Implementation of the RCM Methodology on the Example of City Waterworks

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The paper presents the possibility of application of Reliability Centered Maintenance (RCM) in infrastructure systems, such as waterworks. It introduces the RCM methodology which is adapted to such systems. The RCM methodology offers the best strategy for optimization of preventive maintenance. It covers a new understanding of the way in which the equipment may fail. Failure Modes, Effects and Criticality Analysis (FMECA) was first performed. The most suitable maintenance tasks have been defined for each failure and they belong to one of the four groups: Time-Directed (TD), Condition-Directed (CD), Failure-Finding (FF), Run-to-Failure (RTF). The analysis on the concrete example, a waterworks pumping station, has established that 61% of failures can be prevented by the application of preventive maintenance. The interdisciplinary procedure applied during analyses allows optimization of the existing preventive maintenance in the city waterworks.

Keywords: : RCM methodology, waterworks, preventive maintenance

1. INTRODUCTION

Literature provides numerous examples of succesful application of the RCM methodology: the USA navy and aviation [9], oil industry [10], maintenance of ships and submarines [11], railway [5], different fields of industry [6,7]. There are also certain projects where the results of RCM analysis were not accepted. The Norwegian railway is one of such examples, and this case is probably connected with very ambitious goals of the company [12].

This paper aims at investigation of the possibility of applying RCM in infrastructure systems, such as city waterworks. The pumping station which was the subject of observation, uses traditional preventive maintenance, relying on periodic inspections of certain components of the system. Having the models of large infrastructure systems like railway, RCM analysis was performed on a smaller system – a waterworks pumping station. It had several effects. The insight into the possibility of a more quality way of maintenance in comparison with the existing one was obtained. The interdisciplinary approach used during analysis considered the problems of entire maintenance, and the results of analysis were presented in a way which is completely clear to the maintenance staff and management of the company.

Water supply of the population implies providing high quality water for households, public needs and a part of industry. The quality of drinking water directly influences the health of people and that is why it is regulated by the law. Water supply and public health are the fields which are covered by legal regulations all over the world. Laboratory testing of drinking water is carried out exclusively by authorized health care institutions. In order to satisfy necessary requirements regarding water production and water quality, special attention must be paid to the maintenance of water supply systems.

Not so many people in our country have been introduced to the RCM methodology. One of possible reasons is lagging behind world trends for decades, which has been caused by isolation and sanctions. The second reason can be based on the initial knowledge that reached our country. The end of the eighties of the last century saw the flourishing of the statistical theory of reliability. Everything led to the attitude that only strong computer support and a large database of failures enabled significant optimization of maintenance of large systems. The initial application of RCM was expressed in systems such as civil aviation, atomic energy, navy and aviation, which are representatives of extremely expensive and critical systems. The name itself – reliability centered maintenance contibuted to it, so that it could be easily conluded that it was a methodology that sublimated leading accomplishments of the reliability theory and that it was necessarily based on strong computer support and databases of failures. Today's level of development of RCM shows that the methogology is applied both in military systems and in various branches of economy: metal processing branches, power engineering, mining, oil industry, paper industry, railway, harbour plants, maritime affairs, health care, etc. [15]

2. RCM ANALYSIS – REASONS FOR INTRODUCTION

The term **Reliability Centred Maintenance - RCM** first appeared in 1978, when the leading engineers of the American company United Airlines, Nowland and Heap, gave that name to their report intended for the American army [14]; the report was a thorough presentation of the methodology of improvement of the maintenance process in civil aviation. Nowland and Heap aimed to emphasize, by the title itself, that United Airlines was increasing the reliability of its airplanes.

This method was developed as the product of a real need on the basis of research. In 1960, the Federal Aviation Agency carried out research in the USA with the goal to establish the effectiveness of airplane repair in fixed time intervals. The research resulted in two findings:

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- the planned repair had small effects on the total reliability of complex components, except if the component had a dominant failure due to wear
- there are a lot of components for which there are no effective and efficient manners of preventive maintenance.

Such results have basically changed the approach to reliability. For the purpose of solving complex problems, RCM analysis has been divided into phases. A functional model which observes all functions of the system with their functional failures has been developed. Functional failures have been correlated with all failure modes, with their causes and consequences.

The leading theorist of the RCM methodology, John Moubray, has defined RCM as a process which is basically the same as FMECA (Failure Modes, Effects and Criticality Analysis). The difference is that the manufacturer uses FMECA to sum their knowledge about possible failures, and RCM sums the experience gained by the operator and the person in charge of maintenance for many years.

The results achieved by the application of the RCM strategy, in different cases, are as follows [13]:

- reduction of the number of working hours for preventive maintenance by 87%;
- reduction of the total number of working hours for maintenance by up to 29%;
- reduction of costs for intermediate goods for maintenance by up to do 64%;
- increased availability of the equipment and system by up to 15%;
- increased reliability of technical means by up to 100%.

