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# Challenges and Strategies of Long-life Operation and Maintenance of Technical Objects

*Long-life operation is the feature of the heavy industry systems. Due to its complex and large size character they must sustain, very often, for decades to make those investments economically reasonable. The paper describe some general approach and strategies like corrective, preventive and predictive maintenance. Moreover, there are given more detailed descriptions of selected solutions in power, mining and ventilation systems. Finally, given is discussion about implementation of recent technologies and the future development in the long-life operation of technical objects.*

***Keywords:*** *mining, earth moving machines, FEM, experimental techniques*

## 1. INTRODUCTION

Technical objects which require long time operation are for example: mining machines, earth moving machinery, industrial ventilation systems, power installations. The required durability equals 30 years or in some cases up to 50 years. The reason why the required durability is so high is the fact that systems belong to the group of heavy performance machines, which are complex structures, which means expensive structures.

Mechanical elements of the system like motors, gears, mechanic or hydraulic clutches, bearings or joints wear in the natural way during their exploitation. In long-period time those elements are getting older in the technical meaning, while new cheaper, more effective, lighter solutions are available. Due to that fact the subassemblies of bigger mechanical systems are replaced during modernization process what leads to the decrease of the operation costs and increase of the reliability of the technical systems. Good example is the evolution of the bucket wheel drive from heavy spur gear to the lighter planetary gear what eventually leads to the decrease of load carrying structure load.

Failures of the machines are caused by the design errors, fatigue, error in the manufacturing technology, improper maintenance or the operational conditions which differ from the design assumptions. Design faults are mostly structural notches, what leads to the concentration of stresses, for example: too small radiuses between shaft sections. The improper geometry of the structure is also caused by the calculation methods applied in the time when object was designed. 20-30 years ago engineering methods were not such advanced like it is now. Moreover, actual standards includes many additional parameters (in comparison to the standard used 20-30 year ago) which are the result of the years of experience in design, operation and maintenance.

Load carrying structure, in comparison to the other elements of the structure, is the part which is not replaced during the whole machine life. As a consequence, the durability of load carrying structure should approach infinity. Nevertheless, due to the errors in calculation, manufacturing, etc. smaller or larger fractures are observable. Additionally, the environ–mental conditions introduce another degradation factor which is corrosion.

In order to increase the durability of the load carrying structure, complex, long term structure examinations are done [1]. The procedure consists, inter alia, of the NDT (Non Destructive Testing) which allows to localize the cracks. NDT is recommended especially in the areas prone to the fatigue. Identification of such areas in complex structures is a difficult task, but now with application of the finite element analysis it is possible and it has become more common. It is important that the finite model of the structure consists of the solid and shell elements which allow to represent details in complex structure. It is especially important in the areas of connections between structure sub elements [2].

Important element of the condition state assessment is the identification of actual loads which act on the structure. In case of brown coal mining machines the loads definitions are listed in the standard. In the reality, the actual measured loads exceed the values defined in the standard [3]. Due to that fact, when assessing the conditions state after long-time operation, identification of actual loads is one of the underlining aspects. Obtained results are applied to the numerical simulation giving as a result higher accuracy of the computations.

On the basis of that procedure the prognosis of further operation is developed. Propositions of modernization, maintenance and exploitation are given.

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## 2. MAINTENANCE STRATEGIES

Long-life operation and maintenance of technical objects requires to pay special attention on the condition monitoring methods and strategies chosen in maintenance routine. The knowledge of the current condition of machines aimed for long time operation significantly improves their efficiency, especially since this condition changes over time and is the basis for making operational decisions. Depending on the available technology, it is possible to monitor the condition of such machines continuously or periodically. The scope and method of monitoring substantially depends on the initial condition of a machine and the chosen maintenance strategy.

There are three basic strategies of machine operation:

- operation until failure occurs (corrective maintenance),
- condition-based operation (preventive maintenance),
- operation which prevents and correct failures (predictive maintenance).

The first listed corrective maintenance strategy is obviously not optimal. It often leads to unplanned downtime which significantly reduces production efficiency. If such a strategy is adopted, condition monitoring amounts to periodic inspections and attempts to identify the causes of faults that have occurred. Only simple an secondary meaning machines can run with this type of strategy while critical technical object must be operated with more advanced strategies [4]. The other two mentioned strategies, in particular predictive maintenance, provide a significant improvement to machine operation. They are described in more detail in the following subchapters.

