MATRIX-BASED METHODS FOR PLANNING AND SCHEDULING MAINTENANCE PROJECTS

Judit Kiss[1], Zsolt Tibor Kosztyán[2], Anikó Németh[2] and Ferenc Bognár[1]
[1]Department of Management, University of Pannonia, Hungary
[2]Department of Quantitative Methods, University of Pannonia, Hungary

ABSTRACT
Handling specialities of maintenance projects is a highly challenging task. On the one hand the operations of the maintenance tasks are fixed, and can be described with network or process planning methods. On the other hand the realization sequence of maintenance tasks depends on the risks and reliabilities. Therefore, traditional project and process planning methods are not well suited to manage the maintenance tasks. In this paper a new multilevel planning method is introduced, where project constraints can be taken into account in determining the optimal maintenance project. Tasks which have to be realized can be ranked with our method based on their reliabilities or risk factors. The introduced procedures show how matrix-based methods can be applied for planning and scheduling the maintenance projects on the level of the whole system, the devices, the maintenance tasks and their operations.

Keywords: Multilevel maintenance project planning and scheduling, reliability and risk oriented PEM

1. INTRODUCTION

In case of large number of devices the planning and scheduling of maintenance tasks is very difficult. Despite this fact, lots of companies play down the maintenance activities, they operate their devices until an error occurs (called run-to-failure). However, the reparation or the replacement of some parts can have a very high cost and it can cause a drop-out in production. The managers need to understand, that maintenance is not a necessary evil, it is a very important and usually very complicated task, but still about two third of the companies do not apply any sort of planning methods for maintenance. They want to save their money and time on maintenance tasks; however, continuous maintenance according to a well optimized plan could contribute to the undisturbed production and help to keep the maintenance costs low. A common problem is that the planners actually have never touched the equipment, which have formed an opinion about, they do not know their functions, likely failures and the possible consequences of the failures. It is not uncommon, that those experts who compiled the maintenance plans, do not know, how the system work exactly. During the participation at the failure mode analysis, the planners will learn the possible failures, which were either caused by human error or the fatigue of components and thus they will know what to do to prevent problems. Understanding the consequences of possible failures have got a key role in forming a personal experience that is invaluable when planning maintenance. This process will also help the users to understand the necessarity of maintenance. The aim of our study is to attract the attention to the importance of maintenance planning to schedule and plan which maintenance tasks should be realized in which order during the maintenance process or project. The reliability of the devices or the risk of their failure must be considered as well as the time, cost and resource constraints of the project to repair or replace them. This study aims to develop a new methodology for planning and scheduling maintenance projects, which enables the prioritization of maintenance activities, in order to determine the treatment cycles.

According to the RCM (*Reliability-Centered Maintenance*) (Rausand, 1998) the maintenance tasks are ranked by the probability of device failure in the time interval of the maintenance planning. Those devices, that have high failure rate and therefore have lower operating time between failures, are prioritized and their maintenance tasks are completed first. The order of priority can be more exact if the costs and required time of the inspection and preventive maintenance are compared to the costs and required time of the corrective maintenance and both the material and immaterial loss of the failures. The severity of the failures is weighted by the probability of the failure so the classification and decisions are carried out based on risks (RBM – *Risk-Based Maintenance*) (Khan and Haddara, 2003; Carazas and Souza, 2010; Garbatov and Guedes Soares, 2001).

A widely used risk-based approach is the FMEA (*Failure Modes and Effects Analysis*) (MIL-STD, 1980), where RPN numbers can show the priorities. The RPN (*Risk Priority Numbers*) are the results of the FMEA procedure. RPN numbers can be calculated as the product of three factors like occurrence, severity and detection (Xiao et al., 2011). Based on these priority numbers it is possible to plan and organize the maintenance projects with the help of matrix-based methods.

