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A Unified Proposal for a Set of Maintenance Performance Indicators for Nuclear Power Plants

Technical Report

Paolo Contri, Irina Kuzmina

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EXECUTIVE SUMMARY

Economic deregulation of electricity markets in many countries has placed nuclear power plants (NPPs) in a new competitive environment where capital, operating and maintenance costs must be minimized. Optimization of the maintenance strategy, enhancement of the maintenance efficiency and monitoring the performance are becoming the key attributes to ensure the survival of nuclear utilities in the energy market. The need to collect relevant experience and suggest a consolidated system of performance indicators to measure the maintenance effectiveness was recognized by the Institute for Energy EC-JRC and research conducted aimed to suggest such a system. The research was conducted in two stages:

(1) The first stage (completed in 2006) resulted in the development of Maintenance Performance Indicators (MPIs) system, and

(2) The second stage (completed in 2007) focused on benchmarking the suggested MPI system.

This report provides a detailed overview of the research conducted in 2006-2007 and provides further modifications to the suggested MPI framework. The MPI framework developed by JRC-IE (Ref. [1]) has been further enhanced by addressing the recommendations provided in Ref. [2] and reproduced in Sections 2.4-2.6 of this report, as well as recent meetings of SENUF and PECO. Responding to the recommendations, one additional Key Performance Indicator (KPI) ‘Safety during maintenance’ was included in the MPI framework. Several new Specific Maintenance Indicators (SMIs) were included to support this KPI using data from plant Risk Monitors, as well other KPIs as documented in Section 3. The final listing of MPIs in a user-friendly form comprising the definitions, purpose, and other characteristics of MPIs was compiled and presented in Section 3. The issues of indicators’ representation and backfitting were discussed and an approach for the analysis of compliance with the thresholds was suggested in Section 4. In addition, a discussion on benefits from introducing advanced maintenance approaches using the MPI framework has been provided.

The updated framework for MPIs suggested by the JRC-IE in this report comprehensively covers the various aspects of maintenance-related activities and promotes easy reference and use of the MPI system in the maintenance performance monitoring process. However, for a meaningful use and efficient implementation of the MPI framework, further efforts should be pursued; these are to be concentrated on the development of thresholds for the SMIs. This can be done through an expert elicitation process.

Other issues that deserve attention in the future research activities dealing with enhancing the maintenance effectiveness include collection and dissemination of information on the use of in-plant data collection systems and advanced computer tools to support the computation of MPIs, use of Risk Monitors to provide safety during maintenance, and conducting a survey to evaluate the impact of the regulatory framework on the feasibility to implement changes to the existing maintenance strategies.

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1 INTRODUCTION

1.1 Background

Economic deregulation of electricity markets in many countries has placed nuclear power plants (NPPs) in a new competitive environment where capital, operating and maintenance costs must be minimized. Optimization of the maintenance strategy, enhancement of the maintenance efficiency and monitoring the performance are becoming the key attributes to ensure the survival of nuclear utilities in the energy market.

In order to monitor the maintenance performance in an effective and objective way, the relevant measurable performance indicators should be used. Such a performance measurement systems contain a mix of lagging and leading indicators. For the maintenance application, the leading indicators measure the effectiveness of the maintenance process, while lagging indicators measure results.

When dealing with the maintenance performance monitoring, a business process approach to the maintenance function is applied. This concept of process management is based on the assumption that the process itself produces the desired results and therefore the process has to be managed and measured. This approach ensures successful management of the maintenance process in order to achieve optimal levels of equipment reliability, availability and cost effectiveness. The necessity for tracking the maintenance performance indicators other than just equipment reliability and availability is to pinpoint areas responsible for negative trends (leading indicators).

It is widely recognized that focusing on any single aspect of performance is ineffective and can be misleading. A range of specific leading and lagging indicators should be considered in order to provide a general sense of the overall performance of a maintenance programme and its trend over time.

