DECISION SUPPORT FOR IMPROVING THE DESIGN OF HYDRAULIC SYSTEMS BY LEADING FEEDBACK INTO PRODUCT DEVELOPMENT

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ABSTRACT
Hydraulic systems are used in great numbers and serve a variety of purposes. Still, however, the operating efficiency of hydraulic systems is not as high as it could be. New ways of monitoring the product use provide opportunities to maintenance. Through industrial product service systems the acquired product use information can be lead back into product development where it can be used to improve the development and quality of follower products. This paper presents a concept for leading feedback into product development and the state of implementation of a feedback assistant for decision support using statistical analysis methods and Bayesian Networks as a diagnosis and simulation method. The methods used have been validated on a centrifugal pump as an often used model hydraulic system.

Keywords: Product Use Information, Product Development, Hydraulic System, Feedback Assistance System

1 INTRODUCTION
For several years the need for a stronger relationship between manufacturers and customers has been increasing. In industrial areas this task is fulfilled by using Industrial Product Service Systems (IPS²), whose number is increasing steadily [1]. IPS² combine material products and services and provide benefits for both parties. Besides the high flexibility, which is the most frequently advantage referred to, IPS² allow the manufacturer to obtain access to product use and product use data, i.e. Product Use Information (PUI).
Also, in Condition Monitoring innovations have been achieved in recent years. Most importantly, price degression and smaller overall sensor size [2]. Due to stronger IT (Information Technology) linkage within companies, sensors can be used for Condition Monitoring (CM) and for the support in maintenance issues during product use. CM data, however, is not passed on to other departments of the company.
The described changes may lead to changes especially in the area of hydraulic systems, as these are able to achieve operational efficiencies of more than 90%. Genuine use does not exceed efficiencies of 80%, though [3]. The classic supply business cannot meet the requirements for operating hydraulic systems at high operational efficiencies.
Some research approaches address the use of Product Use Information, mainly for the monitoring of current product state, wear analysis, extension of product lifetime, and for improving the ecological impact of the product use [4, 5, 6].
This paper presents an approach for leading feedback into product improvement to improve follower product generations. It introduces radial centrifugal pumps as a typical representative of hydraulic systems. Furthermore this paper outlines the analysis and diagnosis of PUI by the prototypically implemented assistance system.

2 LEADING FEEDBACK INTO PRODUCT DESIGN FOR DECISION SUPPORT
Two kinds of feedback have to be mentioned: 1) Subjective feedback. For the acquisition of retrospectively subjective customer data, several marketing-driven approaches exist (e.g. user design, Kano method, Quality Function Deployment, or Conjoint Analysis) [7]. 2) Objective feedback. Objective data (also: field data) is acquired sporadically e.g. by sensors, service staff, and operational personnel [8]. The degression of sensor prices, as well as their smaller size, qualifies sensors for

embedded use within products for the purpose of condition monitoring of critical components in preventive maintenance [8].
Objective feedback (here: Product Use Information, PUI) can be subdivided into the following groups:

- **Sensor data of the machine:** Data acquired via sensors during e.g. Condition Monitoring
    - operational parameters (e.g. rotation speed, temperature, oscillation)
    - resource consumption (e.g. energy, material)
    - use incidents (e.g. failures, breakdowns)
- **Sensor data of the environment:** Any data that directly affects the immediate machine environment and impacts on its operation
    - operational environment (e.g. temperature, pressure, humidity of the ambient air)
    - workspace information (e.g. parent assembly, influencing neighbor components)
- **Data generated by service staff:** Any data generated during service activities (e.g. maintenance, overhaul, replacement of components, type of failures/breakdowns)
- **Data about the service staff:** Any data concerning the service staff (e.g. qualification, personnel data, workload)
- **Quality parameters:** This data can be generated both automated and through staff, and comprise any data relevant to the quality of the production (e.g. failure rate, post processing rate)

During the use of several product instances of the product generation *m*, PUI is generated and stored in numerous heterogeneous databases (Figure 1), which are customer-implemented or part of commercial software systems (e.g. ERP, CRM-System) [9]. Depending on the customer, the systems used can vary; therefore a well-known and open data format must be used to collect the feedback of the several sources in one central database in which all information generated during the product use of all product instances is stored. After applying analysis and diagnostic methods, the results are displayed to the product developer in a user-friendly and easy-to-handle user interface.