### a. Preventive maintenance - condition-based operation

This strategy consists of two sub-categories:

Operation with regularly scheduled overhauls – this popular approach uses operational experience and technical information about the implemented equipment, which can be used to predict how long a machine or its element should be in operation before being replaced or renovated. During overhaul, key elements of the machine, which are not scheduled for replacement or repair, are often inspected. If defects, excessive wear, etc. are found, a decision is made to perform corrective actions. This type of operation is relatively expensive, but ensures a certain regularity of repairs and keep the machine in relatively good condition. It is the most popular approach in the operation of heavy industry machines. If a failure occurs between overhaul cycles, a repair is scheduled and decisions are made whether to alter the schedule of future renovations. In some situations the scope of repairs is increased to also include renovation of key subassemblies. In such case it is possible to postpone the date of the next overhaul by a certain amount of time. The disadvantage of such operational strategy is unplanned downtime and increased costs resulting from unforeseen failures. Another problem is the inability to fully take advantage of the durability (bearing capacity) of individual elements of the machine, which are repaired/replaced during the overhaul. This is due to uneven wear of individual assemblies in relation to the scheduled overhaul cycles.

Operation based on the condition – this approach requires periodic, or preferably continuous monitoring of the condition of the machine under test. If symptoms of damage are detected, an immediate analysis of the situation follows and decisions are made to perform corrective actions. This method helps to detect failures early, but its efficacy is strictly determined by the quality of condition assessment. This pertains to the assessment methodology, the implemented monitoring techniques, computational methods and indicators of the process of degradation of the machine under study. Early detection of faults helps to reduce the costs of failure repair and minimize downtime. If it is not possible to perform a quick repair, a temporary correction allows the machine to continue operation until the next most convenient date of repair. The machine can also continue operation on the condition that limitations are introduced, e.g. lowering the thresholds of safety systems, limiting the output, etc. Such actions help to limit the development of damage and offer flexibility in planning the methods, costs and, most importantly, the date of overhaul.

### b. Predictive maintenance

The fundamental difference between preventive and predictive maintenance is that the predictive approach can predict the occurrence of failure. Based on such information, users can take preventive steps in advance. These include both operation and repair activities. In terms of operation, it is possible to modify the parame–ters of the machine (similar to the case of operating with a defect, mentioned above in preventive maintenance strategy), which can increase the operation time.

When corrective actions are performed in advance, structural modifications can be introduced in areas where the fault is predicted to occur, which will decrease the risk of failure. Such actions may be performed at any moment, e.g. during downtime or planned overhaul. The purpose of both categories of activities is to postpone, or eliminate the expected failure. If repairs are required, or if a faulty element must be replaced, preventive actions make it possible to order new machine elements in advance of the overhaul. In some cases it is also necessary to make an early decision to pull the machine out of operation in order to prevent a serious or catastrophic failure.

However, the predictive maintenance strategy requires the application of the most advanced methods of condition monitoring. Depending on the machine, it is usually necessary to perform a wide range of experimental tests, implement advanced measurement techniques and apply complicated computational methods to predict the machine's behavior. The efficiency of this approach to operation, strictly depends on a wide range of tools and is described by the probability of accurately identifying the location and time of failure. This efficiency is usually higher with respect to locating the potential failure area, whereas the moment of failure is much more difficult to predict. This is especially true of fatigue damages, which are in 80÷90% reason of failure especially of load carrying structures of machines.

Among the currently used methods of condition monitoring, which help to oversee the operation of various types of machines, of higher popularity are those that enable the identification of damage to the machine resulting from a long-term degradation [5,6]. As for the operation of different type of heavy industry machines, there are no comprehensive methods that would accurately assess the technical condition and, most importantly, to predict the occurrence of a failure and thus the residual life. For this reason, the authors have implemented their own numerical – experimental method for assessing the technical condition of surface mining machines, which can predict residual life of machines after long-term use and enable safe and economically optimized operation within chosen maintenance strategy [1]. Examples of usage of such approach are presented in the next chapter.

## 3. APPLICATIONS

### 3.1 Adjusting the machines to the changing environmental conditions

One of the approaches in maintaining the long-life operation is constant observation of the operating conditions and adjusting the machine to it. That is especially important in case of machines which are designed for decades of operation, for example open mining machines. Moreover, there are many cases where machines were relocated from one pit to the another where the geological conditions are different. In polish mines we can find machines which previously operated in Germany or Spain.