2. METHODS FOR PLANNING AND ORGANIZING MAINTENANCE PROJECTS

The realization of maintenance tasks can be regarded as a special maintenance project. However, traditional network planning methods have several deficiencies and pose some difficulties when using project planning methods in maintenance. The first shortcoming of network planning methods is the inability to handle circles. It is a frequent problem that a task needs to be realized more than once in a project (i.e. diagnose and revise a part of equipment until it works). However the GERT method (Pritsker, 1966) can handle circles, but still, for detecting and managing circles the matrix-based methods give better alternatives.

The other problem is to determine the sequence of the maintenance tasks. Traditional logic planning methods are hard to use for these projects, because the sequence of operations ina maintenance task can be described with a deterministic logic plan (network plan, Gantt chart etc.). However, most of the sequences in maintenance tasks (i.e. repairing different kind of equipments) are independent from each other. It means that the sequence of maintenance tasks can be reversed or can be ranked by their reliability or risk values. Since network planning methods cannot be used for ranking the maintenance tasks, hereinafter matrix-based methods are introduced. These methods, as it will be shown in the next section, can handle circles and can also be used for ranking maintenance task sequences.

2.1 Matrix-Based Project Planning Methods

There are many algorithms (Gebala and Eppinger, 1991; Warfield, 1973) in connection with DSM method for searching and handling cycles, consequently Dependency Structure Matrix can be a useful basic tool at handling the cyclic dependencies between maintenance tasks. Binary DSM (Steward, 1981) is not appropriate for handling multiple possible ways of realizing maintenance tasks; however, the numerical DSM (Browning and Eppinger, 2002) can express the uncertainty of the relations in form of dependency strength or probability of repetition. Authors have formerly published the Stochastic Network Planning Method (SNPM) (Kosztyán and Kiss, 2010a) for generating all possible project networks. Acronym of SNPM alludes to uncertain project network. Uncertain relations are represented by probability values between 0 and 1 in the off-diagonal cells.

Despite the fact that these methods handle the uncertain relations they cannot handle the realization priority of the tasks. On the other hand the enhanced SNPM method, called Project Expert Matrix (PEM), can handle the uncertain realization of the tasks as well (Kosztyán and Kiss, 2010b). The uncertainty of the task realizations can be noted in the diagonal of the PEM matrix. The certain task realizations denoted as 1 or “X” in the PEM matrix.

2.2 Applying Matrix-Based Project Planning Methods for Organizing Maintenance Projects

Maintenance projects have their specialities. In this study a new method is introduced which have some novelties for planning and scheduling of maintenance projects. Maintenance is one of the most common activities in the industrial sector; however, many companies do not deem it important, because they want to save money and time on keeping the maintenance in background, Planning and scheduling of maintenance projects need *multiple level* thinking. It means a kind of multiple level optimization of the maintenance from the level of the whole company to each maintenance task. The top level is the level of the whole system. The middle level is the level of the devices or equipments and maintenance tasks belonging to each device are on the lower level. Tasks can be decomposed into operations. The values of the matrices on the different levels can represent diverse as it is introduced in the followings. Data can be derived mainly from the maintenance experts of the companies.

Operations of maintenance (i.e. servicing an equipment, evaluating results of diagnostics etc.) usually can be described as a deterministic logic plan (using a task list, Gantt chart etc.). In this case the operations of a maintenance task have a fix order the operations have to be realized in a sequence following the task list.

At the same time the order of the *maintenance tasks* can be different: sequential or parallel as well, the realization order of maintenance tasks can be determined considering the values of reliability and risks. Not just the precedence relations, but also the task realizations can be uncertain, they can have different probabilities. Probability 1 means the certain tasks, which surely have to be maintained, while probability 0 represents that task which can be postponed for later maintenance. There can be probabilities between 0 and 1; they refer to the uncertainty in case of task realizations and relations as well. The "classical" PEM (Project Expert Matrix) method (Kosztyán and Kiss, 2010b) can be used at the level of tasks, where the maintenance project tasks are the elements of the matrix, the probabilities of tasks are in the diagonal cells, and the probabilities of relations between tasks are in the off-diagonal cells.