It is a well-known fact from [1], having in mind the experience of the systems for which the RCM methodology was elaborated and where it was implemented, that 60% of failure modes can be prevented by preventive tasks.

Understanding the importance and possibilities of RCM, the International Society of Automotive Engineers (SAE) established the Technical Committee which in 1999 developed the JA1011 standard: Evaluation Criteria for Reliability-Centred Maintenance (RCM) Process. This standard should help all those who want to implement RCM, since it defines guidelines and clarifies a lot of details and activities that are used during the implementation.

2.1. RCM analysis

Before starting a comprehensive RCM analysis and defining requirements, it is necessary to create a detailed catalogue of technological systems which are the subject of maintenance and carry out detailed introduction to the production process. After the realization of these two necessary steps, it is necessary to make seven basic questions/requirements of the RCM concept for every technological system thus defined and give detailed answers to each of them. The seven questions are [17] :

1. Which functions of the equipment are important in current exploitation?
2. What kind of equipment failure may occur?
3. What are the causes of failure occurrence?
4. What happens when a failure occurs?
5. What is the importance of each failure?
6. What can be done to prevent a failure?
7. What should be done if no adequate preventive activity can be found?

1. Which functions of the equipment are important in current exploitation? As the main task of maintenance is to provide proper, i.e. designed operation of equipment, it is necessary that the maintenance staff knows what is expected from individual technological systems, what “normal” operation mode is, and which standard was used to design the equipment. Therefore, the maintenance staff should know which functions of the equipment are important for the foreseen exploitation and hence it is necessary to pose this question first and give a detailed and precise answer to it.

2. What kind of equipment failure may occur? After the introduction to the functions of the equipment, it is logical to make the second question. It is necessary to identify every possible way of interruption of execution of the planned function, and it is done by means of two subquestions: a) – how can the equipment fail in the execution of its function and b) – what may cause unsuccessful execution of the equipment function?

3. What are the causes of failure occurrence? The aim of posing this question is identification of all ways of failure occurrences – non-fulfillment of the foreseen function, in order to identify the things that should be prevented. While carrying out this step, it is necessary to perform a sufficiently detailed analysis in order to avoid the situation when maintenance activities are carried out for the purpose of eliminating consequences, and not causes of a failure. On the other side, it is necessary to pay enough attention to avoid excessive going into details and unnecessary wasting of time and energy of participants in the analysis.

4. What happens when a failure occurs? When every manner of occurrence of failure is identified, it is necessary to identify the consequences of occurrence of each stated manner of failure occurrence: whether the production stops, whether the production process continues to produce waste, whether there is a threat to the environment, whether there is a threat to the health of workers...

5. What is the importance of each failure? The consequence of every failure is certain amounts of time and money that should be spent in order to eliminate the failure. Besides, failures may have additional consequences related to the stopping of production, production of waste, degradation of the environment, workers’ injuries, damage of other parts of the system. Thus, every failure has its time and financial equivalents as well as additional consequences which are sometimes possible and sometimes impossible (or it is extremely complicated) to be expressed in time and financial units. The more “expensive” the consequences, the stronger the need to prevent such a failure, i.e. to find a preventive activity which would eliminate and postpone failure occurrence, or at least alleviate the consequences of that failure. In order to facilitate the work with these terms, RCM has defined four possible groups of consequences: hidden consequences, consequences related to safety and

the environment, production consequences and non-production consequences.

6. What can be done to prevent a failure? It used to be understood that all elements, i.e. their failures, are governed by the “bathtub diagram“, which is shown in Figure 4.9 and denoted by „A“.

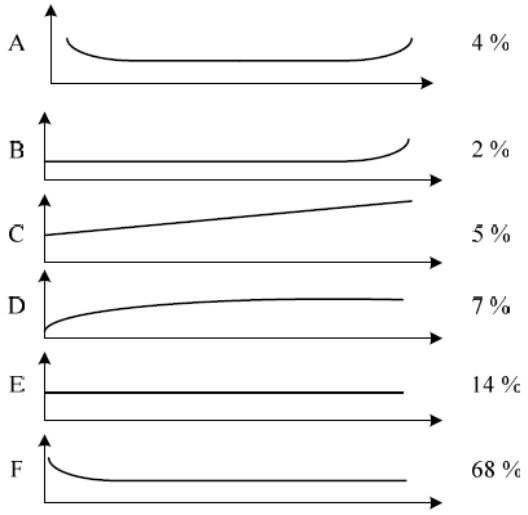

Figure 1. Six forms of failure intensity diagram

However, by monitoring the failure occurrence in civil airplanes, the data presented in the same figure have been obtained and now it can be seen that only 4% of parts have such a shape of the failure intensity curve. The shape of the failure intensity curve designated by “B“ have additional 2% elements. As the preventive replacements are carried out at the moment when there is an increased probability of failure due to intensive wear, it means that only these two shape of the failure intensity curve are justified for application of preventive replacements, i.e. in only 6% elements it is justified to carry out preventive replacements; all other preventive replacements have a negative effect on the reliability of the system and the number of failures of that system. Later studies in industrial conditions have shown that between 77 and 92% of failures are not time dependant, i.e. in those cases it is not recommended to perform preventive replacements.