Good example of the adjusting the machines parameter to the operating conditions are excavators type SchRs 4600. In the "Bełchatów" mine there are two machines SchRs 4600.30 and one machine type SchRs 4600.50 in operation. Carrying structures of these objects differ significantly (fig. 1, fig. 2) but operational parameters such as the most important - output, are the same. In both types of machines there is the same excavating unit, which consists of bucket wheel with buckets (11), shaft and drive (1.6 MW of power).

**Figure 1. Excavator SchRs 4600.30**

Those types of machines started the operation in 1977 and 1978 [7]. The assumption made to the construction were adapted on the basis of the German geological conditions. Present, the machines operate in "Bełchatów" mine where the loads acting on the machines have become higher. It is due to the fact that easily excavated coal bed run out. As a result, excessive dynamic load are observed. Moreover, design of the bucket wheel and buckets do not provide sufficient dredging.

**Figure 2. Excavator SchRs 4600.50**

In order to eliminate the excessive dynamic load, which in years' time will lead to the fatigue failures, and to enable sufficient dredging, the modernization was introduced as a strategy of the long-life operation.

The modernization was conducted with the procedure that was for the first time applied to the surface mining machines. Detailed description is given in the paper [8]. For the first time the designing process of the excavating unit covered full numerical-experimental dynamic analysis of the machines. The additional challenge was the fact that the unit must have operated out of the resonance of tree machines (two different types). As a first step the operational modal analysis was conducted. This approach to the experimental testing of modal characteristics allow to obtain result which corresponds to the operational conditions of the objects. In practice, it means that the identified modes are influenced by the load acting on the structure what is actually desirable. On the basis of the conducted testing, the bands out of resonances were determined. On that basis the number of buckets were selected in purpose to provide required excitation and prevent operation in resonance.

The next step was to identify operational loads (digging force) [9], which were input data to the design of new excavation unit. This was done with the use of scaled strain gauge recording system, located on the bucket wheel drive of existing machines. Location of the sensor is shown in figure 3. Figure 4 is an example of a time-trace of the digging force recorded during operation. There is typical overload of the excavating unit shown, after which immediately stop is present. This system for measuring loads was installed on a machine for several weeks, in order to determine a representative spectrum of operational loads. However, such a system can be used for continuous condition monitoring in the adapted maintenance strategy.

As a result of that modernization, a new design of bucket wheel was developed (figure 5).

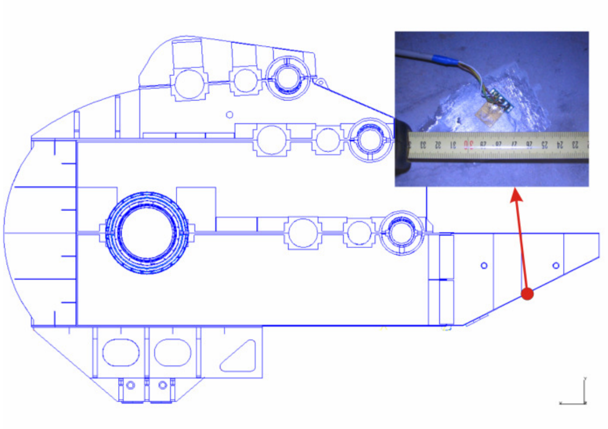

**Figure 3. Location of the point where strain is measured on the bucket wheel drive of the SchRs4600 excavator**

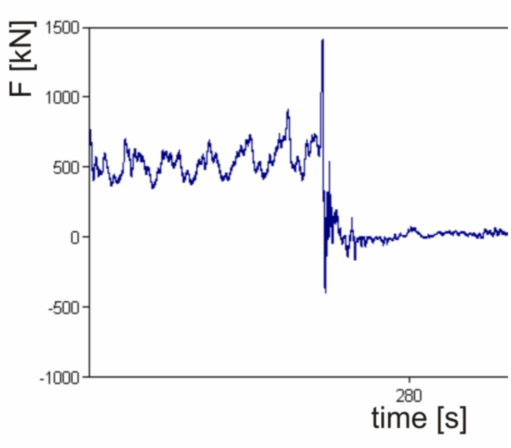


**Figure 4.Time-trace of impact load recorded on the torque beam of the SchRs4600 excavator**

As a result of that modernization, new design of bucket wheel was developed (figure 5).

