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*reliability,*
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# ON A SYSTEMATIC APPROACH TO DEVELOPMENT OF MAINTENANCE PLANS FOR PRODUCTION EQUIPMENT

Abstract: Reliability is a collective term covering several abilities of the technical system: to deliver required functions, to uphold quality of products and services, to assure that the safety requirements associated with the system are properly fulfilled with regards both to the users and the environment, and finally to uphold the durability of the technical system during its whole life cycle. All this has to be performed at acceptable risks, optimal cost, and correspond to operational needs of the business. Even though there is an advanced, well thought-out concept for this purpose – reliability centred maintenance (RCM) – that correctly applied might result in very good quality maintenance programs, it is not broadly used in the industry due to the vast efforts required for its implementation. An appropriate methodology supporting systematic functional break down of a studied systems, and guidelines how to couple functional failures to failure modes, integrated with RCM, would greatly speed up generating of effective maintenance programs. In this paper we present our research towards development of such a methodology, and show a pilot implementation to analysis of machine tool spindle. The methodology is based on Hubka's theory of design and AFD/TRIZ.

## 1. INTRODUCTION

High reliability is one of the most indispensable qualities of contemporary production systems. The new paradigm for European manufacturing sector (The Lisbon European Council strategy of March 2000) sets utilization of production resources to a main competitive weapon. Closer coordination between the demand and supply sides, further increase in efficiency, enhanced customization, and speed of delivery are necessary. To meet these requirements European companies have to achieve much higher operational availability and capability of production systems than it is possible with currently used maintenance methods.

Maintenance is also an immense business. European companies spend about 140 billion euro per year on maintenance activities. Additional, considerable costs are connected

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to consequences of poor or wrong performed maintenance work. As can be seen, the importance of maintenance is growing very fast, and becomes a strategic issue requiring urgent research efforts.

Reliability is a collective term covering topics like ability of the technical system to deliver the required functions in the intended time extend, to uphold equipment condition allowing maintaining of quality of products and services, to assure that the safety requirements associated with the system are properly fulfilled with regards both to the users and the environment, and finally, to uphold the durability of the technical system throughout its whole life cycle. All this requirements have to be fulfilled at optimal cost, and in a way that corresponds to operational needs of the business, so preparation of an adequate maintenance plan is a real challenge.

An important step in advance of this area was development of the reliability centred maintenance (RCM) concept. The RCM process is used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context. Correctly applied, RCM might result in cost-effective maintenance programs by addressing dominant causes of equipment failure, and focusing on delivery of functions that users expect from the equipment [4]. RCM is based on Failure Mode and Effects Analysis (FMEA), and a workflow model helping to determine the appropriate maintenance tasks for the identified failure modes. However, the RCM is only sparingly used in the industrial praxis due to immense efforts required for its implementation. The main problems here are caused by lack of methods supporting appropriate functional breakdown of the studied systems, and adequate coupling of functional failures to failure modes. Such methods would greatly speed up this process.

Availability of an asset is affected not only by the failures taking place, but also by the extent of preventive maintenance tasks. Any maintenance carried out on an asset – whether it is a replacement, refurbishment or even inspection – forces downtime, and additionally induces a risk of failure (wrong assembly, human error, contamination of disassembled components, and the like). Therefore, looking for improvements, one has to pay attention to reduction of need for maintenance measures.

The applied maintenance strategies should be reviewed as well. For instance, the commonly used scheduled preventive maintenance concept regularly results in a poor performance. The constant time intervals selected for execution of the individual maintenance tasks are based on failure statistics (e.g. mean time between failures, MTBF). However, typically large spread in these measures makes the predictions of wear-out time inaccurate and results in low availability. Also, access to these statistics becomes now limited, because we strive after failure-free equipment, and design increasingly better machines. In contemporary production systems most of the equipment failures cannot be related to a certain wear-out time. The traditional maintenance paradigm based on a ‘bath-tub’ curve is outdated – in more than 80% of cases one cannot observe any increase in failure frequency along the exploitation time. This means that the failures are rather unpredictable, and periodic maintenance practices implies high risks.

Condition based maintenance techniques (CBM) seem to be an effective way to predict development of failures and address them before they occur. CBM helps to detect a change in performance levels, predict when a maintenance measure will be required and in consequence, by better planning, reduce the efforts needed for maintenance. However, enhanced use of CBM requires providing the equipment with additional sensors and systems for carrying out condition monitoring. This in turn results in more expensive design, which has to be economically justified by the benefits it provides to the production system during its life cycle. At the same time the installed equipment increases maintenance need itself and leads to a decreased sense of failure accountability by the operators (operators not noticing a deviation from the required performance of the asset) [6].

In accordance to RCM's proactive concepts and the abovementioned factors, it becomes clear that the most efficient way to improve equipment availability is to properly address the safety, reliability and maintainability issues already during the design phase.

In this paper we describe progress in our project aimed at development of a formal methodology for design of maintenance programs for industrial equipment. At the current stage, we focus on potential techniques that could aid the RCM method.

