2009; Abramovici et al., 2011). Still an approach using this information for detecting the causes of a failure and predicting the behavior of a changed configuration within the product improvement process is not known to the authors at this point.

For that reason, an integrated approach for the collection, aggregation, and processing of objective product use data for improving existing products has been missing to date. Especially the use of this data for product behavior prediction is quite new. The Feedback Design Assistant (FDA) outlined in this paper provides methods of supporting the product developer in improving existing product generations by leading and processing data and information from the product use phase into product development.

2.4 Feedback Design Assistant

Based on a concept presented by the authors earlier (Abramovici and Lindner, 2011; Abramovici et al., 2011), an extended concept for a FDA is presented (figure 1). This concept presents new methods within the FDA.

The data generated and collected during the product use is stored in several heterogeneous databases. These databases are placed at the site of the customer. The data stored in those databases is structured but can be redundant. Therefore the data has to be filtered, cleansed of semantic and syntactic defects, and aggregated (Abramovici and Lindner, 2011; Abramovici et al., 2011; Dienst et al., 2011). Common methods such as Extraction, Transformation, and Loading (ETL) can be used. The data is copied by an interface between the FDA and the considered external source databases either periodically (e.g.

daily, weekly), driven by the operation time (e.g. every 100 hours of operation), or by incidences (e.g. repairs, breakdowns).

On the next stage two databases are available for the storage of the results from analysis methods. In these databases also retrospective and prospective data is stored. Retrospective data is data collected and aggregated from the several databases mentioned before. This data will be used to analyze and diagnose the use of the current product generation. Prospective data is data required to predict the future behavior of solution alternatives. This is information about new or changed requirements or new available product configurations (solution alternatives), as well as characteristics of the solution alternatives (e.g. material characteristics and parameters).

The *problem analysis* of the current product generation is performed using traditional retrospective analysis methods for investigating product use data or service data distribution (e.g. failure frequency, maintenance cycles, workload). Here statistical analysis methods can be used (Abramovici et al., 2011).