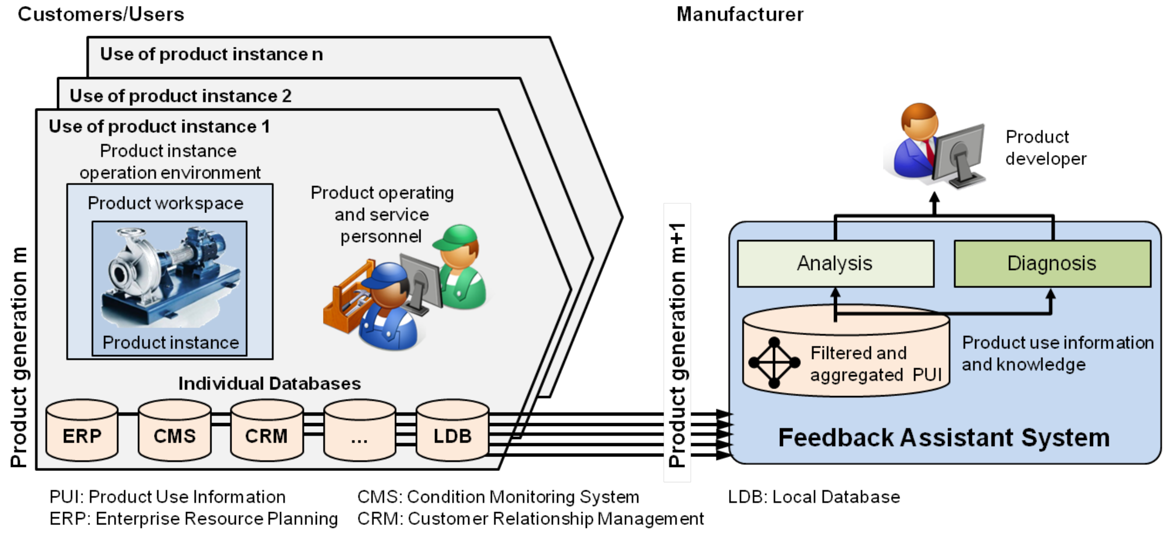

Figure 1. Leading Product Use Information back into Product Development

The PUI is the basis of the knowledge-based assistance system, which is coupled with a system-specific interface in a Product Lifecycle Management (PLM) system (Figure 2). PLM is an integrated approach that comprises a consistent set of methods, models, and IT tools for managing product information and engineering processes along the various phases of the product lifecycle [10]. It is aimed at global, interdisciplinary collaborations between manufacturers, suppliers, partner companies, and customers [11]. The PLM System is the system the product developer uses during the development phase, including product improvement. It is a well-known system to them, which includes all required information (e.g. CAD). That is why the PLM is used as the graphical user interface for requests, e.g. in the form of graphical models.
The Feedback Assistance System is based on a Data Warehouse (DWH), which is coupled to a PLM System (Figure 2). The DWH uses an adapted PLM data model, which is based on the STEP

specification. As the PLM and DWH are coupled, some PLM-Methods can be transferred, such as the PLM user management or the PLM data identification.

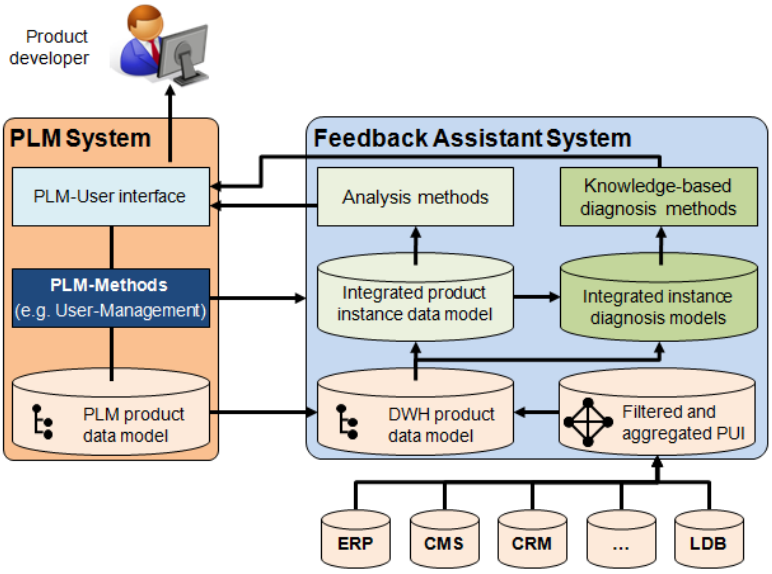

Figure 2. Concept of the Assistant System

The PUI is transferred from the heterogeneous customer databases into a central database of a DWH. Here the DWH-Method Extract, Transform and Load (ETL) is used for filtering and aggregation of the PUI (e.g. filtering of outliners).