## 2. A METHODOLOGY FOR DEVELOPMENT OF MAINTENANCE PROGRAMS

RCM systemizes selection of maintenance tasks. Decisions on how to address a failure are taken based on its consequences. Failures with safety or environmental consequences have to be eliminated without any other consideration, while failures with operational or other consequences must be treated with actions technically feasible and cost effective.

The methodology that we propose in this paper supports the RCM and consists of four steps:

1. Functional Analysis of the system.
2. Identification of functional failures, failure modes and risk scenarios.
3. Evaluation of failure consequences.
4. Maintenance task design.

### 2.1. FUNCTIONAL ANALYSIS OF THE SYSTEM

The first step is to identify and document functionality of the studied system. When preparing a maintenance plan, we have to first list out what functions has to be delivered by the system, and to what performance, and then assert a potential functional failures, their failure modes and then their causes. Having the list of functional failures we can systematically analyse the potential consequences of what will happen if the functions will not be delivered, and then find out technical feasible and worth doing maintenance tasks to address these consequences. This process however is usually not simple. The functions interplay with each other, their relations are entangled and difficult to understand, and the consequences of losing them are difficult to foreseen. A formal approach, based on an appropriate and consistent design theory is required to make the process effective.

In our opinion, the most appropriate theory which fits the needs is developed by V. Hubka and E. Eder "General Procedural Model of Engineering Design" [2]. In this model context, a technical process (TP) uses technical systems (TS) to transform an operand's (the subject of the process – Od) state (vector of operand's properties) by using a certain technology (Tg) which follows a certain technological principle (TgPc). The technical system, together with the humans involved, constitute the operators (Op) of the model, which have effects (Ef) on the operand, i.e. the means of transformation and actions applied on the operand. The process is also subjected to secondary inputs, desirable or not and produces secondary outputs, usually undesirable. See Fig. 1.

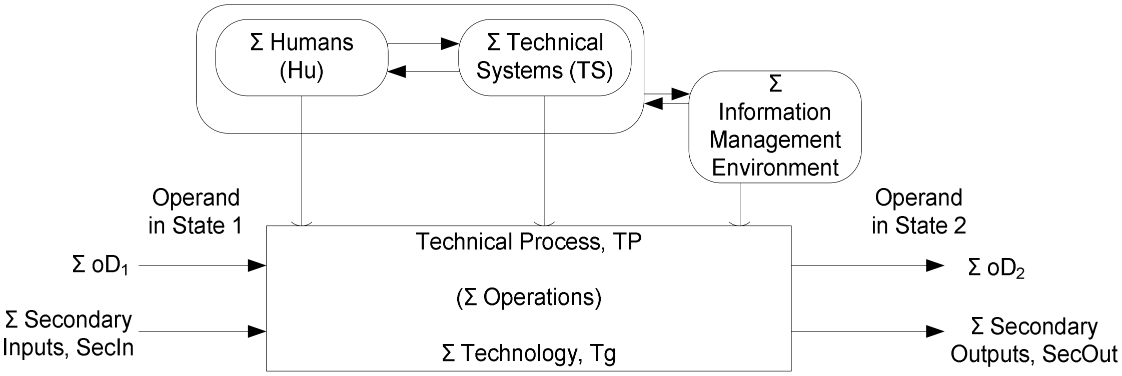

Fig. 1. The technical process general model

The technical system performs the transformation through a set of internal functions, often using an action medium. These internal functions, delivered by respective components or subsystems comprise an action chain affecting the operands (i.e. changing their states).

This theory is perfectly fitting our needs. It's both accurate and consistent enough to allow rigorous description of system hierarchies, component structures, delivered functions together with all the possible and complex relations, mechanisms, dependencies, causes and effects – all the means which are required by a formal methodology.

The first step in performing the functional analysis is to define the system's boundaries and decompose hierarchically the technical system in terms of both functions and components. The functional decomposition is documented as a set of basic functions, functional modules, and interactions. This is the first hierarchical level, where each functional module is regarded as a technical process. The list of functional modules has to be completed with corresponding required performance standards. These performance standards can be:

- Functional (speed, power, load capacity, overall size, communication capabilities, suitability for specific requirements etc.).
- Operational (reliability, maintainability, energy consumption, required space for operation, economic etc.).
- Safety & Ergonomic (operator safety, disturbances, etc.).
- Environmental (impact on the environment, ways of disposal, social impact etc.).
- Aesthetic (appearance, form, colour, etc.), and
- Statutory.