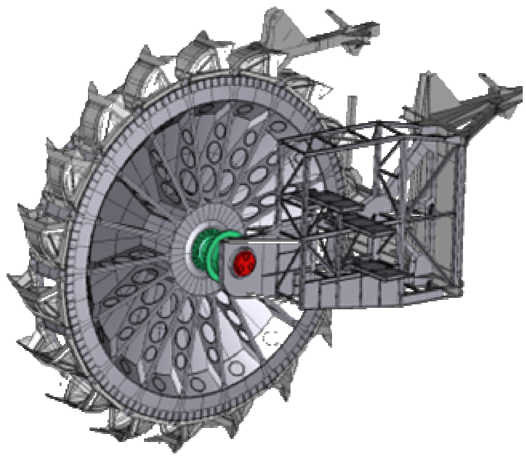

**Figure 5. Design of new bucket wheel**

In the original solution 11 buckets were placed on the wheel. In the preliminary design, the new wheel consist of 17 buckets [8]. However, the numerical simulations indicated that initial modal characteristics will be changed due to the higher mass of the unit. As the resonant areas are shifted the proper anti-resonance excitation will be 0.93Hz which corresponds to 18 buckets. Manufacturing of the new excavation unit is on advanced stage. Example of already done work is shown in figure 6.

**Figure 6. New excavation unit in the workshop**

### 3.2 Technical condition state assessment

As a second example the process of condition state assessment of the bucket wheel excavator will be described. The excavator SRs 2000 (fig. 7) was taken into operation at the turn of the 80' and 90'. There are many of this type of machines operating in open pits in Europe and also in Asia. It was designed in Germany.

**Figure 7 . Bucket wheel excavator SRs 2000**

For the condition state assessment the special numerical-experimental method [1] was used in which the following task had to be completed:

- Operation history analysis
- Operational and maintenance documentation
- Visual inspection
- NDT testing
- Vibration level measurements
- Identification of actual loads
- Numerical simulation of the structure.

Figure 8 presents a block diagram of the method. Its key component is the identification of the loading state, which is performed mainly by means of experimental tests, which enable identification of dynamic operational vibrations of the entire structure (figure 9) and loads coming from excavation. The main focus of this method is on the numerical identification of the state of stress using three-dimensional computational models based on FEM, which are then used for fatigue calculations [10]. The third activity, which determines the reliability of this method, is the prediction of residual life based on the identified state of stress and loads in the structures under study. The final, complementary step in the proposed method, is non-destructive testing aimed at determining the condition of the load-carrying structure, especially in areas directly responsible for excavator safety and in sites identified as highly stressed, using fatigue calculations. These tests complete the knowledge of the degree of degradation of the load-carrying structure and its estimated service life.

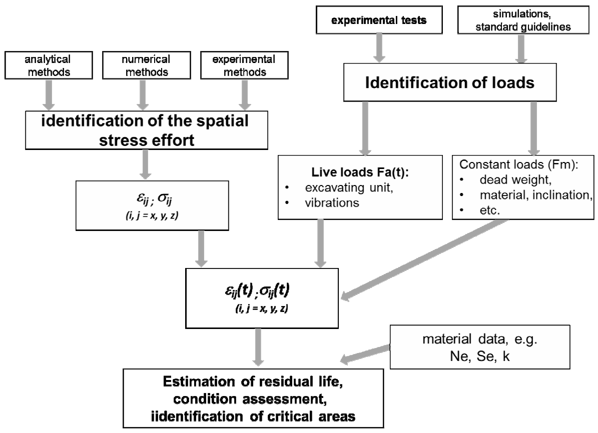


**Figure 8. Block diagram for the method of assessing the condition of surface mining machines and predicting their residual life**

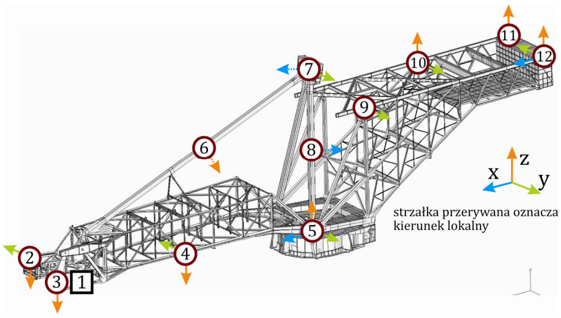


**Figure 9 . Placement of the vibrations measurement points**

On the basis of obtained results from the above method, recommendations for required modifications are given. Moreover, vulnerable areas are selected. For these regions durability is predicted as well as strategy of control and maintenance (figure 10).