7. What should be done if no adequate preventive activity can be found? There are some cases when it is not possible to find an adequate preventive activity which will prevent failure occurrence and then it is necessary to perform an economic analysis: whether it is economically profitable to let an element fail and then replace it or whether it is necessary to do something so that the failure could have minimum consequences.

RCM has defined four groups of failure consequences and, depending on the group to which consequences of a failure belong, the possibility of treating each failure, i.e. its causes and consequences is searched for. If it is a hidden failure, it is necessary to define the activities for discovering the failure (these activities are widely used in the army, but they are also used in the functions of fire protection). If it is a failure with the consequences related to safety and the environment, it is useful to carry out only the activities that reduce or eliminate the consequences of the failure. If such an activity does not exist, the observed element should be redesigned or it is necessary to change the whole process in which that element participates. In the failures which have only production consequences, it is recommended to perform preventive interventions only when the total costs of those preventive interventions are lower than the costs arising due to the failure of that element. The situation is identical with the failures that do not have direct influence on the production.

In both cases, if it is not possible to find the preventive activity which will reduce the total costs, it is necessary to let that element fail and then replace it. The exception is the situation when the costs arising due to the failure are extremely high and then it is recommended to redesign the element of the whole system.

3. RCM METHODOLOGY

RCM can be regarded as an efficient tool that covers guidelines for executive managers who want to achieve high standards of maintenance. This includes identification of critical equipment and development of optimum maintenance policies based on the reliability data. RCM can be used for formulation of the maintenance strategy for production equipment and for the analysis of functional failures, which includes aspects of the environment and human factors.

The RCM methodology can be presented in 7 steps, which cover one or several activities, as shown in Figure 2.

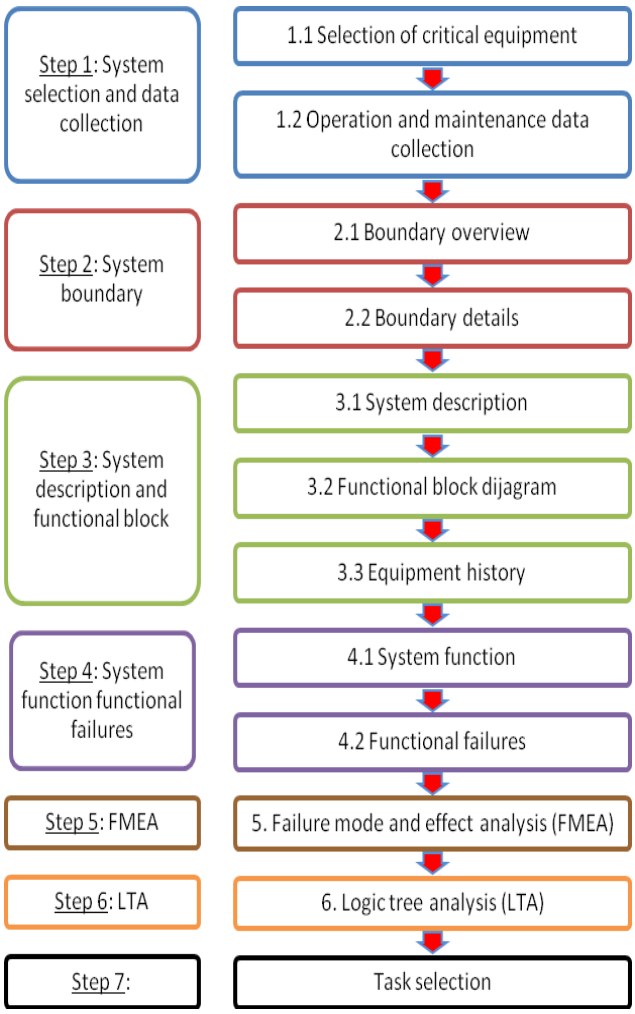

Figure 2. Flow diagram in RCM methodology

3.1. Selection of the system and collection of information

The level at which RCM analysis is performed can be selected as part of a large system or plant. The system is connected to the starting point of the RCM process because there are several failure modes, ranged by their priority due to limited resources of preventive maintenance (PM). Different factors, such as: costs, safety and environment protection can influence selection of the system. Documents such as the scheme of the system and/or block diagram, history of failures of similar equipment or operating instructions should serve as the basis for collecting information about the system.

3.2. Definition of system boundaries

The main equipment included in the system is identified with primary physical boundaries. Precise definition of boundaries is important from two aspects. Firstly, we should make sure that the potentially important functions are not neglected and secondly, the boundary represents a link between the entrance to the system (energy signals, flow...) and the exit from the system (output interfaces). This approach facilitates drawing of the block diagram.