The PUI is then transferred to fit the product instance data model. From here, product developers can analyze the data. Traditional analysis methods are used within the analysis module.

Furthermore, knowledge-based instance diagnosis models can be generated by using learning algorithms (e.g. Bayesian Network (BN) [12]) [13]. BN, which are based on the probability and graph theories [14], can be analyzed within the diagnosis module with the functions of the knowledge discovery component of the assistance system, such as aggregation (merging multiple graphical models to extract universally valid product information).

In this way the product developer can derive product improvements and potentials of multiple product instances of one product generation. For instance, the probability of a failure by a heating will increase if the oil pressure drops, which is visualized in a graphical model by using a What-If analysis [13]. If the falling oil pressure is often the reason for a failure of the heating, the product developer decides that the component responsible for the oil pressure is to be improved. A decision is a choice between alternative possibilities for action, which results in complex decision-taking situations, which deal with multiple input factors and a number of alternative solutions [15, 16]. The aim is to support decision-makers through the use of a system, but not to automate the process [17].

A prototype of the Assistant System has been realized by using Siemens' PLM-System Teamcenter Engineering [2]. Due to the architecture of Teamcenter Engineering, a PLM-System is used, which is based on a service-oriented architecture (PTC Windchill) for further realization. The further paper deals with the questions of the implementation and shows the already implemented analysis and diagnosis function for product developer for the sample product of a hydraulic system.

3 SAMPLE PRODUCT HYDRAULIC SYSTEM

3.1 General Description of hydraulic systems

Hydraulic systems are used for transporting incompressible fluids by increasing the pressure and velocity of a fluid. For this task mainly pumps are being used. Most commonly are centrifugal pumps. Basically centrifugal pumps consist of a (volute) chamber, an intake (suction side) and outlet (pressure side). Within the chamber the fluid is compressed or accelerated via an impeller, hence pressure and velocity of the fluid at the outlet are higher as at the intake. Pumps are used

- in open systems (e.g. pipe lines),
- in closed systems (e.g. central heating),

- for conveying fluids from great depth (e.g. oil production) or
- for actuating purposes (e.g. car braking system).

The pump itself is powered by a drive. In most cases, an electric motor is used for actuating the pump, but also pneumatic or combustion drives are used.
Centrifugal pumps are common hydraulic systems and often used because of their high efficiency and simple design. Due to their common use, they are a good option as a sample product.
The pump itself can reach efficiencies of over 90%, which depends on the quality of its dimensioning and the availability of an optimal pump for the existing challenge. In practical use this high efficiency is not reached. Instead, efficiencies of 80% are more realistic [3].

3.1.1Elements of a hydraulic system

The motor drives the pump via its pivoted driveshaft, which is mounted on two bearings and drives an impeller (Figure 3). The impeller sucks the fluid on the suction side and forwards it with higher pressure to the pressure side. All mentioned parts are installed in the volute chamber, which has to be sealed. The pump is connected to the piping system by the upstream and downstream pipe flanges.

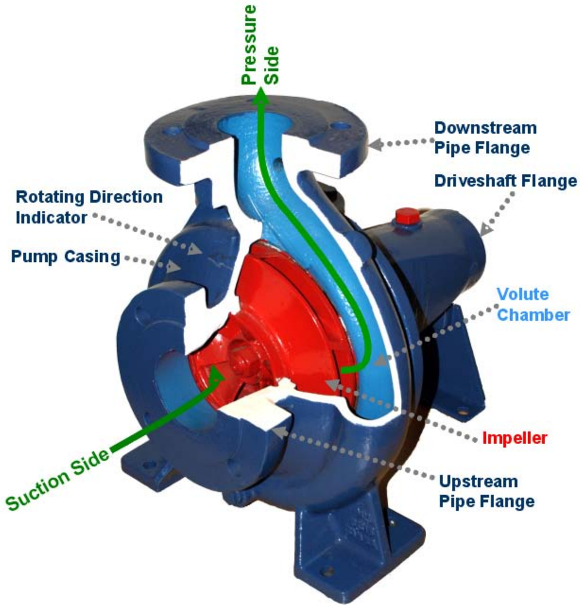

Figure 3: cross-section of a centrifugal pump, cit: Wasserwerk Delmenhorst

In most cases pumps are produced in type series [18]. Hence, there is a basic design with a range of sized models, which have to be used to cope with all different kinds of uses, such as different pressures, different flow rates.