What kind of values can be represented in the PEM matrix? How the values can be determined? Where the values come from? These are very important questions which can be answered through different ways. The values of the PEM can derive from different sources. They can represent reliability or risk, probability or priority regarding the different levels. Various procedures can be applied for determining the values of the PEM matrix.

At the lower level tasks of a process can be derived from flowchart or extended event-driven process chain (eEPC). These figures can be transformed into PEM matrix form. The relative frequencies of the task occurrences are indicated in the diagonal of the PEM. All of these forms are capable of using the "exclusive or" (XOR) operator to help the representation of the decision situations. Applying operators for planning maintenance projects is newly introduced in our paper, as well. The probabilities of precedence relations are in the off-diagonal cells.

After defining the possible values of the task realizations and precedence relations, time, cost and resource data can be assigned to the tasks. Consequently different project scenarios (different task variations) with cost needs can be determined. After that different project structures of a project scenario (different realization ways of tasks) can be determined and their time and resource needs can be calculated according to the values of the PEM matrix. The application of matrix-based methods (like PEM and DSM) during the task and operation levels of maintenance projects is summarized on figure 1. It means a scheduling exercise on the level of tasks. The average and maximal maintenance time and the expected maintenance cost can be calculated during the scheduling. A project plan is infeasible if (time, cost, resource) demands are higher than the project constraints. The optimal project plan is that feasible project plan that possesses the highest probability.

The probability of task realizations can be determined from the values of reliabilities or level of risks and can be represented into the diagonal of the rPEM matrix. Maintenance tasks should be ordered by their probability of realizations. Preferred sequential and parallel realization can be expressed by the strength of relation between two tasks. Accordingly the budget feasible project scenarios can be specified and can be ranked by the probability of project scenarios. Project scenarios can be represented by an SNPM or an NDSM matrix. In this phase we can answer WHAT maintenance tasks should be realized in agreement with the project budget. According to the time and resource constraints feasible project structures can be specified and can be ranked depending on the probabilities. In this phase we can answer HOW to realize the maintenance tasks. The logic plan of project structures can be represented by a DSM matrix. Duration and resource demands can be represented by a resource sheet. Finally it can also be answered HOW MUCH are the cost and resource demands of this solution.

Such possible repairing and preventing tasks can be assigned to all *failure causes of a given device*. On the next level the relations between the possible failure causes can be represented with the help of the special PEM method, with the rPEM (*reliability and risk oriented PEM*). The basis of this method is the Reliability Block Diagram (or dependence diagram), which is a representation of parallel or series connected blocks, where each block means a component of the system with a failure rate (Modarres et al, 2010). It is investigated whether an error occurs it causes a system failure or not. If the reliability is sequential, all tasks have to operate perfectly or the whole system goes out of order. The failure causes are the elements of the rPEM on the level of devices.