3.3. Description of the system and the functional block diagram

Description of the system and the functional block diagram should provide certain important information that relate to:

a) functional description of the system and its functions, excess functions, protective functions, etc.
b) representative functions of the system
c) input/output interface
d) a list of equipment and functional subsystems
e) history of failures of equipment during the past 2 - 3 years

3.4. Functions and functional failures

Function is a desired activity which should be performed by the equipment or system during a defined time interval. Every system has its primary and secondary functions.

In the process of function identification it is necessary:

- to consider all functions
- to describe the functions by the expressions that contain specific constraints/restrictions
- to describe the functions in the expressions that show what a user needs, and not overall capabilities
- not to combine the functions
- to describe the functions so that the description includes a verb, an object and an applicable constraint/restriction

The importance of this issue is supported by the fact that there are certain standards which give guidelines for identification of important functions. One of those standards is NAVAIR 00-25-403. In addition to definition of important functions, it is necessary to eliminate inconsistent functions.

A functional failure must refer to the defined functions. A functional failure does not have to be a complete loss of a function. It is necessary to point out the functional failures where the effect of function degradation is different from the total loss of function.

3.5. MEA and FMECA analysis

FMEA is the basic procedure for qualitative estimation of technical system reliability. The logical continuation of FMEA is quantification of the corresponding values related to the failures of technical system elements and examination of criticality. Criticality most frequently means a relative measure of consequences of failure modes and the frequency of its occurrence. FMEA and CA make the Failure Modes, Effects and Criticality Analysis – FMECA. Systematic monitoring of failures of elements and creation of a database provides a basis for application of the FMECA procedure. Necessary conclusions for development of corrective measures for the purpose of elimination of noticed weaknesses can thus be drawn.

The existing standards, which refer to the FMEA method, are different. The differences are smaller or bigger, which depends on the standard. They are most often connected with the look of the form for documenting FMEA, terminology, designation of certain values/quantities, etc.

3.6. Logic tree analysis (LTA)

When the lists of failure modes are formed for each component of the system and when the functional dependence among all failure modes of components and functional failures are found, it is necessary to establish the influence of each failure mode at the local level as well as at the levels of system and plant. Such decisions are not at all simple, so the logic tree shown in Figure 3 is used for that purpose.

The failure modes classified in this way can be in one of the following three branches of the logic tree (algorithm, Figure 3):

- Evident
- Safety
- Outage

Classification of the effects of failure modes according to the logic tree analysis puts every failure mode in one of the following 4 groups:

- A – safety problem
- B – outage problem
- C – minor (insignificant) economic problem
- D – hidden failure

This analysis, taking into account a huge number of combinations that can appear when failure modes and their causes are in question, once again confirms the inevitability of creation of a database of failures.

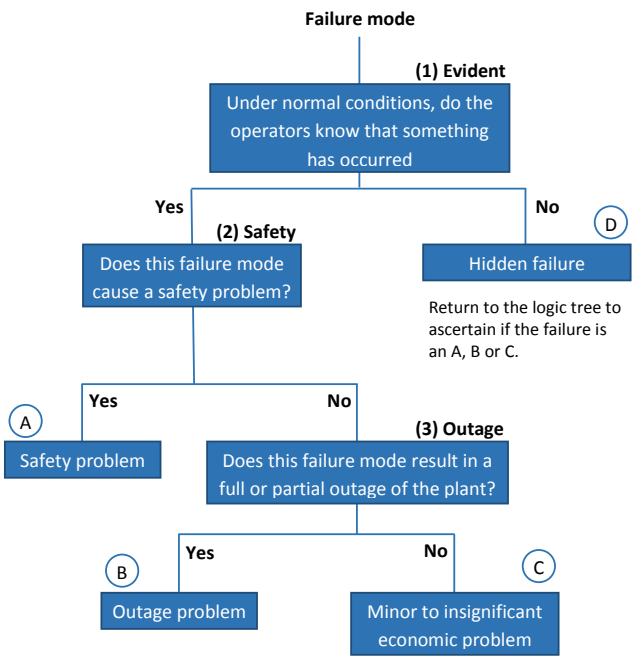

Figure 3. Logic tree analysis

3.7. Classification of maintenance tasks based on the RCM analysis

The aim is to find such a maintenance task which has the highest performance regarding prevention of failure occurrence. If the failure mode cannot be prevented, then the mechanism of failure occurrence should be monitored through a measurable parameter which has its defined dependence with the failure mode during a time interval. If there is no preventive task (activity), or if techno-economic analyses are taken into account, in certain cases it can be decided that the system component (or some of its elements) should operate until it fails.

Potential maintenance tasks belong to one of the 4 possible categories (Figure 4):

- TD – Time – Directed
- CD – Condition – Directed
- FF – Failure Finding
- RTF – Run to Failure

It is necessary to assign a maintenance activity to every failure mode. That activity should prevent the occurrence of the failure mode in the most efficient way or provide maximum reduction of its effect. Every selected type of activity should have its description and details about its periodic repetitions.