3.1.2 Construction of centrifugal pumps

A basis for the dimension of a pump is the function of the pumping head according to its flow rate. The pumping head is the height conforming to the complete pressure drop in the piping system. To specify this value: it is the pressure drop divided by the density of the fluid and gravitational acceleration. This function has to be identified by the manufacturer. Most commonly this happens via a diagram in which the function of the piping system's pumping head according to the flow rate can be added by the product developer. The intersection point of the two functions is the working point of the pump at a specific drive speed. [3]

3.1.3Possible damages of pumps

Typical damages of pumps can be categorized in the following instances [19]:

- **Dry run:** If the suction side of the pump doesn't get enough fluid, the pump runs dry. In the following, the bearing overheats and is at risk of sustaining damage at the bearings.
- **Overheating:** If the pressure side is blocked or a valve at the pressure side is closed, the fluid circulates in closed cycle in the volute chamber. The energy provided by the shaft gets

transformed to thermal energy. The result is an overheating of the fluid and the pump. The biggest damages will occur at the bearings.

- **Cavitation:** Cavitation is the result of low pressure at the suction side. When the pressure falls under the vapor pressure of the fluid, vapor bubbles appear. As vapor has a higher specific volume than any liquid, pressure rises again. The result is a high-frequent pressure variation attended by hydro jets, which damage the impeller and the chamber in a fatal way. Pumps equipped with floating bearings can take damage by cavitation at the bearings so that imbalances occur in the further run.
- **Blockage:** If deposits block the impeller, the flow and the operations of the pump stop. The result is a standstill. In some cases the impeller or the seals can be damaged by a blockage.
- **Impact damage:** In some cases deposits or foreign objects can cause impact damage without blocking the impeller. In this case the impeller gets damaged inevitably.
- **Casing corrosion and/or erosion:** Some fluids can corrode the casings of a pump. Corrosion can also affect the impeller.
- **Leaking external seal:** When a seal is not installed correctly, the result can be a shorter lifetime (e.g. of the bearings) than expected.
- **Maintenance errors:** Also the human factor can cause a reduction of lifetime. Examples can be the installation of wrong gaskets or improper cleaning processes.

In view of the types of damage mentioned above, most of the damages will affect one of the following parts:

- impeller
- bearings
- seals
- coupling

Therefore, these parts have to be monitored to identify damages and errors, which may reduce the operating efficiency or even may lead to breakdowns of the operation of the pump.

3.2 Sample centrifugal pump

The sample hydraulic system is displayed in the following figure. The drive is an electric engine, which can be assumed to have an operating efficiency of approximately 98% [3]. Therefore, an improvement of the drive is not the central aim of this work and thus not considered.

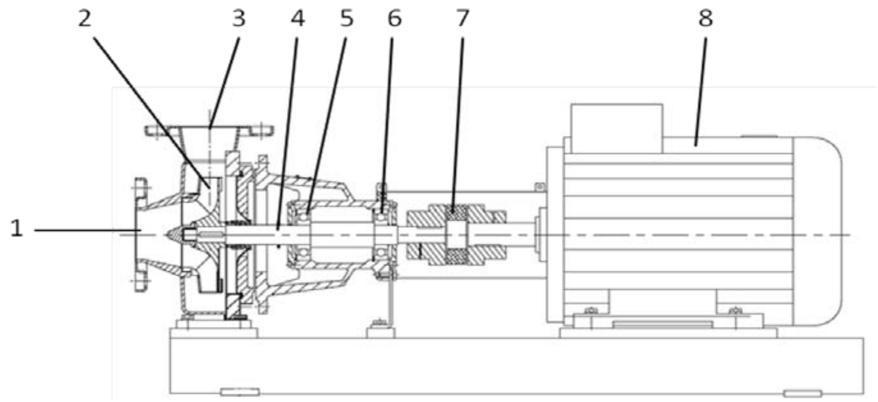

Figure 4. Sketch of the sample centrifugal pump [18]

The displayed centrifugal pump is equipped with several embedded sensors for the following measurements (see Table 1):

1. **suction side:** temperature (*ts*), pressure (*ps*); Sealing 1
2. **impeller:** rotation speed (*fi*)
3. **pressure side:** temperature (*tp*), pressure (*pp*); Sealing 2
4. **driveshaft:** no sensors attached
5. **bearing 1:** temperature, vibration (*s1*)
6. **bearing 2:** temperature, vibration (*s2*)
7. **coupling:** no sensors attached