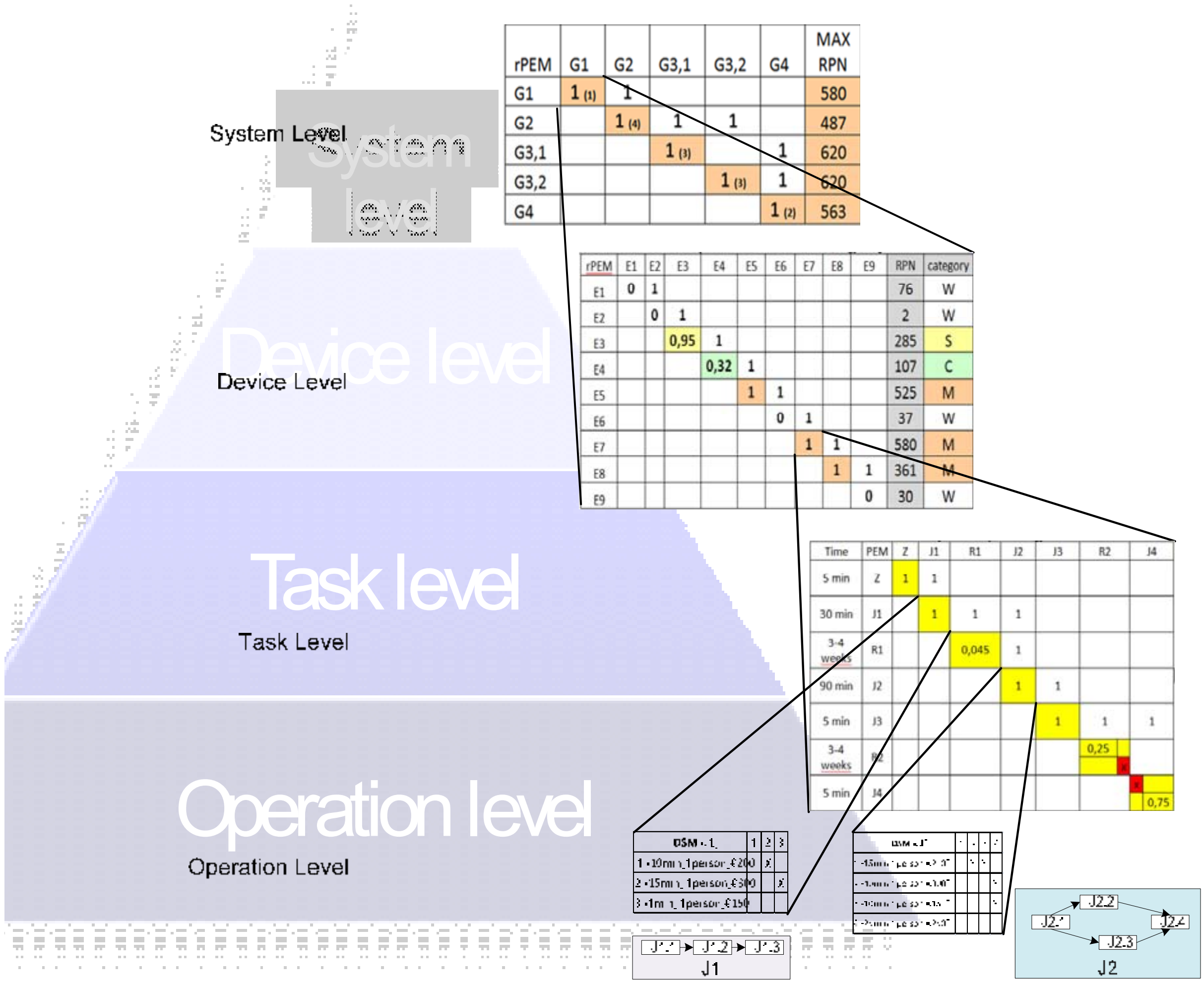

Figure 1. The summary of the maintenance project planner procedure

So called RPN numbers can be assigned to the failure causes. RPN numbers are the outputs of these procedures at the same time they are the inputs of the rPEM matrix.

Based on RPN numbers different intervening categories of failure cases can be composed. One of these categories is that option when maintenance won't have realized (category W) below a certain RPN value. It is notated in the rPEM matrix by 0. However, repairing and preventing tasks or diagnostic inspections must have performed above a certain RPN value (category M). It is marked in the rPEM by 1. According to MoSCoW analysis two other categories can be differentiated: category S (should have), where it is necessary the revision or at category C (could have) the intervention can be omitted. Based on these categories it is possible to decide whether intervention is necessary or not at occurring a failure of a device. The scheduling of the maintenance tasks of a failure is the exercise of the previously introduced step and level.

Not just the level of the devices, but also the level of the *whole system* can be characterized by RPN values. The general risk of the devices or subsystems can be specified based on the general or summed RPN values. Taking the maximal RPN values into account gives information where intervention is proposed. Regarding the rPEM matrix of the subsystems a priority can be determined, which subsystems in which order need to maintain. This level means the top of the maintenance project planning.

3. SUMMARY

Maintenance projects have their specialities, which can be hardly solved by traditional planning and scheduling methods. In this paper a multilevel matrix-based method was introduced for supporting the maintenance of a whole system.