4. RCM ANALYSIS ON THE EXAMPLE OF CITY WATERWORKS

City waterworks has been chosen for practical realization of the RCM methodology. As the process of water production is continuous, preventive maintenance has a very important role in the reliability of such systems. Costs of preventive maintenance can be optimized by proper selection and frequency of maintenance tasks.

The first step of the standard RCM methodology is to identify the system which should be analyzed. Potential users of the analysis should always be borne in mind. The company managers and the maintenance staff have different requirements. Therefore, the standard RCM methodology must be modified and adapted to specific requirements of users. Taking into account that the city waterworks is a large infrastructure facility which consists of several sources, pumping stations, tanks and water supply network, Figure 5 proposes the infrastructure organization of the waterworks, which can meet the requirements of the RCM methodology. The levels of details in the RCM methodology are shown at certain organizational levels.

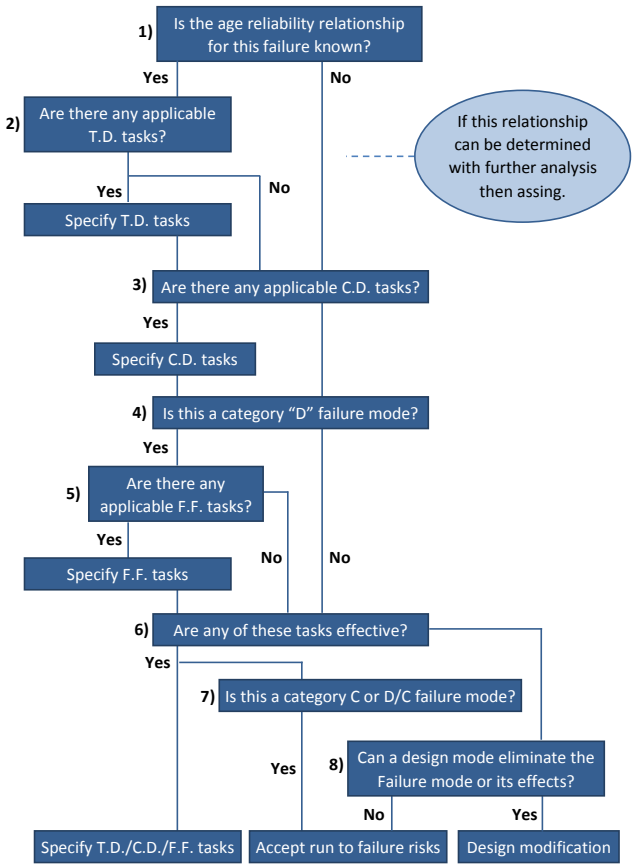

Figure 3. Classification of maintenance tasks based on the RCM analysis

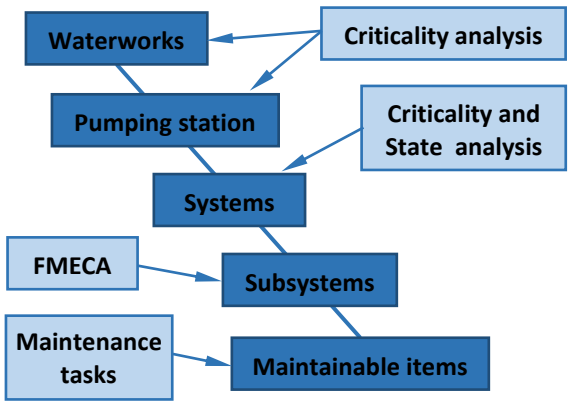

Figure 5. Waterworks infrastructure organization

The waterworks is at the highest level in the structural organization. The criticality analysis establishes the parts of the waterworks which should be covered by the RCM analysis in order to avoid comprehensive analyses at unnecessary points. The pumping stations are the most important parts of the water supply network, so they are given as an obligatory part of the structural organization. For the generality of analysis, when systems

are in question, legal regulations that differ from country to country should also be taken into consideration.

The selected pumping station consists of a source and a powerhouse with the pump aggregates and the plant for water chlorination. The powerhouse is located next to the well from which water is taken and directly pumped toward users. The well is dug, with the walls made of compacted concrete.