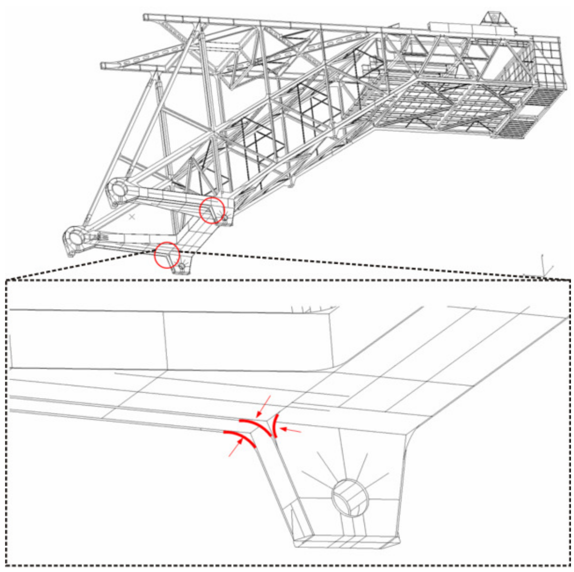

**Figure 10. Selection of the areas for technical inspections**

In some scenario the assessment of selected machines is done simultaneously. In that case, the machines are ranked in the criterion of industrial usability. As a result of such assessment an object can be selected for earlier renovation or final decommission. In opposite scenario, the object of the best technical condition is selected to operate in hard conditions or to be used in different pit.

### 3.3 Rotating machinery

Industrial ventilation systems are designed as a part of plants or facilities which in most cases will have to operate for decades. Moreover, sufficient flow of the medium is one of the crucial factors to keep continuous productions process. This ensures that the ventilation system will be of high reliability, what can be assured by proper design, operation and maintenance planning.

From the technical point of view, maintenance of the long time operating ventilation systems brings the benefits for the operation costs and downtime reduction. Another very important factor is efficiency of such equipment, which reflects on power consumptions. Improvement of efficiency can bring big savings in long term operation. Therefore, modernization works of industrial fans are a good and cheap way to improve operational factors of existing equipment.

The design process and applied engineering tools are strongly related to the days of its erection. For the new projects the up to date CAE tools are applied. While the long-life operation is taken under consideration, actual solutions and toll will be “the old one” in the future. As it was already mentioned, the application of CAE is the main trend. A good example is implementation of new impellers for the old ventilations stations (fig. 11) in a mine where many problems with the fans durability occurred (fig. 12). Even the design of fans is known for years, new solutions dedicated to the particular installation can improve the operation.

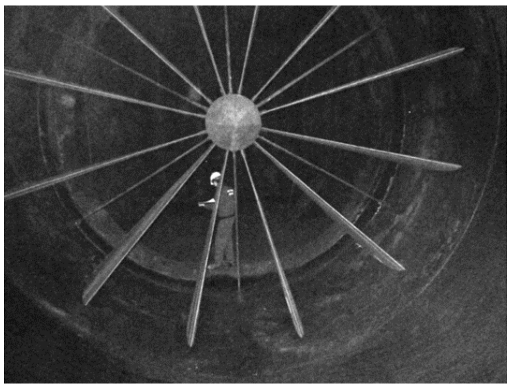

**Figure 11. View of the flap at inlet to the ventilation station**

**Figure 12. Fracture of fan impeller, large deformation of blade**

The old solution of the impeller [11] which was characterized by a lot of fatigue cracks and deformations (figure 12), caused by the excessive vibrations, was substituted by the new one with new design solutions of weak areas and optimized geometry to obtain better efficiency. For this purpose, a modified number of blades was also applied [12]. This resulted in better performance parameters and increased the efficiency. As a result, the general vibration level of the ventilation system was decreased and the costs of operation dropped significantly due to the smaller power consumption. Annual power savings calculated for 8 fans (2.5 MW each) equals 800.000 EURO.