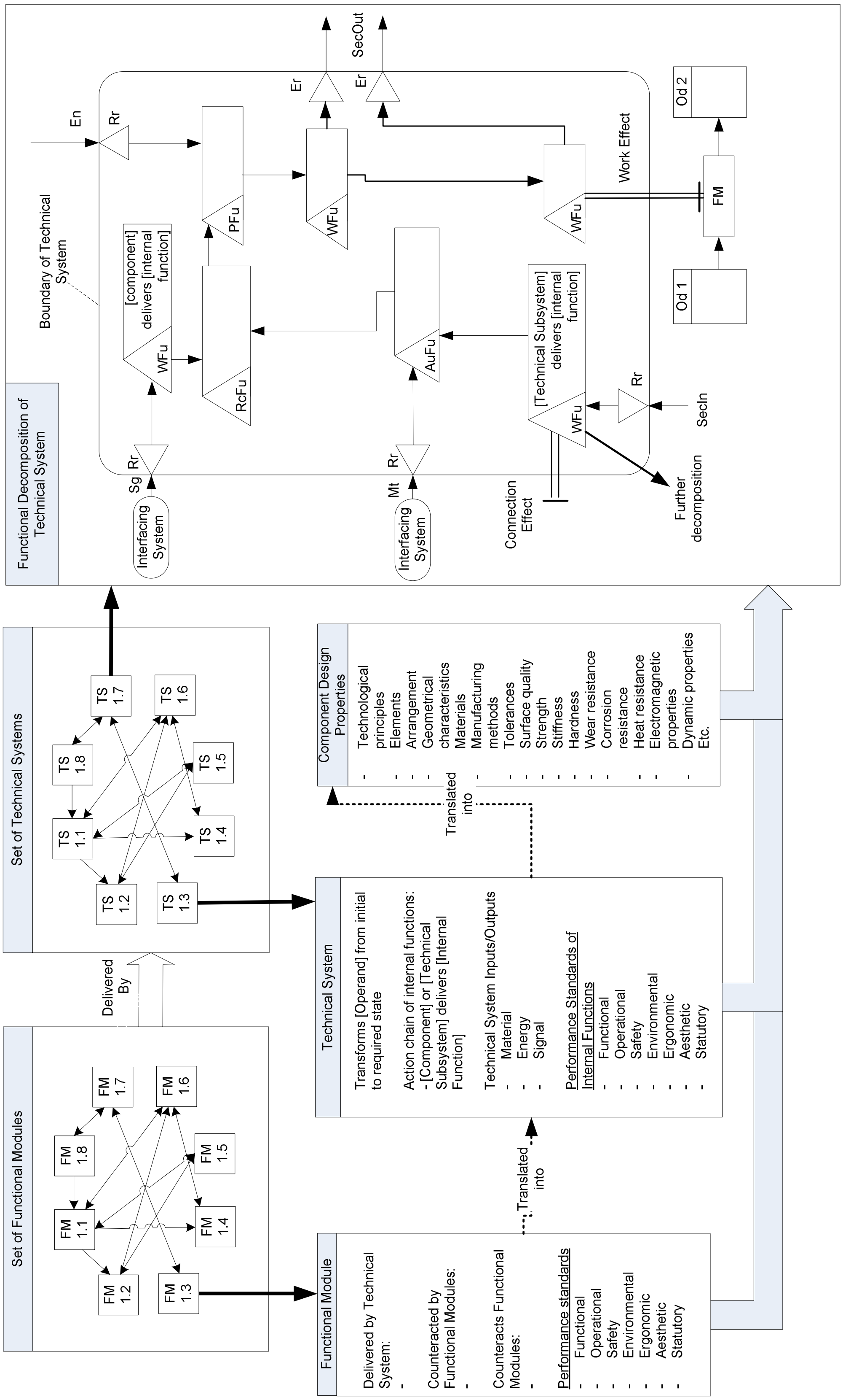

Fig. 2. Structured decomposition of a system – V. Hubka and E. Eder “General Procedural Model of Engineering Design”. Source [2]

The structural decomposition is documented as a set of technical systems that deliver the identified functional modules, as well as relations between the technical systems corresponding to the interaction scheme of the functional modules (Fig. 2). In this way each technical system has a well defined boundary, an action chain of internal functions, and a set of interactions with the other technical systems. Action chains, identified by the functional decomposition, are performed by a set of subsystems/components identified by the structural decomposition. Next, the technical system’s inputs (materials, energy, signals) and outputs are identified, together with the effects on the operand’s states. If a subsystem requires further decomposition then the same process is carried out in a hierarchical way, modelling the subsystem as a technical system and the internal function as a technical process and so on.

The internal functions must be associated with performance standards as well, otherwise we will not be able to decide if the function is delivered or not ( or if there is a fault state or not). Since the internal functions acting as action chains are delivered by the functional modules, these performance standards must correspond to the performance standards of the functional modules (e.g. the power requirements of a functional module dictate the power the shaft must deliver and the allowed power loss at the power transmission technical system). Therefore, in order to ensure that the performance requirements of the functional modules will be met, we must “translate” them into performance requirements for the internal functions. Also the internal function standards must themselves be translated into required properties of the components delivering them.

Following this chain of “translations” helps us to ensure that the top level performance requirements will be transformed into design constraints for the components of the technical systems.

Such constraints may be:

- Technological principles.
- Elements.
- Arrangement of elements.
- Geometrical characteristics.
- Materials.
- Manufacturing methods.
- Tolerances.
- Surface quality.
- Strength.
- Stiffness.
- Hardness.
- Wear resistance.
- Corrosion resistance.
- Heat resistance.
- Electromagnetic properties.
- Dynamic properties etc.