On the level of the whole system the criticality of devices and subsystems are regarded. On the level of the system and the devices RPN numbers determine the order of the maintainable devices. The so called reliability and risk oriented PEM (rPEM) can be applied at these levels. Failures can occur at each device, and there are some tasks which have to be realized during the maintenance. These tasks can be scheduled with the help of the PEM method. However, maintenance tasks have a fixed operation sequence.

The summary of our method are represented on Figure 1. This procedure can be the basis of an expert system, which can give where, at which devices have to be intervened, according to the failure cause which elements of the devices have to be maintained, what kind of tasks have to be executed during the maintenance process. Our methods can contribute to increase the efficiency of the production system taking the cost of the enterprise into account.

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Contact: Judit Kiss
Department of Management,
University of Pannonia
Egyetem u. 10.
H-8200 Veszprém
Hungary
Phone: +36-88/624-243
Fax: +36-88/624-524
e-mail: kissjudit@gtk.uni-pannon.hu

INVEST ON VISUALIZATION

Matrix-Based Methods for Planning and Scheduling Maintenance Projects

Judit Kiss[1], Zsolt Tibor Kosztyán[2], Anikó Németh[2] and Ferenc Bognár[1]

[1]Department of Management, University of Pannonia, Hungary
[2]Department of Quantitative Methods, University of Pannonia, Hungary

Technische Universität München

INVEST ON VISUALIZATION

Index

- Specialities of the maintenance projects and processes
- The difficulties of the planning of the maintenance projects
- The constraints of the scheduling of the maintenance tasks
- Matrix-based methods for planning of maintenance projects
- The novelties of our method
- Case study

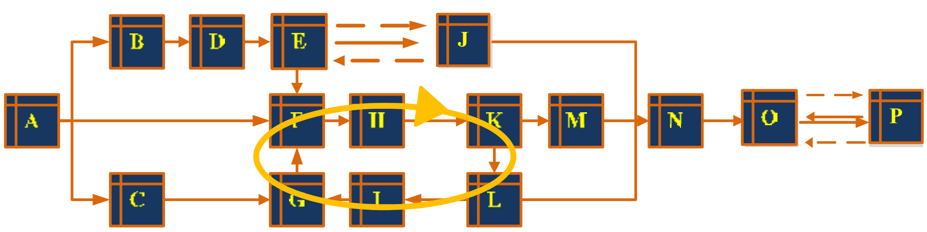
Maintenance Project and Process Planning

- The **difficulties** of the maintenance planning:
  - The shortcomings of the knowledge
    - about the functions and failures of devices, as well as
    - their effects and consequences.
  - How to use the results of analysis during the planning.
  - The order of the tasks can change.
  - Tasks can be postponed.

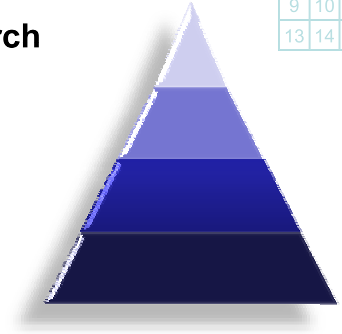
- The **constraints** of the maintenance tasks' planning
  - Time;
  - Money;
  - Resources;
  - Complexity of the maintenance.

How to Plan the Maintenance?

- **Questions** of the maintenance planning:
  - Can „traditional" project planning methods be applied at maintenance?
    - Which maintenance tasks have to be realized?
    - How to plan the circles?
    - In which order?
  - How much is the time, cost and resource need of the tasks?
  - Where can the required data be obtained from?