8. **electrical drive:** rotation speed (*fd*)

For a complete monitoring of the centrifugal pump additional data is required. This data is also collected via sensors, as well as by the service staff (e.g. maintenance reports), and listed as follows:

- operational data: time of use, load during use
- use incidents: time of failure
- data generated by service staff: kind of failure (incident, cause)
- environmental data: temperature (*te*)

The data is stored in several databases (Condition Monitoring database, Service Staff database). Datasets are generated periodically (here: once a day). Additional datasets are generated for incidents (e.g. breakdowns). For the clear identification of every dataset, the datasets inherit timestamps providing the date and time the datasets were generated.

Table 1. Excerpt from the Product Use Information

Date	time	ps	pp	ts	tp	te	s1	s2	fi	fd	Incident	Cause
25.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	237,5	237,5		
26.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	238,5	238,5		
27.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	229,0	229,0		
28.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	232,8	232,8		
29.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	235,5	235,5		
30.09.07	6:00	1,07	3,03	31,53	40,46	24,92	7,10	5,82	229,4	229,4	breakdown	bearing 1
30.09.07	7:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	232,8	232,8	cleared	
30.09.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	230,8	230,8		
01.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	230,0	230,0		
02.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	229,3	229,3		
02.10.07	14:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	236,6	236,6	maintenance	
03.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	231,0	231,0		
04.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	232,3	232,3		

The PUI in Table 1 is generated for a pump working in an air-conditioned environment. The main requirements are high efficiencies (>86%) and mean time between failures (MTBF) of 40 days or more. This derivative data is not stored in the database and generated during the use of the feedback assistance system using analysis methods.

4 USE OF THE FEEDBACK ASSISTANCE SYSTEM

During the product development of a follower product generation the Feedback Assistance System supports the product developer on two main tasks:

- First the developer is supported in finding weak points of the parent generation,
- second in identifying appropriate actions for the removal of weak points.

Weak points of a product generation can be frequent breakdowns of components as well as requirements which are not met (anymore) due to changing customer requirements or system failures [20]. The identification of the weak points is task of the analysis module (Figure 5). The identification of improvement actions is fulfilled by the diagnosis module.

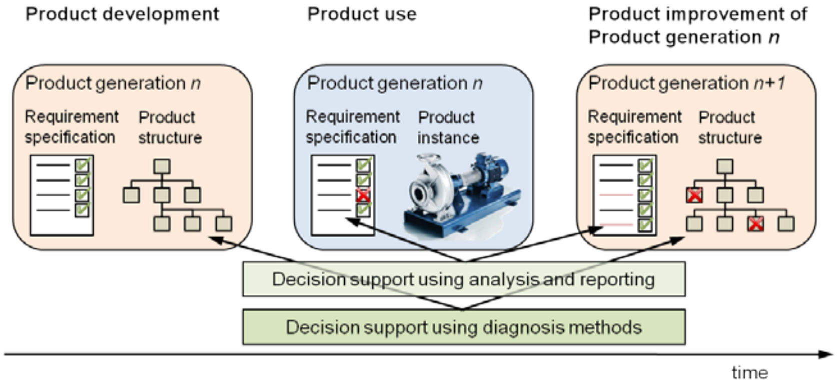

Figure 5. Decision support by using the analysis and diagnosis module

During the analysis phase of the product development the requirement specifications of the follower product generation are constructed by transforming the requirement specification of the parent generation [20]. Only modified or new requirements have to be adopted and added. Changes occur due to shifting customer requirements, new guidelines, engineering standards or technical expertise [20]. Also unexpected system or component behavior (e.g. frequent breakdowns) can lead to additional requirements. The analysis module supports the product developer in analyzing the requirement specification of product generation *m* to determine for the requirement specification of product generation *m+1*, if all requirements are still met, new have to be added, or other improvements are necessary.

The diagnosis module then supports to decide how the improvement of the follower product generation according to the requirements can be performed. Especially during conceptual and form design phase the product developer is supported by the diagnosis module and its functions (e.g. What-If-Analysis) [20] as room of action can be found and support can be given for finding possible solutions.

The modules are described in the following subsections.

4.1 Analysis Module

The analysis module provides traditional data analysis methods for the product designer. They are:

- data searching and retrieval,
- compression of data,
- statistical distribution,
- visualization of results, and
- report generation.