## 2.2. IDENTIFICATION OF FAILURES, FAILURE MODES AND RISK SCENARIOS

The next step of the proposed methodology is identification of possible failures that may occur in the analysed system and identify their causes. This step may be significantly supported by use of Anticipatory Failure Determination (AFD) concepts, and especially its failure determination template. AFD is an application of TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch – Theory of Inventive Problem Solving) in the field of risk analysis. TRIZ is a “human-oriented, knowledge-based systematic methodology of inventive problem solving” [5] based on a wide body of knowledge, heuristics, principles (“the 40 principles of invention”), techniques and patents to assist problem solving. This method emphasizes formulation of internal contradictions and use of them in the problem solving process. Easy access to all the known physical phenomena and over 2 millions patents allows to overcome the psychological inertia of the solvers preventing them from understanding the problem and restraint their creative thinking [5]. The aim, according to TRIZ, is to reach an ideal system, i.e. a system that delivers its required functions without any harmful effects.

The aim of AFD is to help to “produce” all the possible failures that can occur in the system. Knowing them, one may plan how to prevent their consequences. A success scenario in this context (ie. a successfully completed mission, success trajectory) describes a correct operation of the system – an action chain of the internal functions of functional modules when the system operates properly. It is also the first input from the functional analysis data into the failure prediction process. All the possible risk scenarios start from some point along the success trajectory called initiating event (IE). The risk scenario develops then through a number of mid-states (MS) by divergences and convergences to a number of possible end states (ES). The end states may be, but not necessary are harmful (harmful end states, HES). All the MS, ES and HES indicate that one or more internal functions are not delivered to the required performance standards (ie. a failure occurred), and a departure from the success trajectory took place. The {IEs, MSs, ESs, HESs} network describe all the possible developments of failure scenarios, and helps to identify and categorize the failures and their consequences. The as a rule used diagrams like fault tree, event tree or HAZOP are all subsets from this network. See Fig. 3 below.

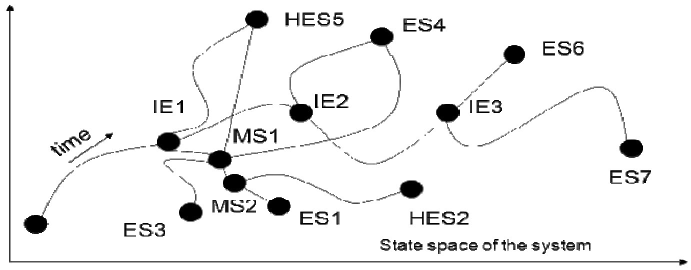

Fig. 3. An example of a risk scenarios network

In accordance to AFD, a failure occurs first when all the required ‘resources’ are in place [3]. Therefore, the technical system is now analysed in terms of physical phenomena, chemical substances, etc. existing within its boundaries. Again, checklists are available to support this task:

- Substances.
- Fields.
- Space resources.
- Time resources.
- Functional resources.
- Information that can be obtained from the system.
- Systemic Interactions.

- Change interactions.
- Differential resources.
- Inherent resources.
- Organizational resources.
- Small failures and disturbances.
- Hazardous elements.
- Control devices.
- Protection systems.

Knowing the resources, we can identify (‘produce’) all the possible failures. Guidelines for this are provided in form of two checklists: the ‘General Mechanisms of Failures Checklist’ and the ‘Typical Failures Checklist’ [3].

General Mechanisms of Failures checklist:

- Gradually increasing effects.
- Critical effects.
- Trigger mechanisms.
- Probabilistic effects.
- Sporadic effects.
- Failure as the result of a systemic effect.
- Creation of a new, harmful system.
- Chains of harmful events.
- Time-dependant harmful mechanisms.
- Failure mechanisms that include feedback.
- Failure mechanisms resulting from mitigation measures.
- Auxiliary mechanisms.

Typical Failures:

- Explosion.
- Combustion.
- Corrosion.
- Malfunction of electric or electronic device.
- Deformation or destruction.
- Disappearance of useful object or substance.
- Appearance of harmful object or substance
- Disturbance of the system’s useful functioning.
- Appearance of harmful effect in the system.
- Failures over the product life cycle.