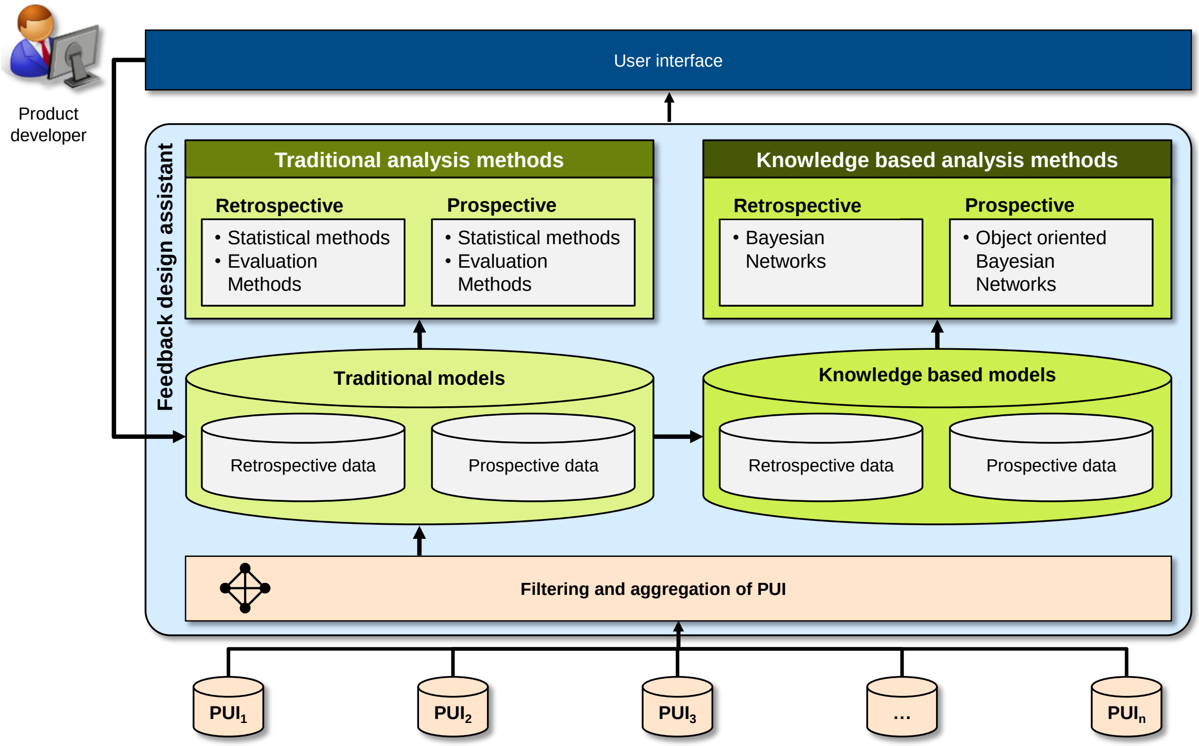

Figure 1. Concept of the feedback design assistant

The use of retrospective knowledge based analysis methods (Bayesian Networks) is the next step. The aim is the detection of the *reasons for the problems*. For example, problem causes can be an unfavorable product operational environment (e.g. an exceeded operational temperature) or a higher product workload than originally expected. These parameters cannot be changed by the product developer. In contrast to these operational and environmental use profiles, the product designer can optimize other design parameters like product type, material, dimensions, or shapes in order to improve the product. This task includes the identification of any mentioned unchangeable parameters as well as that of changeable product features, which cause the identified problems. Here Bayesian Networks (BN) and "What-If" (Lutters et al., 2004) analyses are used (White, 2009).

BN are acyclic graphs, modeling e.g. faults and related influence factors as nodes and their dependencies as directed edges. Each node represents a variable and features an associated conditional probability table (CPT) describing the probabilistic distribution of different variable values. The probabilistic distribution of the target node variable values (e.g. the probability of a fault occurrence) can be calculated from the probabilistic distribution of the parent nodes variable values (e.g. influence factors variables) (Abramovici and Lindner, 2011; Abramovici et al., 2011).

For the *evaluation of solution alternatives* new decision support methods are needed. For this evaluation traditional prospective analysis methods like Cost Benefit Analysis (CBA), qualitative methods like Strength Weaknesses Opportunities and Threats (SWOT) Analysis, or combined methods, like Analytic Hierarchy Process (AHP) or Pairwise Comparison (PWC) could be used. The result of using these general methods is a ranking of the considered solution alternatives, which could be the basis for a preselection or for a final selection of alternatives. These methods are mainly based on the personal subjective rating by at least one product developer. It is not guaranteed that the best rated solution is the best solution under the given operation situations. Later the use of PWC will be demonstrated.
Stating that the operation conditions do not change, the collected product use information can be used within consequence analysis. For this consequence analysis knowledge based analysis methods like object oriented Bayesian Networks (OOBN) can be used. OOBN are extensions of Bayesian Networks, which have additional nodes called instance nodes (Koller and Pfeffer, 1997). These instance nodes represent instances from other networks to integrate a sub network in an existing Network. Here OOBN include additional data and characteristics of solution alternatives into the BN. By adding this data and information to the already used feedback data, a prediction of the future behavior under the known operation situation of a component is made possible. Upon successful checking of all of the influence nodes a final *decision* of a product improvement solution alternative can be made by the product developer.

3 SOFTWARE PROTOTYPE IMPLEMENTATION

The proposed FDA has been implemented in a software prototype. This prototype uses an open source data warehouse system (PENTAHO) for the acquisition, storage, and management of all product use information. The filtering and aggregation of the PUI is realized using KETTLE, which is an ETL-tool and connected to PENTAHO. The open source knowledge representation and inference environment (WEKA) allows the representation of the specific BN and OOBN models and consequence, impact, or "What If" analyses. The strong integration of WEKA and PENTAHO is handy.