For easier use templates of generated reports [21] and data analysis can be stored and filled with data of different datasets.

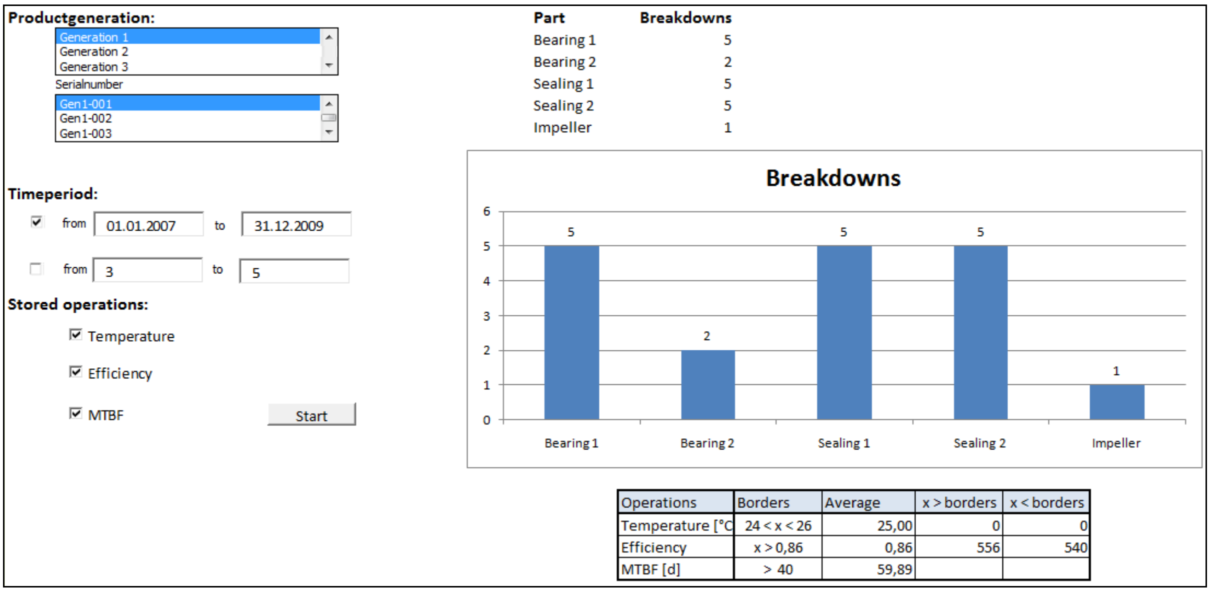

Figure 6: graphical interface of the Assistance Systems analysis module

Figure 6 shows the user interface of the analysis module. Here the data of several product instances of one product generation at a time can be chosen for analysis. Additionally the time period as the time for evaluation can be chosen as well, giving the product designer two options: First he can select a date, second he can select the duration of operation. The duration of operation is to be chosen monthly and always starts at the date of the start of use. Therefore, if two product instances are chosen and in the report the duration of operation “1” to “2” is set, the data recorded in the first two months of the operation of each product instance will be used for subsequent analysis.

Also the breakdown of components (parts) is displayed, which are presented in two different ways:

- first there is a table showing the number of breakdowns of the components;
- second there is a diagram displaying the number of breakdowns of each component, which had a breakdown.

Under “stored operations”, the analysis operations generated earlier by a product designer are stored. In the model, three analyses were stored. The results of the analysis are listed under the breakdown diagram. The first analysis operation generated considers the ambient temperature (at an average of 25°C). Here, a statistical evaluation is performed and the statistical distribution is presented (“x” representing the taken data, in the selected time period 1096 datasets were taken). The second analysis calculates the operational efficiency for every dataset and also presents the statistical distribution (borders 0.86 to 0.96; operational efficiency too low in 540 cases, as desired in 556 cases). Third, the last analysis operation calculates the mean time between failures (average of 59.89 days). As the requirement efficiency is not met, it has to be determined how the efficiency can be increased.

4.2 Diagnosis Module

The second module is the diagnosis module, which enables the product designer to perform knowledge-based requests. For diagnostic purposes, Bayesian Networks (BN) have been found to be an adequate solution among various knowledge representation approaches and knowledge discovery algorithms (i.e. rule-based, tree-oriented, Artificial Neural and Bayesian Networks) [22]. A BN is a probabilistic graphical model that represents a set of variables and their probabilistic dependencies [13]. Principally, BNs are directed acyclic graphs whose nodes represent variables, and whose edges encode the conditional dependencies among the variables [23]. The advantages of BNs are an easy visualization and interpretation of cause-incidents-relationship (e.g. product breakdown) and the performance of knowledge-based request (e.g. what-if). BN are described in detail in [2].