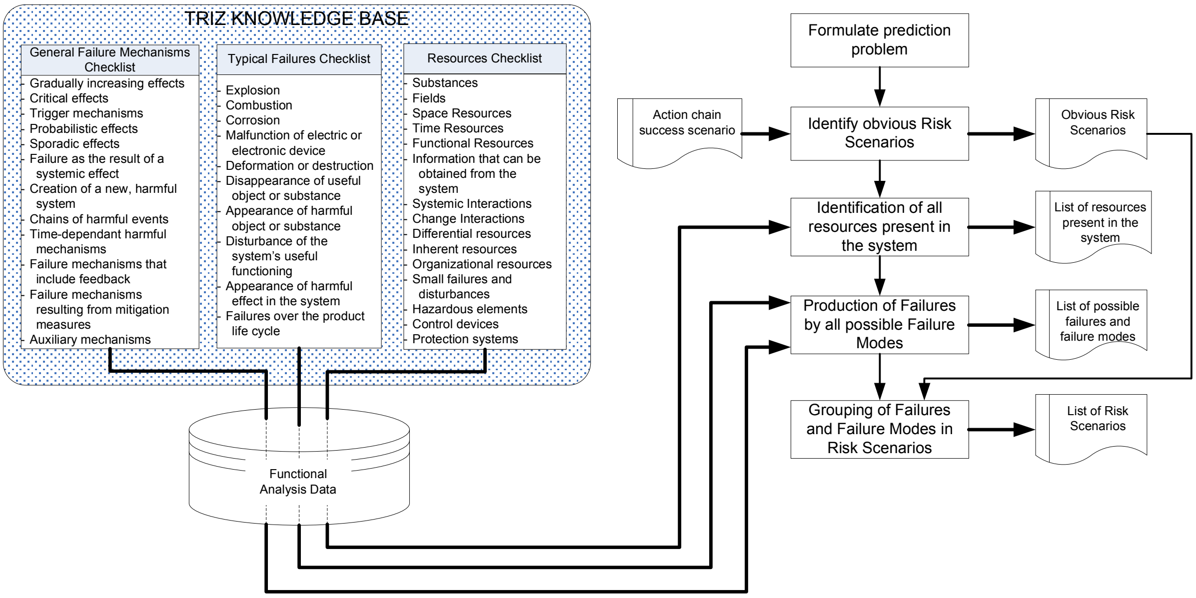

Fig. 4. The checklists provided by TRIZ used to generate risk scenarios

The result is a list of potential failures that may occur in the studied system, together with information on how these failures can be produced. The last information is especially valuable, because it gives us the information on all the possible failure modes.

The last move in this step is to group the failures into risk scenarios (or chains of functional failures) in the aim to document the relations between the failures (Fig. 4). Again an important step, since one failure can be a failure mode for another failure and so on.

### 2.3. CONSEQUENCE EVALUATION

By completing the previous step of failure prediction, we’ve got a list of all possible risk scenarios, i.e. the chains of all the events that can lead to the technical system’s failure (ie. inability to provide a required function). Now, these scenarios have to be completed with evaluation of the consequences they may have. The causality of the analysis process so far, provides that the consequences of the risk scenarios are ultimately the consequences of the failures themselves. Based on the RCM directives these consequences can be classified as hidden failure consequences, safety and environmental consequences, operational consequences, and nonoperational consequences, and then ranked for severity.

### 2.4. MAINTENANCE TASK DESIGN

The task selection process proposed by RCM is a well thought out strategy focusing on consequences of the failures. Two types of tasks are foreseen – in the first place a proactive task, aimed to prevent the item from getting into a failed state should be selected. Proactive tasks are: scheduled restoration, scheduled discard and on-condition maintenance. Default actions are chosen when it is not possible to identify an effective proactive task, and include failure finding tasks, running to failure, and redesign. The task selection process is shown in Fig. 5.

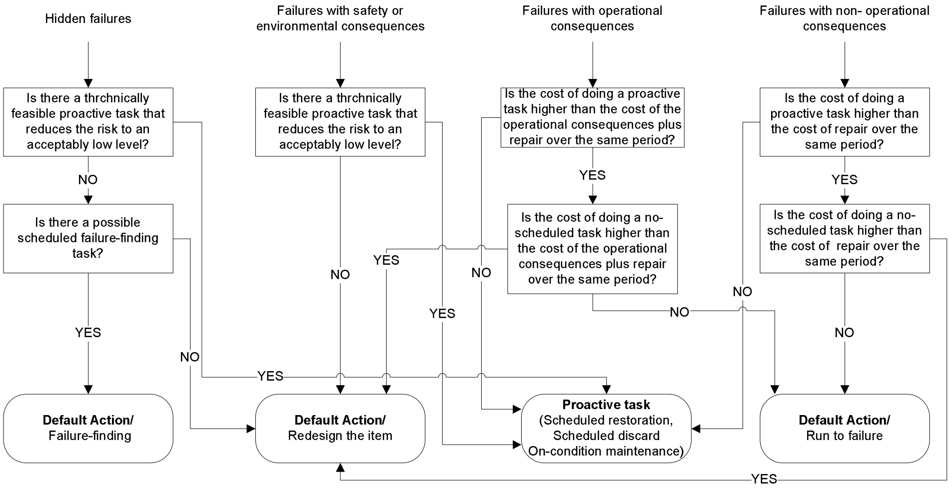

Fig. 5. The task selection process in RCM

The functional analysis and failure prediction performed ahead provides us here with exactly the information we need – the documented system structure, functional decomposition and consequences of functions not being delivered. It is now possible to identify necessary changes in order to improve the system's reliability. For that we apply the TRIZ concepts for eliminating or preventing failures [3]:

- Avert the causes of failure by:
    - Eliminating triggering events.
    - Apply a task with harmful effects that are easier to cope with.
- Stop the effects of failure by:
    - Localizing its harmful effect.
    - Reducing the effect.
    - "Blending in" defects.
    - Transient using of a harmful effect.
    - Facilitating detection.
    - Creating a compensating effect.
- Eliminate the failure by:
    - Remove or change the source of harm.
    - Modify the harmful effect.
    - Counteract the harmful effect.
    - Isolate the system from the harmful effect.
    - Increase the system's resistance to harmful effect.
    - Modify or substitute the effected object.