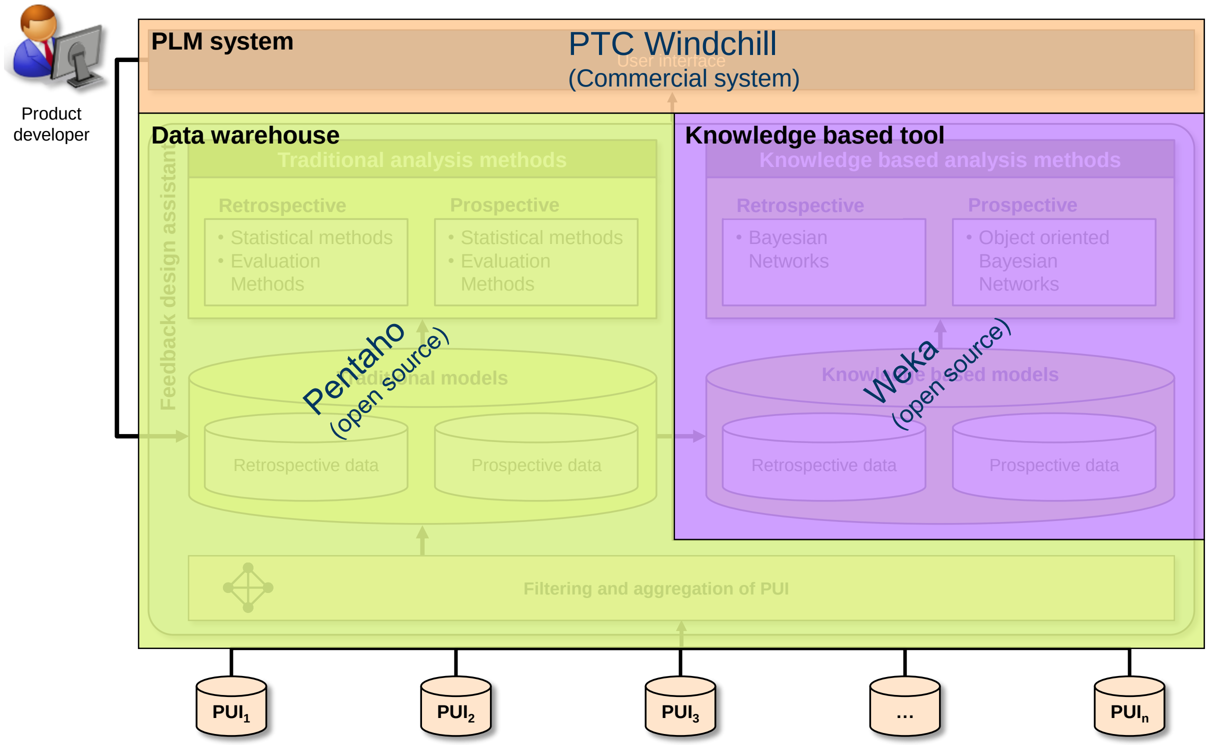

Figure 2. Feedback design assistant prototype

The backbone of the data warehouse data model is the product type structure (Bill of Material), which is imported from the Product Lifecycle Management System WINDCHILL (by PTC) and entered use data collected from all of the monitored product instances. Unfortunately the WINDCHILL data model

does not support product instances in PLM, therefore the data model had to be extended. Instead of extending the data model of the commercial PLM-system WINDCHILL the authors decided to only use the user interface of the PLM-system and integrate the product instance data in the data warehouse PENTAHO due to performance issues (Dienst et al., 2011). This also opened up the opportunity to use the ETL and Report and Analysis functions (including dashboards) provided by PENTAHO.
The traditional decision making methods (e.g. Pairwise Comparison) have been implemented using tools of the PENTAHO system. The report designer allows the generation of dashboard, which are used for the Pairwise Comparison and representation of the statistical failure distribution.

4 METHODS AND TOOL VALIDATION

The use of the developed approach has been validated using centrifugal pumps (cf. Figure 3). These pumps have been determined to be an appropriate validation sample (Abramovici et al., 2011). Centrifugal pumps consist of a pump-unit and a drive (here: electrical drive). As the efficiency of the drive has been exceeded, only the pump is considered a matter of current improvement. The pump, its data, and possible weaknesses have been discussed in (Abramovici et al., 2011).