Simultaneously with the structural modifications, it is crucial to monitor the rotating unit. There are two major reasons to perform such tests. One is to obtain dynamic behavior of the fan to check and validate numerical model, which is used for design of new object. The other is to conduct continues monitoring of the fan with the use of dedicated systems. In figure 13 the fan unit with applied sensors is presented. Accelerometers are placed on the bearings, housing, motor and supporting frame. The purpose of the presented monitoring system were short-term tests to investigate dynamic behavior of the fan.

**Figure 13. View of the placement of vibrations sensors on the ventilation unit**

The diagram with placement of the selected sensors is visible in figure 14.

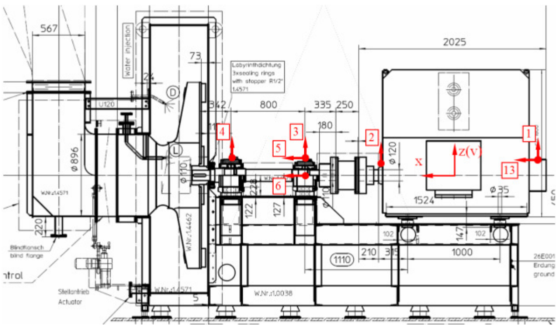


**Figure 14. Diagram with placement of selected accelerometers on the ventilation unit**

In case of such a complex experimental testing it is possible to correlate the structural vibrations of the fan elements and the excitation generated by the rotating parts [13, 14]. For continuous monitoring of the rotating machinery it is common practice to place on the supporting bearings of fan and electrical motor shafts [15]. The signal is processed and information like vibrations energy (RMS), peak to peak, kurtosis, and what is most important, tracing all the trends are available. Analysis of that signals allows to identify the dangerous states of the machine, also very often it is possible to identify the defect and predict its final failure. It is common practice to monitor rotating machinery in order scale [16].

The acquired signal (figure 15) can be detailed post-processed with the most sophisticated DSP methods.

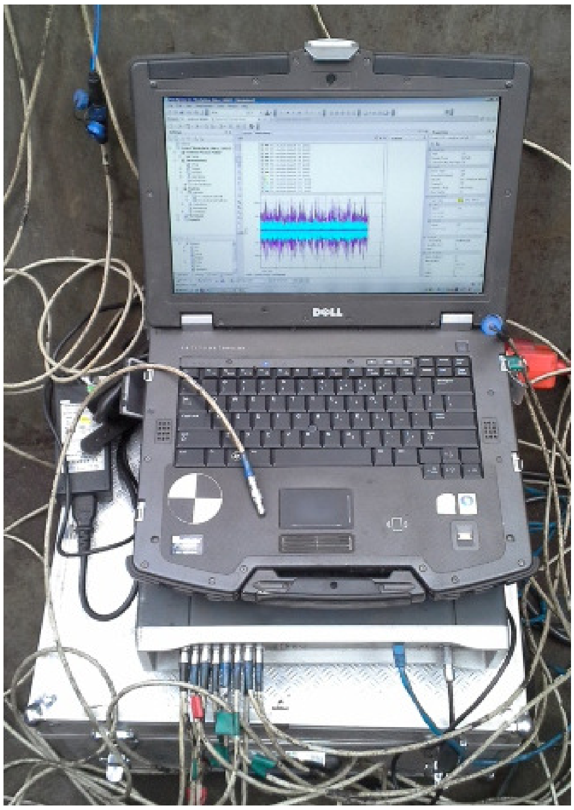

**Figure 15. Data acquisition system**

For the cases where continuous monitoring is applied to the supports, it is common that special software is developed and adapted to the general IT system of the plant.

Example of such condition monitoring system for cement plant equipment was developed by authors and it is presented in the next chapter.

## 4. FUTURE TRENDS IN MACHINES LIFE-TIME EXTENSION

There are three basic areas which enable lifetime extension of machines:

- structure optimization,
- development of condition monitoring systems,
- development of active automation and safety solutions.

The development of the computer based methods enables that all of the classic engineering solutions can be optimized. The trends in the structural design can be developed due to the virtual prototyping, design and simulations. Thanks to that, all the new solutions, can be applied to the virtual model without high costs. Strong development of the new materials and production techniques gives designers totally new solutions or enable to modify existing one but with better technical parameters.