These guidelines and design principles can also help to reveal useful changes in technical systems' and components' functionality or introduce new useful functions. Eliminating failures can itself reduce the need for maintenance activities. After all, according to the TRIZ concept of ideality, the aim is to create an ideal system that will have no need for maintenance.

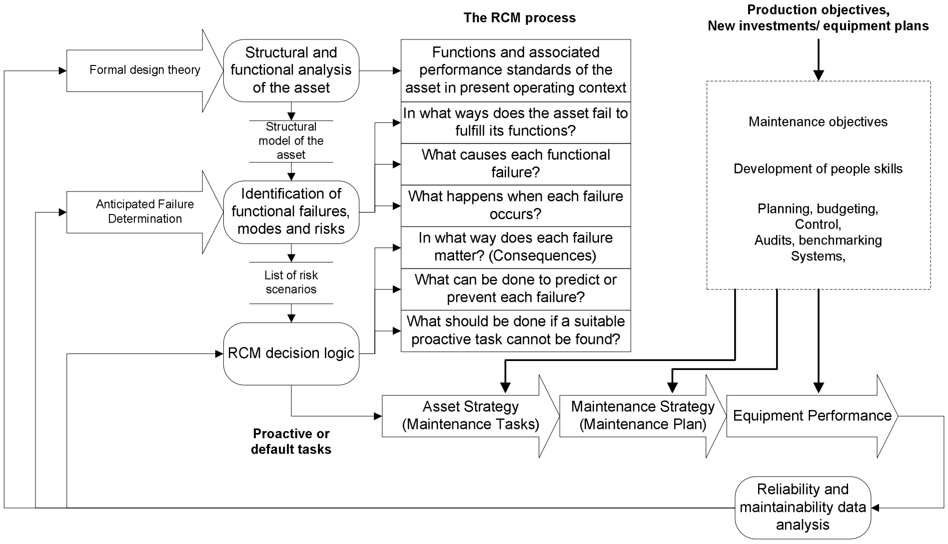

Fig. 6. The RCM in the context of a close-loop maintenance process

Needless to say that functions and components introduced are evaluated again with this framework in order to ensure that no harmful effects are created by the improvements. This mechanism is exposed in Fig. 6, which shows this in the context of the whole maintenance function.

## 3. APPLICATION OF THE PROPOSED METHODOLOGY ON A MACHINE TOOL SPINDLE HEAD

The methodology is now exemplified by analysis of a spindle unit in a T-type milling machine. The studied machine was build based on reference architecture developed in a research project ‘MAREA’ [1], which directly provides us with lists of the recognised functions. See the Table 1 below. Observe that the basic functions refer to functional modules, and the elementary functions refer to internal functions of technical systems (actions chains) delivering the basic functions.

Table 1. Basic and elementary functions of a machining workstation

| Basic Functions | Elementary Functions | | Basic Functions | Elementary Functions |
|---|---|---|---|---|
| Cutting Rotation | Tool Cutting Rotation | | Pallet Exchange | Pallet Loading |
| | Workpiece Cutting Rotation | | | Pallet Changing |
| Motion | Rectilinear Motion | | | Pallet Storage |
| | Rotational Motion | | Waste Removal | Waste Removal |
| Tool Holding | Tool Blocking | | Central Control | Central Control |
| | Tool Clamping for Rotation | | Process Casing | Process Casing |
| Workpiece Holding | Workpiece Blocking | | Auxiliary service supply | Hydraulic System |
| | Workpiece Clamping for Rotation | | | Pneumatic System |
| Process Cooling | Process Cooling | | | Electric System |
| Tool Exchange | Tool Loading | | | |
| | Tool Changing | | | |
| | Tool Storage | | | |

In the rest of this paper we are studying function “Tool Cutting Rotation” delivered by the technical system “Spindle Head”.

### 3.1. FUNCTIONAL ANALYSIS OF THE SPINDLE HEAD

At the first system level, the identified spindle head’s functions are:

- To rotate the tool holder at the required angular velocity, within a specified maximum deviation in both length and direction.
- To protect components from the working environment.

- To ensure safety for the working environment.
- To avoid environmental damage.

The internal functions necessary to deliver the abovementioned functions are:

- Spindle drive provides power.
- Central Control regulates Spindle Drive speed.
- Spindle drive provides power.
- Belt mechanism transmits power to Spindle Shaft.
- Spindle shaft rotates Tool Holder.
- Bearings provide support for the Spindle Shaft.
- Tool receptacle provides tool holder positioning.
- Tool Clamping System provides closed loop force.
- Spindle Housing isolates components from the environment.
- Cooling System provides coolant to the Tool Holder through the Spindle Head
- Pneumatic system provides compressed air.
- Lubrication System provides lubricant to necessary components.