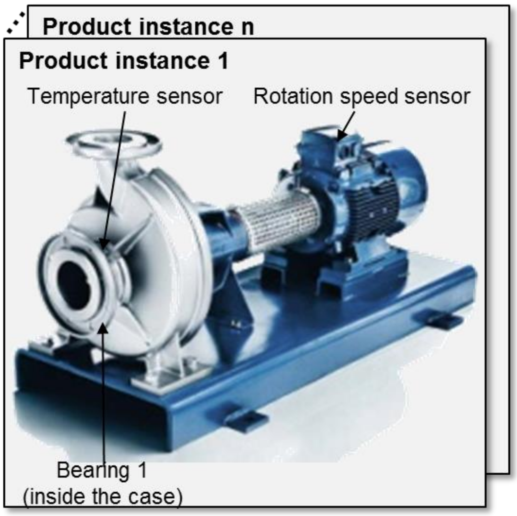

Figure 3. Sample product centrifugal pump and its sensors (Abramovici et al., 2011)

The product use data of the centrifugal pump used in the validation sample has been analyzed using traditional statistical analysis methods and has shown the weakness of one out of two existing bearings. Subsequently, the bearing had to be exchanged more frequently than expected and has thus been a subject in product improvement (Abramovici et al., 2011).

Table 1. Pairwise comparison of different bearing solutions (example)

		Decision alternatives							
Improvement objectives (decision criteria)	**Weight**	**Groove bearing**		**Cylinder bearing**		**Roller bearing**		**Needle bearing**	
Existing requirements		**SR**	**WR**	**SR**	**WR**	**SR**	**WR**	**SR**	**WR**
Reliability (>90%)	8	1	8	2	16	4	32	2	16
Mean time to repair (<1h)	18	3	54	3	54	3	54	4	72
Installation costs (<200€)	6	4	24	4	24	4	24	5	30
…	…	…	…	…	…	…	…	…	…
New Requirements									
Long lifetime (>10.000h)	9	4	36	4	36	5	45	3	27
Mean time between failures (>30d)	14	5	70	3	42	3	42	2	28
Disposal cost (<50€)	2	5	10	5	10	4	8	1	2
…	…	…	…	…	…	…	…	…	…
Sum of weighted rates (%):	100	326		314		**426**		264	
Ranking:		2		3		**1**		4	
Fulfillment compared to the existing solution: 1-2: worse; 3: equal: 4-5: better									

SR: Simple Rates; WR: Weighted Rates

The requirement list for the next generation product therefore names the point to solve the problem with the bearing. To solve the problem of frequent breakdowns, four solution alternatives have been developed by a product developer (cf. table 1). These solutions have been developed within boundaries, as the layout of an existing product cannot be changed completely. Here the use of other bearing types was preferred, rather than editing dimensions, materials or parameters. These alternatives have been evaluated by another product developer according to the requirements of the requirement list. Here the pairwise comparison has been used. Every requirement is weighted and the sum of all weights must sum up to 100%. Then the fulfillment of every decision alternative compared to the initial solution (ball bearing) and to a single requirement is rated ranging from 1 (worse) to 5 (better). These single rates are multiplied with the weights given the requirements. The sum of all weighted rates indicates the suitability of a decision alternative. The highest value indicated the best suitability. Choosing a roller bearing has been found to be the best solution. In this example the pairwise comparison is supported using an excel-sheet, a support using dashboards derived from PENTAHO is possible as well.

Now a prediction of the behavior of the chosen bearing type can be made to verify the decision derived from the pairwise comparison (cf. Table 1). Figure 4 displays the OOBN for the validation sample. Here the different developed alternatives and additional characteristics (e.g. materials) have been added.

The FDA therefore provides a double checking of the different solution alternatives. The first performed pairwise comparison delivers results based on the experience of product developers. The OOBN uses objective use data, hence it is expected, that the solution found will be suitable for solving the named problem. The quality of the OOBN still is strongly connected to the amount of data available, as a large set of data increases the quality of the results. Thereby the risk of inefficient improvement is on the one hand minimized by the double checking process, one the other hand by a large set of data.