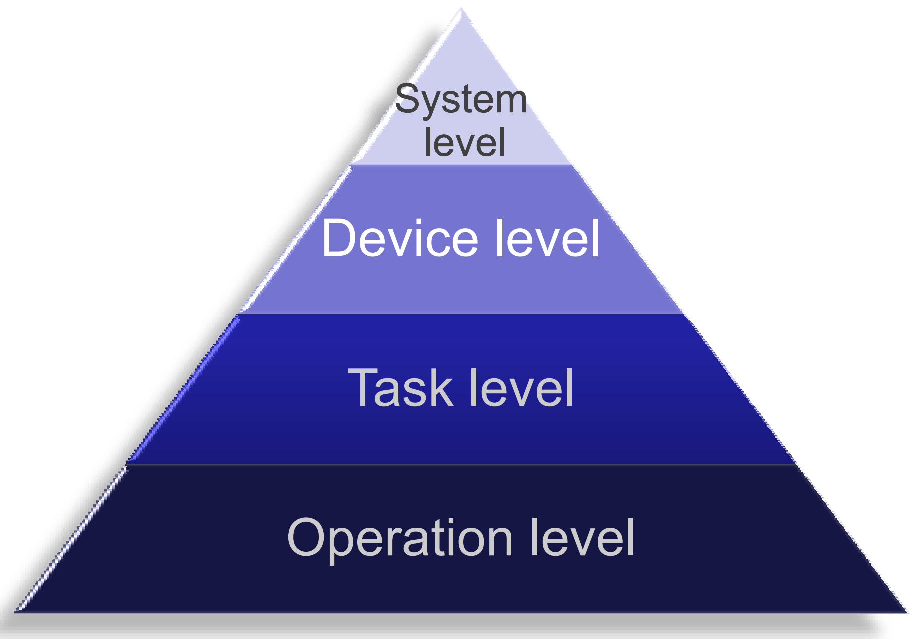


The Novelty of Our Research



- Multilevel thinking.
- Different meaning,
  - The meaning of the values in the matrix can be different in different levels, but similar algorithms can be used.
- Applying operators.
- Optimization according to single or multiple objectives.
- IT support
  - Genetic algorithms

Multilevel Thinking at Maintenance Projects



Case Study

- Continental Teves Hungary, Veszprém site
- Multinational company with German parent company
- Electronics products, mainly for the automotive industry (predominantly detectors, sensors).
- The test machine (SensorCluster) was an element of an automated production line.
- The study was carried out in spring 2011.

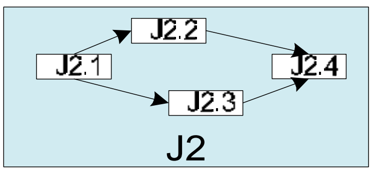
Operation Level

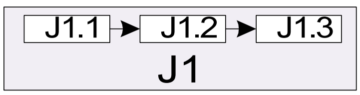
- The operation order of maintenance tasks is fixed.
  - In the DSM matrix,
  - In the reliability block diagram.

Operation level

DSM (J2)	1	2	3	4
1 ¦15min,1person,€200¦		X	X	
2 ¦40min,1person,€300¦				X
3 ¦10min,1person,€150¦				X
4 ¦25min,1person,€250¦				

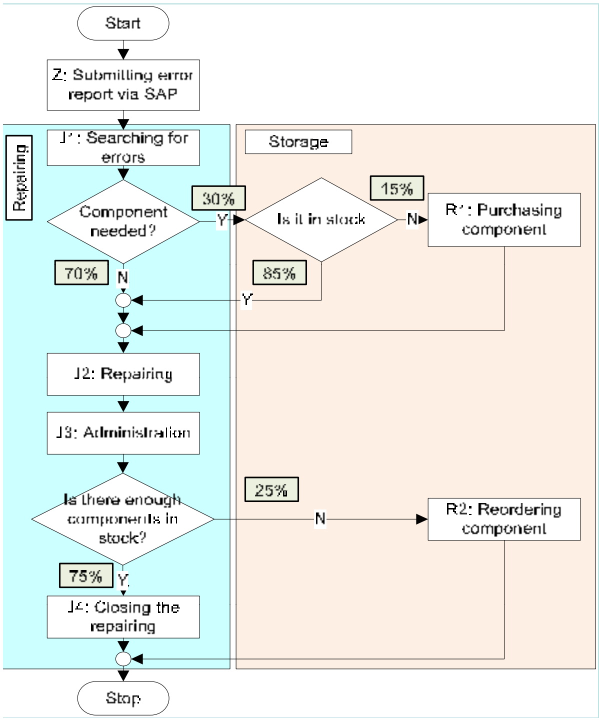
DSM (J1)	1	2	3
1 ¦10min,1person,€200¦		X	
2 ¦15min, 1person,€300¦			X
3 ¦1min, 1person,€150¦			