For the generating of BNs the open source tool Waikato Environment for Knowledge Analysis (WEKA) developed at the University of Waikato, New Zealand, has been used. The component of the WEKA “weka.filters” allows the user to group the PUI into intervals. In the example (Figure 7) five intervals were generated (temperature bearing 1: Interval 1: 0.0°C to 30.51°C, Interval 2: 30.51°C to 31.52°C, etc.) as it has shown that five intervals are appropriate for diagnosis purposes. The weka.filters package incorporates classes that transform datasets by removing or adding attributes, resampling it, removing examples, etc. [24]. The uploaded PUI is saved in a database and can be numeric or true-false events (e.g. breakdown). WEKA can be connected directly to the PUI database stored in the DWH. Out of the selected PUI (by product developer) diagnosis models are learned using the machine-learning algorithm LAGD Hill Climbing. The result is a XML-file which was saved in both systems in PLM and DWH. The amount of data for learning a BN is limited within WEKA. But it is possible to learn several BNs and aggregate the probability distribution of individual diagnosis models with the Linear Opinion Pool (LinOP) [22, 25].

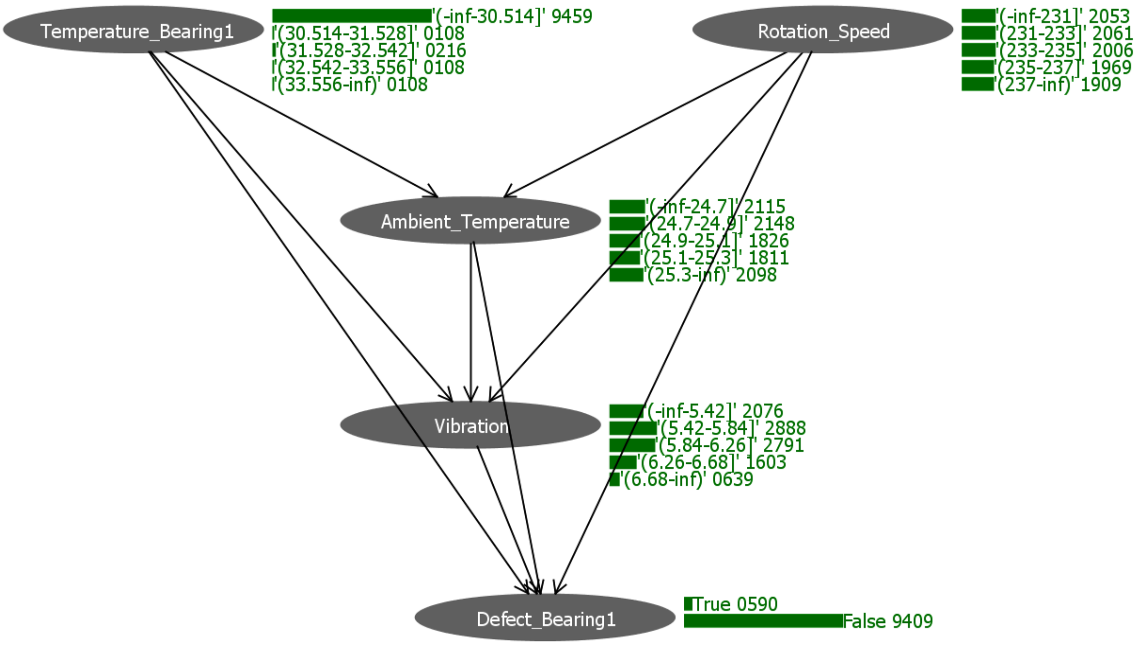

Figure 7. Bayesian Network of bearing 1

Figure 7 displays the BN learned for the incident “defect of bearing 1”, as the defect of the bearing 1 is the main cause for poor efficiencies. The influencing parameters (ambient temperature, rotation speed, vibration and the temperature of the bearing 1) have been chosen for learning the BN.
A statement about the certainty of a state of an attribute is called evidence [12]. This state occurs at a probability of 100% and the directed edges determine the causal dependencies as well as the flow of information in the network [22]. This also means that setting types of evidence to all nodes within a BN, which are connected to each other, has an effect, and thus spreads the probabilities under the given evidence [23]. On the basis of a BN, a What-If analysis is performed by changing the evidence and observing the dependencies and changes of the probability distribution of the other nodes [22].