The most important in condition monitoring systems is to choose proper measuring parameters, provide adequate measuring techniques and after performing analyses of the obtained results to finally set proper threshold values for warnings and alarms. In such systems trend analysis is very popular and useful tool to recognize symptoms of faults. Depending on how accurate is monitoring system, we may get early information on future problems. As soon as such information is available corrective actions can be taken. Nowadays such comprehensive monitoring systems are designed with the help of numerical tests, which enable to investigate behavior of tested structure, choose the best locations and monitoring technics or to calculate different scenarios for corrective actions in case of warning signals are obtained. Such approach is especially useful in critical equipment, where serious faults are not frequent and monitoring system cannot be check and adjusted properly in such cases.

New and more accurate measuring techniques as well as miniaturization and fast data transmission lead to the solutions where the operator will be able to monitor the system in almost every place and every time. Elements of the monitoring system could be applied as the application to our handy and similar daily routine electronic devices giving almost total control.

An example of a simple but useful monitoring system for online trend analysis is shown in figure 16. We can see the process parameter, which is fan rpm (green trace) and RMS measured on the fan bearings.


**Figure 16. Online trend analysis**

Another, more comprehensive example is condition monitoring system for cement rotary kilns, which are critical core equipment of cement plants. There are few critical faults, that may happen during operation of such equipment such as:

- kiln crank,
- supporting rollers bearing failure (hot bearing),
- formation of free material in a shape of ball inside the kiln (snowball).

Based on the operational information and various numerical tests and analyses, a special condition monitoring system was established. In order to have a complete set of all valuable information for the kiln condition, supporting rollers deflection measurements were chosen as a good tool for early fault recognition. Together with rollers displacements some other data were taken from existing measurements systems such as kiln shell temperature, bearing temperature, capacity of the kiln, power consumption etc. Figure 17 presents locations of eddy-current probes on the kiln supporting stations.

Since failure of kiln happens rarely but costs a lot of money, the new condition monitoring system was adjusted and calibrated (setting warnings and alarms values) with the use of numerical model of the entire kiln and simulations of critical faults. An example of kiln crank effect simulated with the use of numerical model is shown in figure 18.

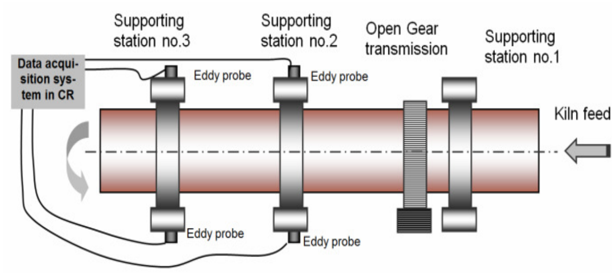


**Figure 17. Installation scheme of eddy current probes**

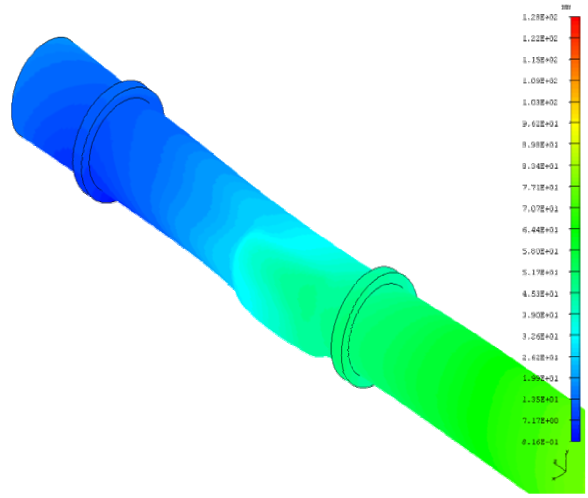

**Figure 18. Model representing crank effect in upset condition (Huber Mises stress in the kiln structure)**

The above described condition monitoring system enables to use proactive and predictive approach in maintenance of such cement plant equipment. It has been verified as a useful tool, that reduces downtimes and operational costs. More detailed information are presented in the literature [17].

The development of active automation and safety solutions is possible due to the multidisciplinary approach which allowed to create automated, sometimes intelligent mechatronic systems. It starts form simple loads identification (which can be used also in the structure development) and automation of the operation process, through safety systems that protect the structure against overload or other catastrophic factors [1, 17-19]. This type of active solutions are part of continuous monitoring systems.