Maintenance Task Level

- With flow chart
- With event-driven process chain



Maintenance Task Level

- On **P**roject **E**xpert **M**atrix
  - In the diagonal: frequencies,
  - In the off-diagonal cells: precedence relations between tasks.

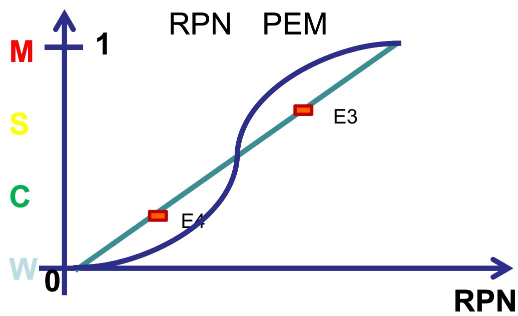
Maintenance tasks

Time	PEM	Z	J1	R1	J2	J3	R2	J4
5 min	Z	1	1					
30 min	J1		1	1	1			
3-4 weeks	R1			0,045	1			
90 min	J2				1	1		
5 min	J3					1	1	1
3-4 weeks	R2						0,25 x	
5 min	J4							x 0,75

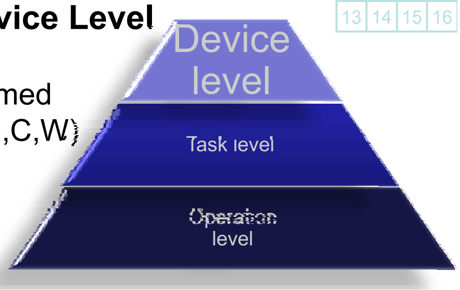
Applying operators for decision points

Determining Values on the Device Level

- **Elements** of the reliability PEM: evaluation faktors or failure causes in connection with devices
- Aggregated prefence table taking the opinion of relevant experts into account (using the method of paired comparison?)
- RPN numbers to failure causes
- RPN number is the product of the occurrence, severity and detection factor   results of the FMEA (Failure Modes and Effects Analysis)
- RPN numbers into categories (M, S, C, W)
- Conversion RPN numbers into [0,1] for the diagonal of the rPEM



Reliability Oriented PEM to Device Level



- In the **diagonal** of rPEM numbers [0,1] were transformed from the RPN numbers based on the categories (M,S,C,W)

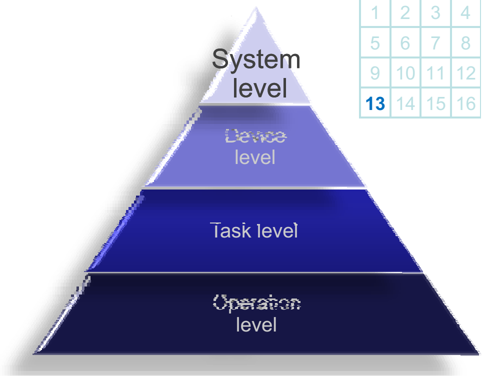
rPEM	E1	E2	E3	E4	E5	E6	E7	E8	E9	RPN	category
E1	0	1								76	W
E2		0	1							2	W
E3			0,95	1						285	S
E4				0,32	1					107	C
E5					1	1				525	M
E6						0	1			37	W
E7							1	1		580	M
E8								1	1	361	M
E9									0	30	W

$\overline{RPN}=$ 95

MAX(RPN)= 580

$$r_{i,i} = \begin{cases} 0, & \text{if} \quad RPN < 100 \\ 1, & \text{if} \quad RPN > 316 \\ \dfrac{\sqrt[3]{RPN - 100}}{6} & \text{otherwise} \end{cases}$$