Following the steps of the proposed method we also acquired a complete list of interfaces between functions and components, together with a set of performance standards associated with the internal functions (e.g. maximum radial and axial run-out, acceptable range of revolution etc.) and a set of inputs and outputs to and from our system (e.g. energy, heat, vibration etc.). A structural model of the spindle at the first level of decomposition is shown in Fig. 7.

### 3.2. IDENTIFICATION OF FUNCTIONAL FAILURES, FAILURE MODES AND FAILURE CONSEQUENCES

The prediction problem is now formulated as follows:

*“There is a system called spindle head for delivering the following functions:*

- *To rotate the tool holder at the required angular velocity, within a specified maximum deviation in both length and direction.*
- *To protect the components from the working environment.*
- *To ensure safety for the working environment.*
- *To avoid environmental damage during its operation.*

*It is necessary to ‘produce’ all the possible undesired effects that can occur within, or as a result of, this system and to identify the ways in which these undesired phenomena can occur.”*

Now, step by step, as described above, we systematically identified all the possible failure modes corresponding to the known functional failures. The failure modes were then further reviewed by use of the idea of intensification and masking of their effects. Also the operating conditions and the effects of failures were exaggerated in order to reveal further failure modes and effects that were not obvious, or that occur only in extreme conditions.

The analysis resulted in over a thousand failure modes documented in form of hierarchical lists representing the cause and effect relationship between the failure modes (see Table 2). Based on it, we could also create the following three failure scenarios:

- Tool Holder does not rotate.
- Tool Holder rotational speed is lower than required.
- Tool Holder rotation is imbalanced.