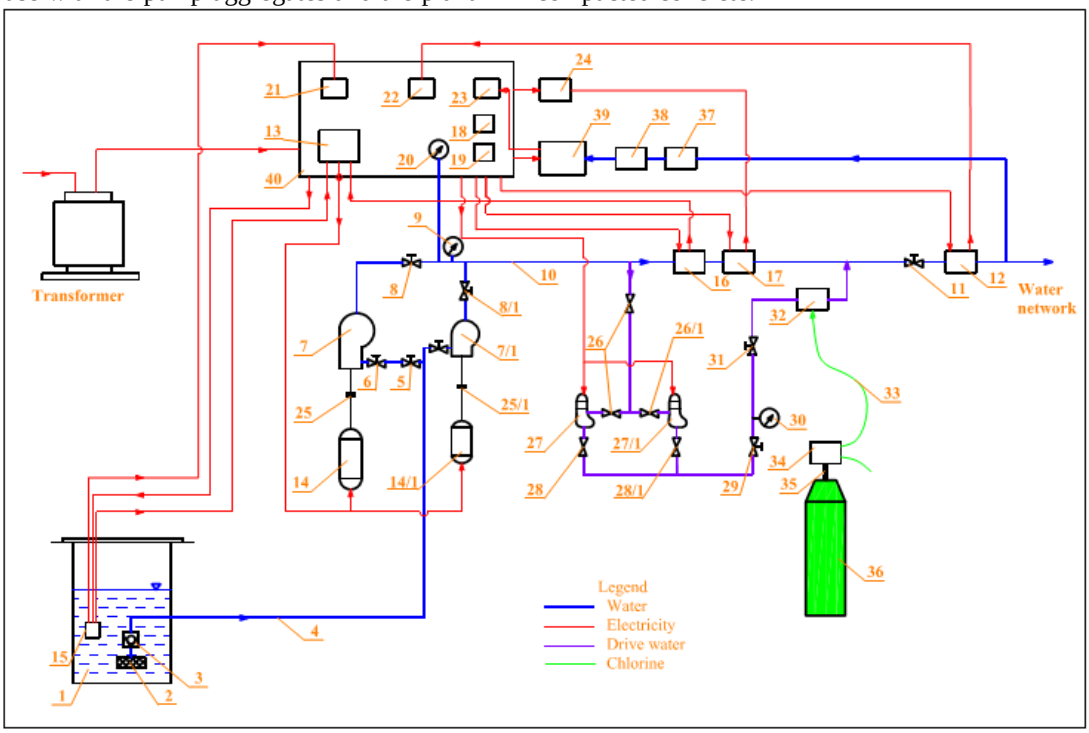

Figure 6. Schematic presentation of the pumping station for water supply

Pumping station consists of the following basic components (Figure 6): 1 - well, 2 – suction chamber, 3 - irreversible valve, 4 - suction pipeline, 5 - valve on the suction branch, 6-tap of the pipeline for filling; 7-centrifugal pump, 8-valve on the pressure pipeline, 9-pressure gauge, 10 pressure pipeline, 11-valve V2, 12-flow meter, 13-frequent regulator, 14-motor, 15-hydrostatic level sensor, 16-pressure transducer, 17-flow transducer, 18-switch with indicator of centrifugal pump; 19 -switch with indicator for booster pump operation, 20-sensor for pressure in the pressure pipeline, 21-sensor for water level in the well; 22-sensor of flow in the pressure pipeline, 23-sensor of chloral level 24- flow indicator; 25-connector, 26-gate valve ; 27-booster pump, 28-valve Z3, 29-valve on the pressure branch of the water flow, 30-gauge of water flow, 31 - valve V3, 32-injector, 33-vacuum hose, 34-vacuum regulator, 35-valve for chlorine ; 36-bottles for chlorine; 37-flow regulator of chlorine analyzer; 38 - pressure regulator of chlorine analyzer; 39-analyzer of free chlorine, 40-distribution cabinet.

There are two centrifugal pumps in the powerhouse, one of them being controlled by a frequency regulator. Both pumps are intake and discharge pumps at the same time. The pumps have parallel connection to the water supply network. The pipe fittings allow simultaneous operation of both pumps. Most frequently only one pump operates, and the other serves as a back-up pump. The pump operation variant depends on the necessary quantity of water and the well yield. For the purpose of increasing energy efficiency, the higher flow pump is controlled by a frequency regulator. The speed regulation system changes the pump characteristic by adjusting the discharge head (generated in the pump) according to the required parameters of the pipeline and the desired flow.

4.1. Selection of the system

Pumping stations are the most important parts of the waterworks system. That is why the pumping station was selected as a subject of the RCM analysis in this example. The pumping station consists of three functional systems: a well, water production and chemical treatment of water. It should be particularly emphasized that some undesirable consequences which can threaten the safety and health of people may occur during chemical treatment of water. In addition, the maintenance costs for the pumping station has the largest share in the total maintenance costs for the waterworks. These are the key reasons for selection of the system.

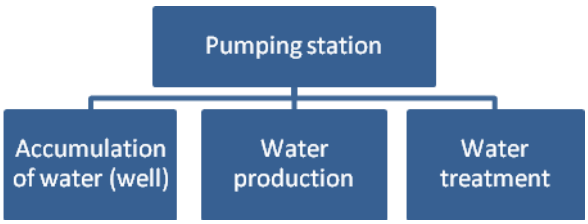

Figure 7. Functional systems in the pumping station

a. Boundaries of the system

In the pumping station, the boundaries of the system are selected in such a way that they cover all important functions which should be performed by the pumping station. The selected boundaries provide a link between the input and output of certain functional systems in the pumping station. At the same time, this represents preparation for the performance of further activities, such as drawing block diagrams.

b. Functional block diagram

If **water production and water treatment** are designated as a system, it can be separated into three functional subsystems:

- drive,
- pumping water
- chlorination of water.