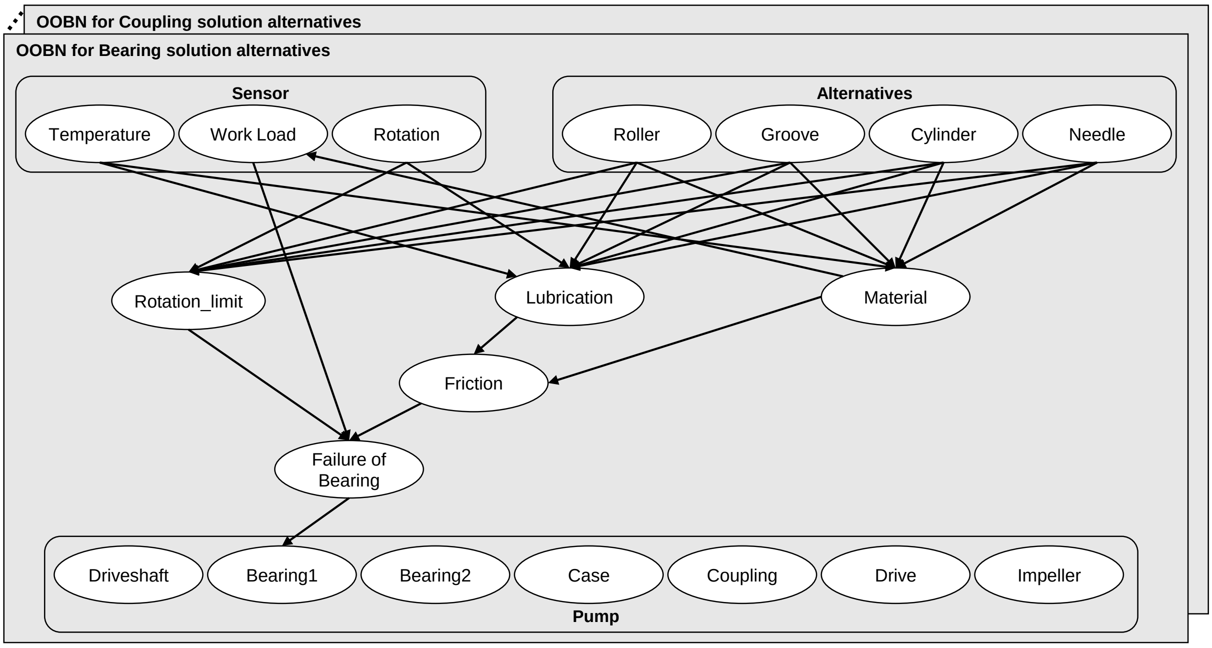

Figure 4. OOBN designed for predicting the behavior of bearings within centrifugal pumps

The OOBN consists of four parts. In the top left of the figure the object “sensor” is placed. The sample product is equipped with sensors for measuring temperature, work load, and rotation (here only the sensors relevant for the bearing are listed). The data have been collected during the use of a large number of product instances. The CPT calculated for the BN used for diagnosis tasks are fixed and are not changeable by the product designer. Those CPT reflect the real life operation environment the new bearing solution alternatives will experience. On the top right the object "alternatives" is displayed. Here the developed solution alternatives are presented. On the bottom of figure 4 the components of the sample product are listed within the object "pump". The middle of the figure displays on the one hand nodes for characteristics of the alternatives (e.g. material and rotation limit), and on the other hand nodes for characteristics influencing the use parameters of the product (e.g. lubrication). These nodes bond the three objects and the edges show the dependencies between them. All those factors lead to one event, which is the failure of the bearing 1. Figure 4 displays the basically layout of the OOBN. For other components of the pump individual OOBN have to be designed.

The OOBN has been built for the existing bearing type (ball bearing). The nodes CPT displayed in the middle of the OOBN will change for every solution alternative but the sensor values will be true for every solution alternative as they display the operation environment the bearing we be used in. To predict the use the different solution alternatives an individual BN for every alternative has to be derived from this OOBN.

Using the tool WEKA a BN is generated for every bearing solution alternative. The structure of the BN is taken from the OOBN and the probability distribution for the event "Failure of Bearing" is learnt. The probability distribution depends on the distribution of the product use information, which is fixed and cannot be changed by the product developer. The characteristics as e.g. material can vary from solution alternative to solution alternative. Therefore CPT values for the event "Failure of Bearing" vary in the BNs.

Now a What-If analysis can be realized, to simulate what is happening if the new alternative is in use. For example on the node "*Temperature*" the probability for "high" is set to 100%, the probability distribution of the connected nodes is recalculated e.g. the node "*Material*" the probability for steel increases. That indicates, that the expected success increases, if the product developer chooses the material steel.