The combined solution of structure design and electronics is visible in the automatic control. While up to now the mega machines (surface mining machinery) vibrations were reduced by the structural changes or excitation limitations [20], the newest solution points to the automatic vibration control and damping [21-23].

Similar concept is being prepared for load carrying structures of mega machines and it is developed by WrUT and AGH team. The general assumption is that the tuned mass dampers can be applied to the structure and eliminate the vibrations problems.

Preliminary design is focused on small elements like operator cabin boom, but the project is planned to develop solutions for the whole structure. Application of tuned mass dampers in the load carrying structures of heavy industry objects that are exposed to dynamic loads [24] is the upcoming strategy for its long-life operation.

Another example of the new prototype solution, which is in the stage of concept design, is the innovative unit for excavation of hard-mineable overburden in surface mining. So far it is almost impossible to excavate such overburden, with the use of specialized mining equipment such as bucket wheel excavators. Such heavy conditions creates high dynamic overloads and accelerate degradation of entire machine (mechanical parts and load carrying structures) and may lead to catastrophic cases [4, 25]. With the new prototype solution presented in figure 20, it is expected to eliminate such disadvantages.


**Figure 19. Active vibration control of belt conveyor [22]**

While the concept presents an approach never applied before, it rises a lot of doubts and promises as well. Thanks to the numerical tools it will be possible to evaluate and improve the preliminary design. If the project succeed, it will be possible to introduce new surface mining technology.

In the final stage both condition monitoring systems and active safety solutions (such as anti-overload systems) will be adapted to monitor new solution and prevent overloads.

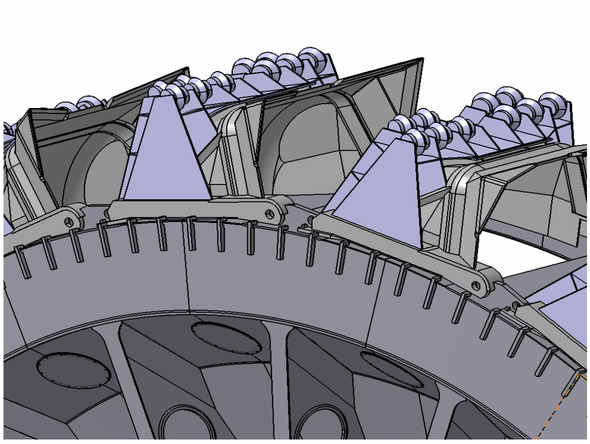

**Figure 20. Conceptual excavation set – *patent application P4111009* [26]**

## 5. CONCLUSIONS

Cost of operation is one of the most important factors taken into account in almost all types of industry. Reduction of the costs and extension of life-time of expensive and complex machines are the most important areas, in which many new solutions, improvements and inventions have been made lately.

Introduction of modern and useful maintenance strategies such as proactive or predictive approaches is one of the way to reduce costs of operation of existing or new equipment. Among them, a very important factor is to establish efficient and properly adjusted condition monitoring systems to control and prevent failures. Another way is to introduce new, active systems, which can reduce (limit) danger conditions of machines such as overloads, excessive vibrations etc. Another way of cost savings is to introduce high efficiency solutions by modernization of existing objects or by replacing them with a new, more efficient one. This area of interest is very popular in heavy industry, where energy consumption is the main operational cost [27].

In this paper, basic information and examples of such actions taken on long-life operating of technical objects are presented. What is obvious, implementation of new comprehensive solutions requires interdisciplinary approach. This is due to the fact that there are many different factors and goals, which must be considered and achieved to provide effective and reliable solutions for technical equipment we want to design, save, or improve.

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## ИЗАЗОВИ И СТРАТЕГИЈЕ ДУГАЧКОГ РАДНОГ ВЕКА И ОДРЖАВАЊА ТЕХНИЧКИХ ОБЈЕКАТА

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Дуготрајно функционисање је основна карактe–ристика система тешке индустрије. Сложеност и димензије ових система су такви да често морају да трају деценијама да би инвестиција била економски оправдана. Рад описује неколико општих приступа и стратегија, као што су корективно, превентивно и предиктивно одржавање. Осим тога, дат је

подробнији опис одабраних решења за енергетске, рударске и вентилационе системе. Најзад, приказује се разматрање о примени најновијих технологија и будућем развијању дугачког радног века техничких објеката.