The functional subsystems and their relationships are shown in the block diagram in Figure 8.

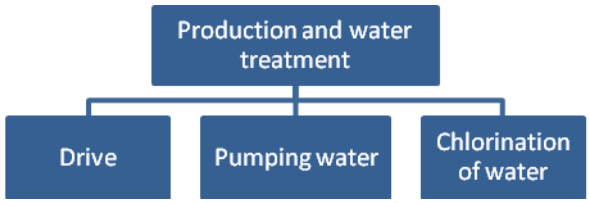

Figure 8. Functional subsystems

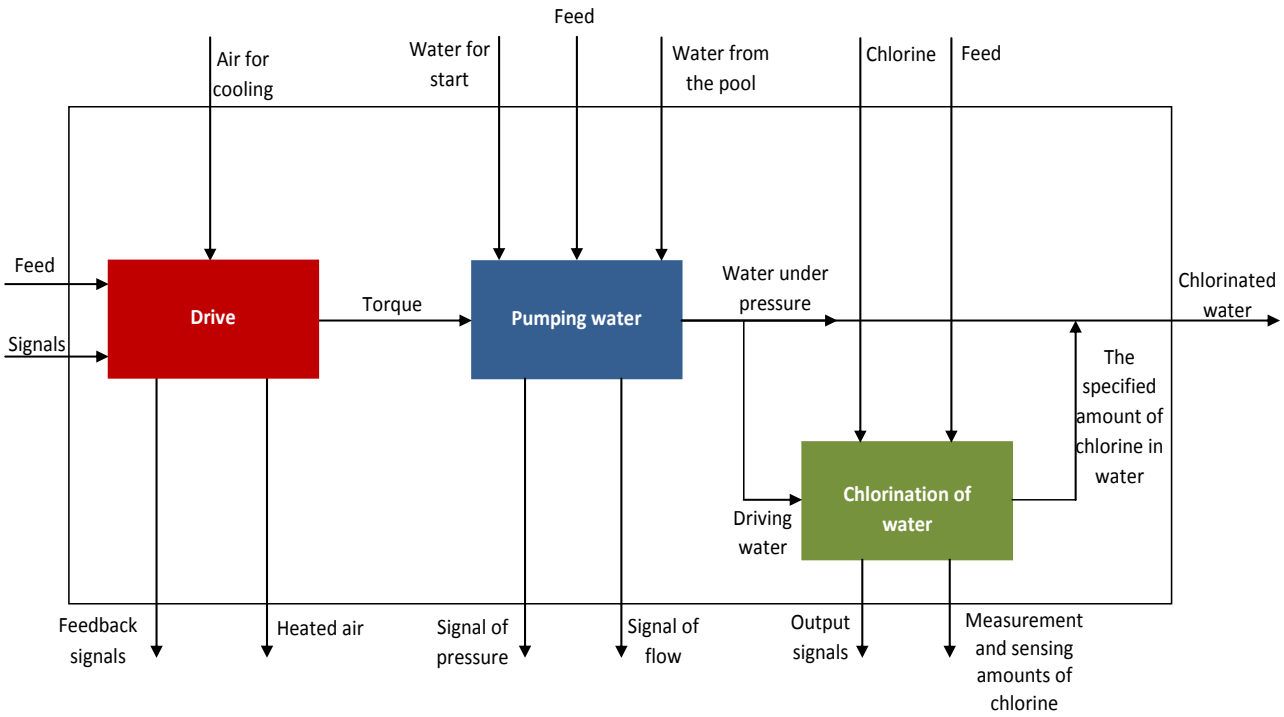

Figure 9. Functional block diagram

4.2. Functions and functional failures

Definition of functions and functional failures is presented in the example of the subsystem for chlorination of water.

For chlorination of water, it is necessary to use the injector for achieving a defined value of subpressure/underpressure, so that the vacuum regulator could provide chlorine flow to the discharge pipeline. Within this subsystem, a very important function is also realized – measuring and inspection of concentration of free chlorine.

Table 1. Functions and functional failures in the subsystem for chlorination of water

Providing the necessary flow of chlorine	Leaking of chlorine
	Insufficient flow of chlorine
	Dropping of the chlorine dosage
Indication of the quantity of chlorine	Indicator on the vacuum regulator shows “empty“
	Quantity of chlorine in water cannot be read
Providing the necessary subpressure/underpressure	Insufficient pressure
Providing operation without disturbing factors	Water in the vacuum installation
Measuring concentration of free chlorine	Insufficient flow of water through the measuring block
	Insufficient electrode current
	Unstable value of chlorine concentration
Providing operating water of the given pressure	There is no flow of operating water to the booster pump
	Flow of water in the discharge pipeline cannot be controlled
	Insufficient pressure of operating water
	Pressure of operating water cannot be inspected

4.3. FMEA

After the data about systems with their subsystems, components of the systems and their failure modes with causes of failures and functions of the systems with functional failures are formed, it is necessary to establish the relationship between functional failures and failure modes of components. This part is the most complex part of the RCM analysis, and it is solved by means of the matrix of interdependences between failure modes of components and functional failures, which is presented in Table 2.