E1 → E2 → E3 → E4 → E5 → E6 → E7 → E8 → E9



System Level

- The **elements** of the matrix are the devices/sub-systems
- Extra column for the **maximal RPN** numbers of the devices/sub-systems
- In the **diagonal** [0,1] numbers transformed from the RPN numbers based on the categories (M,S,C,W)
- In the diagonal in brackets are the priorities
- In the **off-diagonal** cells the realization order of the sub-systems

rPEM	G1	G2	G3	G4	MAX RPN
G1	1(2)	1			580
G2		1(4)	1		487
G3			1(1)	1	620
G4				1(3)	563

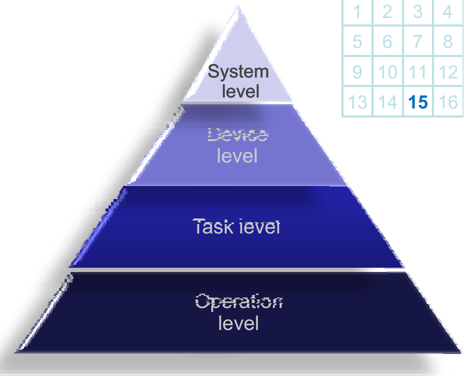
System Level

rPEM	G1	G2	G3	G4	MAX RPN
G1	1(2)	1			580
G2		1(4)	1		487
G3			1(1)	1	620
G4				1(3)	563

Parallelisation
Priorities change

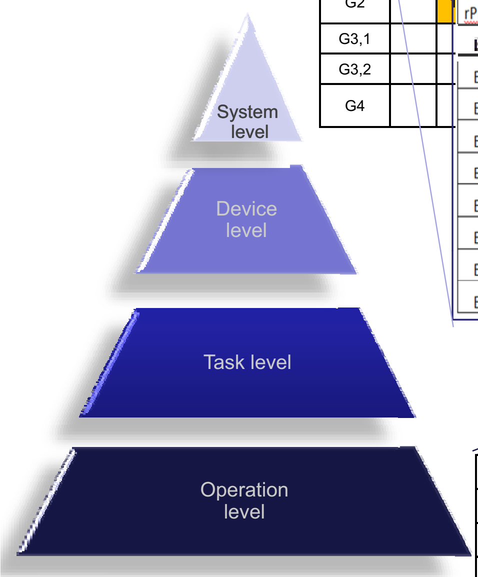
rPEM	G1	G2	G3,1	G3,2	G4	MAX RPN
G1	1(1)	1				580
G2		1(4)	1	1	1	487
G3,1			1(3)		1	620
G3,2				1(3)	1	620
G4					1(2)	563

Summary



- Sub-systems and devices can be prioritized at the level of the whole **system.**
- Possible failure causes can be considered at each **device**
- Values of the reliability oriented PEM matrix can be determined using quantitative (like criticality estimation – RCM/RBM) or qualitative (like FMEA) methods.
- **Tasks** can have different priority/probability.
- Operators can be applied for supporting decisions between maintenance tasks.
- **Operations** are given for the maintenance tasks

Application



rPEM	G1	G2	G3,1	G3,2	G4	MAX RPN
G1	1(1)	1				580
G2						
G3,1						
G3,2						
G4						

rPEM	E1	E2	E3	E4	E5	E6	E7	E8	E9	RPN	category
E1	0	1								[illegible]	W
E2		0	1							2	W
E3			0,95	1						285	S
E4				0,32	1					107	C
E5					1	1				525	M
E6						0	1			37	W
E7							1	1		580	M
E8											
E9											

Time	PEM	Z	J1	R1	J2	J3	R2	J4
5 min	Z	1	1					
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5 min	J3					1	1	1
3-4 weeks	R2						0,25 x	
5 min	J4							x 0,75

DSM |J1|	1	2	3
1 ¦10min 1person €200|		X	
2 ¦15min 1person €300|			X
3 ¦1min 1person €150|			

What? How? How much?