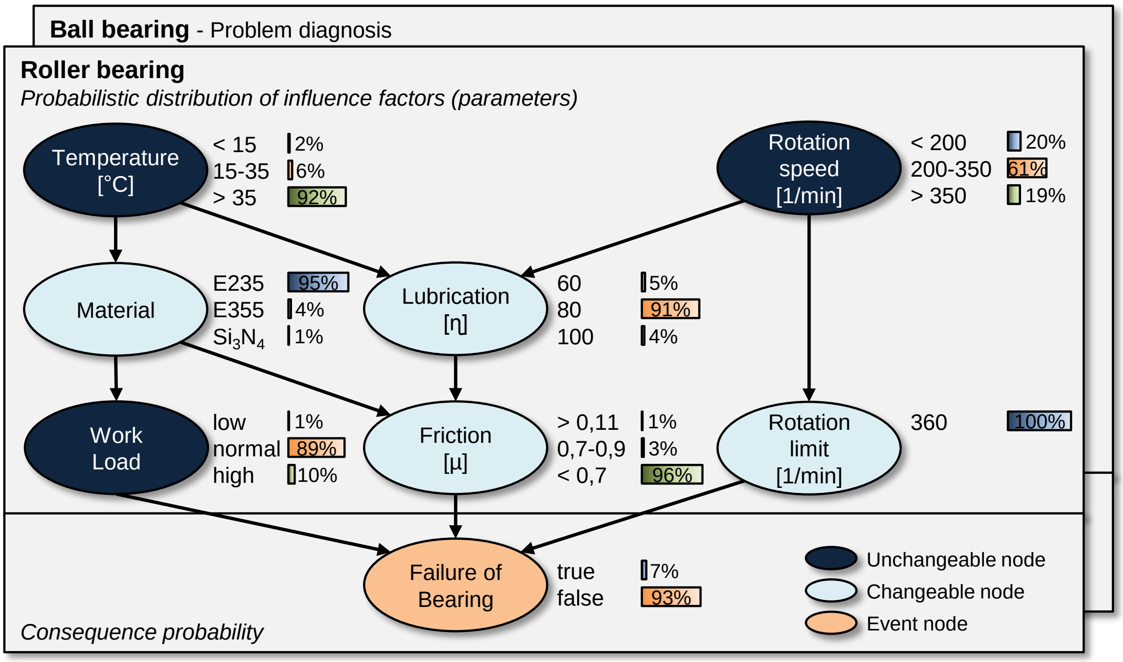

Figure 5. Bayesian network for the solution alternative "Groove Bearing"

For the initial set up of such an OOBN and the derived BN the product developer can be supported be an experienced engineer. Once the OOBN has been built, the product developer can manipulate the values himself. The OOBN is used for consequence, impact, and "What If" analyses. Here the impact of e.g. different roller bearing materials or even different bearing types (see solution alternatives) can be determined. Thus using the OOBN the product designer has the opportunity to check the assumptions made earlier when performing the pairwise comparison. Specific influences prior unknown to the product developer will appear and affect the CPT of the event node. At this stage the product designer can revisit his assumptions and update the design accordingly.

5 CONCLUSION AND OUTLOOK

The paper in hand has presented the concept, design, and prototype of a Feedback Design Assistant. Product use information are collected from several industrial products and aggregated in one central database. The retrospective analysis methods and tools are used to analyze the use of a current product generation. Weaknesses and the reasons for those weaknesses can be detected based on these methods.

The focus of the paper has been on the prediction of the behavior of solution alternatives within decision support. The presented prospective methods assist the product developer in choosing solutions alternatives for identified problems. Therefore, the risk of inefficient improvement has been minimized as the product developer can estimate the impact his changes will have on the product.

In future, the FDA will be extended to process structured and unstructured data. Especially unstructured textual data from service engineers should be available in the FDA as well. Here text mining methods will be used and the text data will be bonded to product components. It is expected that a lot of crucial information is hidden within service data. At present, that data is only scarcely used for product improvement.

In addition, new methods of visualization for this new information to the product development teams need to be elaborated. The state of the art implementation is suitable for product developers only. While working in large development teams, the information has to be accessible to all members of the team in very short time and in a comprehensible way. Digital engineering visualization methods could deliver solution initiatives. In this further framework, methods of data, information, and knowledge visualization will be combined with those methods of digital engineering visualization, to provide an even better solution.

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