Table 2. Matrix of interdependences between failure modes of components and functional failures

Com. #	**Component name**	**Functional failures**													
		3.1.1	3.1.2	3.1.3	3.2.1	3.2.2	3.3.1	3.4.1	3.5.1	3.5.2	3.5.3	3.6.1	3.6.2	3.6.3	3.6.4
23	Sensor of chloral level					X									
26	Gate valve											X			
27	Booster pump			X			X								
28	Valve Z3												X		
29	Valve on the pressure branch of the water flow													X	
30	Gauge of water flow														X
31	Valve V3													X	
32	Injector			X			X	X							
33	Vacuum hose		X												
34	Vacuum regulator	X	X	X	X		X								
35	Valve for chlorine	X													
36	Bottles for chlorine	X													
37	Flow regulator of chlorine analyzer								X		X				
38	Pressure regulator of chlorine analyzer										X				
39	Analyzer of free chlorine								X	X	X				

4.4. LTA

Within the RCM analysis, all functions of the pumping station with its functional failures have been treated. All possible failure modes with their causes have been formed for key components of certain subsystems, such as the electromotor, the centrifugal pump, the injector for chlorination and the vacuum regulator, as well as for a large number of other components. In order not to become too extensive, the paper leaves failure modes for certain components to be further developed.

Table 3. Presentation of the RCM analysis

RCM category	**Number**
System	1
Subsystems	3
Components	40
Functions	17
Functional failures	37
Failure modes (with causes of failures)	94

Establishing of all necessary relationships required by RCM results in a wide platform for research not only into reliability but also into other indicators which characterize maintenance of a technical system.

Failure modes are classified into two groups:

- Group 1 (A, B, D/A and D/B)
- Group 2 (C, D/C)

Table 4. Categorization of failure modes by groups

	Group 1	Group 2
A – safety problem	4	
B – outage problem	40	
C – minor economic problem		35
D/A - hidden failure / safety problem		
D/B - hidden failure / outage problem	13	
D/C - hidden failure / minor economic problem		2
Total	57	37

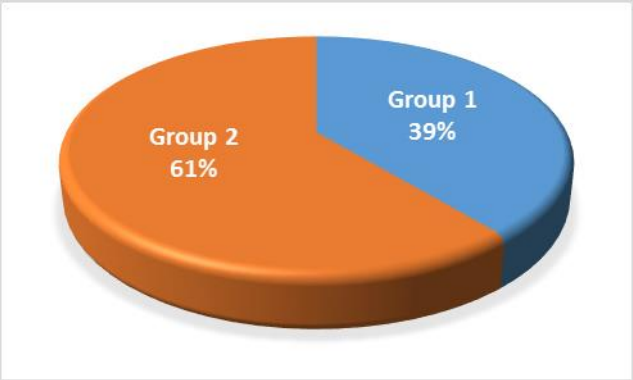

Figure 10. Classification of failure modes by effects

On the basis of the diagram from Figure 10, it can be concluded that 61% of failure modes should be planned for preventive maintenance, and 39% for corrective maintenance.

4.5. Maintenance tasks

Potential maintenance tasks belong to one of the 4 possible categories:

1. TD – Time – Directed
2. CD – Condition – Directed
3. FF – Failure Finding
4. RTF – Run to Failure

When the relationship between the effects of failure modes and maintenance tasks is established, the situation is as shown in Table 5.

Table 5. Relationship between the category of failure modes and maintenance tasks

	TD	CD	FF	RTF	
A –safety problem	4				4
B –outage problem	22	10	3	4	39
C – minor economic problem	20	7	9		36
D/A - hidden failure/ safety problem					
D/B - hidden failure / outage problem	5	2	5	1	13
D/C - hidden failure / minor economic problem	2				2
Total	53	19	17	5	

5. CONCLUSION

Classification of failure modes and maintenance tasks on the example of a pumping station of the waterworks was carried out by applying the algorithms developed in the RCM methodology. The most effective task of preventive maintenance was selected for every failure mode, so that this example also confirms that RCM equally treats all maintenance concepts. RCM is led by safety and costs. The selection of maintenance activities is based on consequences: safety, operational, non-operational and consequences of hidden failures. Safety must be achieved at any costs, and after that costs become a criterion.

By applying the RCM methodology, on the example of a pumping station of the waterworks, and by the analysis of a set of all possible failure modes, it was established that 61% of failures could be prevented or that their effect could be reduced by proper selection and periodic repetition of preventive maintenance tasks. Hence, it can be concluded that city waterworks are suitable systems for application of the RCM methodology. Besides the suitability for application, the other positive effects of RCM application stated in the paper may be expected in these and similar systems. In addition to a series of advantages, the RCM methodology also has its weaknesses, which primarily refer to the length of duration and necessity of software support. RCM analysis on a relatively simple example, such as the pumping station, cannot be successfully realized without computer support.

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