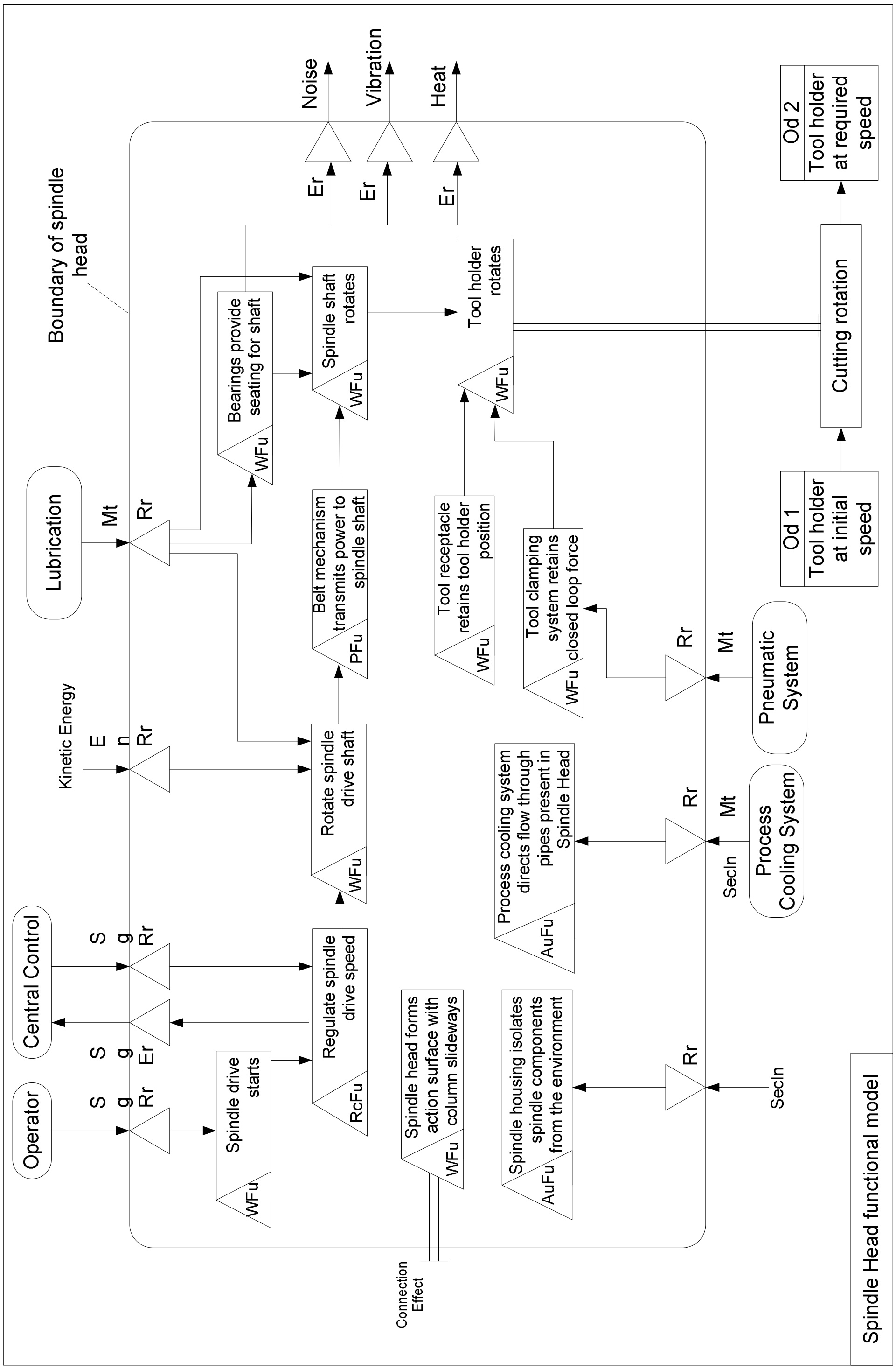

Fig. 7. The functional model of the spindle head technical system. First level of decomposition

In Table 2 below we show a fragment of such a chain of events from one of the risk scenarios. The failure effect at the top level is increased heat. Failure modes in bold, mean that they have also other failure modes that can potentially cause them.

Table 2. A chain of possible failure modes that can cause increased heat in the system

| | |
|---|---|
| **1** | **Increased Heat in the system** |
| **1.1** | **Increased friction between moving components** |
| **1.1.1** | **Improper lubrication of contact areas** |
| **1.1.1.1** | **Disappearance of lubricant** |
| **1.1.1.1.1** | **Lubricant evaporation** |
| **1.1.1.1.2** | **Damaged lubrication tubes cause leakage** |
| **1.1.1.1.3** | **Fittings lose sealing properties, causing leakage of lubricant** |
| 1.1.1.1.4 | Large wear particle clogs lubrication tubes |
| 1.1.1.1.5 | Clogging of lubrication system outside the Spindle Head boundaries |
| 1.1.1.1.6 | Leakage of lubrication system outside the Spindle Head boundaries |
| 1.1.1.1.7 | Inadequate quantity of lubricant in lubrication system |
| 1.1.1.1.8 | Damaged control valves of lubrication system |
| **1.1.1.2** | **Improper lubricant properties** |
| **1.1.1.2.1** | **Improper lubricant viscosity** |
| **1.1.1.2.2** | **Contamination of lubricant** |
| 1.1.1.2.2.1 | Improper sealing of lubrication system |
| 1.1.1.2.2.2 | Improper storage of lubricant |
| 1.1.1.2.2.3 | Poor filtering of lubrication system |
| 1.1.1.2.2.4 | Water contaminates lubricant |
| 1.1.1.2.2.5 | Increased presence of wear particles from contacting surfaces |
| 1.1.1.2.2.6 | Oxides from corrosion contaminate lubricant |
| 1.1.1.2.2.7 | Wear particles from tubes contaminate lubricant |
| 1.1.1.3 | Lubrication system failure |
| 1.1.1.4 | Thermal deformation exceeds tolerances, hindering lubricant application on contacting surfaces |
| 1.1.1.5 | Foreign particles hinder lubricant application |
| 1.1.1.6 | Surface deterioration hinders lubricant application |

### 3.3. CONSEQUENCE EVALUATION AND MAINTENANCE TASK DESIGN

The developed chains of possible failures modes – hopefully complete regarding all the known phenomena – allow now for a straight forward, linear process of consequence evaluation and deciding how each of the failure modes will be addressed. This is shown in Fig. 5 above. RCM itself offers very efficient methods for this purpose, so we will not go into it here in detail.

## 4. CONCLUSIONS

About 70% of all failures encountered during operations originate from decisions made in the design phase of the equipment. This is mainly due to lack of integration between design and operations, an unclear, widespread, short-term minded management practice within maintenance, and lack of proper economical models allowing tracking of maintenance related costs in the context of the whole life cycle. It is then of great interest to explore the possibility of integrating the design, operations and maintenance phases in a systematic way that would allow better control over equipment availability.

An important lead in this context is establishing of an efficient, systematic and formal method allowing identification of failure modes and effects in a predictable way. In this paper we presented and exemplified such a method. The results are very promising. The process was easy to handle despite of the huge number of functional failures and failure modes (more than one thousand). Use of the different checklists and strategies to identifying them was manageable. The use of AFD platform proved to be very helpful. It provides very efficient guidelines how to analyze the system in terms of events, scenarios and harmful effects, and delivers on a silver plate a detailed and consistent prediction process that reveals numerous ways of producing a failure. It also triggers what is described in TRIZ as "inventive" thinking.

The use of Hubka and Eder's concepts about engineering design was very helpful in this context for two reasons. Firstly, because following these principles results in a well thought-out, and detailed description of the system structure, functionality, and behavior. In addition, this description is fully compatible with the AFD input requirements. Secondly, because both methodologies identify causality as the core of the technical processes and functions. Something that is absolutely necessary during the development of failure scenarios. The formulated engineering design principles can also expose the required functionality already at the conceptual level.

We are at the beginning of the road (and believe that it is the right one), and a lot of research is still ahead of us. Probably the most argent task for now is development of a knowledge base system that would help us to deal with the huge amounts of information used during the functional analysis [8].

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