Figure 8 shows the evidence on the *“Defect Bearing1”* node is set to “True”. It is of great interest to observe how the probabilities of the nodes have changed compared to the nodes in Figure 8. It is obvious that vibration in bearing 1 (*Vibration*) and temperature in bearing 1 (*Temperature_Bearing1*) are the most influencing variables on/to the bearing 1. This shows, for example, that the probability has increased from 1.15% to 52.08% if the “*Temperature_Bearing1”* is in the interval [33.55; 42.0] °C. Therefore it can be assumed that decreasing the temperature in bearing 1 could be a suitable solution for preventing the defect of bearing 1 and thus increasing the efficiency.

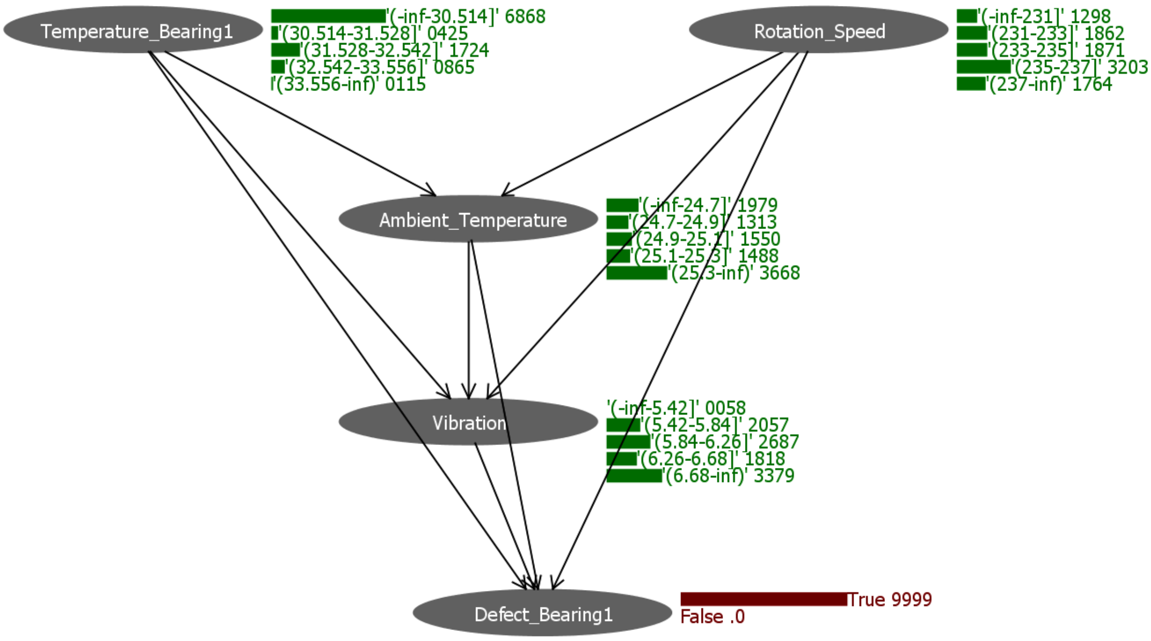

Figure 8. What-If-analyses for the defect of bearing 1

5 SUMMARY AND OUTLOOK

The paper has presented a knowledge-based feedback assistant for the decision support in product development. For the product developer, two modules have been implemented, which have shown their feasibility in analyzing and diagnosing feedback from the product use phase for decision support during product development. The Long during search for weak points and improvement actions can be shortened and results improved by using the feedback assistance system for decision support and design improvement. The basic problem in developing and implementing the assistant aystem is the large amount of data needed to operate the system. Therefore, existing datasets have been enlarged for the detection of a proper learning algorithm for the product sample shown above.
In future works, additional analysis and diagnosis methods will be implemented. Thus the developer is provided with alternatives to analyze PUI. Moreover, analyses will be done on how ontologies can be used for the decision support in product development and implemented in the feedback assistant.
The then implemented analysis and diagnosis methods will be useful not only for the product development, but also for other divisions of the company, such as the maintenance or purchasing department.
In view of the general shift away from product-selling to service providers, new business models (e.g. availability-oriented business models) can be generated by using the aggregated data. The aim is to optimize the use of the product and to reduce standstills. Additionally, new business models would

lead to a closer relation among manufacturers and users, which may well have a positive influence on the provision of PUI.

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