The maintenance performance monitoring was one of the research tasks of the SENUF (Safety of European Nuclear Facilities) network established in 2003 to facilitate the harmonization of safety cultures between the Candidate Countries (CCs) and the European Union (EU). After 4 years of successful operations, the SENUF network was integrated into the new Direct Action of the European Commission, SONIS (Safe Operation of Nuclear Installations), where research on maintenance monitoring and optimisation plays a major role. The Joint Research Centre, Institute for Energy (JRC-IE) of the European Commission is in charge of a large research project on Nuclear Operation Safety called SONIS. An important task of SONIS is dedicated to “maintenance optimisation and plant life management models”, as a result of consultation with the Member Countries on the research priorities in the EU.

The overall objective of the research was to analyse the state-of-the-art operational and engineering practice in the EU and carry out the necessary research tasks in order to develop optimised organisational and technical models to be proposed to both operator and scientific communities as contributions to the harmonisation of the operational practices at EU nuclear installations. To achieve the goal, specific research studies were undertaken by the EC-JRC Institute for Energy in 2006 and 2007 on the issues of maintenance optimization approaches and maintenance performance indicators.

The research activities undertaken in 2006 were focused on the analysis of the existing practices in relation to maintenance performance in nuclear and non-nuclear industries, and on the development of a comprehensive list of indicators that can be used by NPPs for the evaluation of their own maintenance programmes. This research resulted in issuing a report entitled “Monitoring maintenance effectiveness using the performance indicators” [1]. The report suggested a framework for maintenance performance indicators and provided guidance for the implementation of the proposed system of maintenance performance indicators to specific NPPs

Further research conducted in 2007 was concentrated on benchmarking activities using as a basis the experience of selected European NPPs. The aim was to check the applicability, usefulness, and viability of the proposed framework for maintenance performance indicators, as well as to evaluate to what degree the proposed framework is in compliance with the contemporary practices. A questionnaire was developed and circulated amongst the European NPPs. Responses were received from 10 NPPs in different European countries. The responses were processed and summarized in the report “Benchmarking study of maintenance performance monitoring practices” [2]. As a result of this stage of the research, a number of modifications have been suggested to the initial framework for maintenance performance indicators outlined in Ref. [1]. These suggestions need further effort to elaborate and implement them, and finalize the proposed maintenance performance indicators framework taking into account information from recent meetings of SENUF and PECO[1], and other available publications (Refs [3]-[14]).

1.2 Objectives

The overall objective of the present report entitled “Unified Proposal for a Set of Maintenance Performance Indicators for Nuclear Power Plants” is to improve the proposal of the JRC-IE on the maintenance performance indicators framework (Ref. [1]) based on the recommendations provided in Ref. [2] and taking into account information from the subsequent meetings of SENUF and PECO and other sources available. Specifically, the report is aimed at providing information on MPIs in a structured and user-friendly form, and addressing the issues of MPI applicability, representation, definition of thresholds, and providing a feedback.

[1] JRC Enlargement and Integration Workshop IE-W06 "Optimization of maintenance programs at NPPs with consideration of safety and economical aspects“, 13-14 November 2008, JRC-Institute for Energy, Petten, The Netherlands.

1.3 Structure of the report

Section 2 of the report provides a detailed overview of the research on maintenance performance indicators completed within 2006-2007, including details of the approaches applied, results, and insights. Section 3 describes further modifications to the MPI framework and provides the final listing of MPIs along with their definitions and other characteristics. Section 4 discusses the issues dealing with utilization of MPIs including the thresholds for MPIs, the issues of MPIs' representation and feedback, and benefit from the application of the proposed framework for MPIs. Section 5 summarizes the main conclusions and recommendations for further research and development. References are provided in Section 6.

2 OVERVIEW OF THE RESEARCH ON MAINTENANCE PERFORMANCE INDICATORS COMPLETED WITHIN 2006-2007

2.1 Introductory notes

The goal of NPP maintenance is to allow nuclear operators to use all functions necessary for safe and reliable power production by keeping these functions available and reliable. Plant maintenance includes the aspects of both safety and economy.

Maintenance activities in NPPs are traditionally performed during planned refuelling and maintenance outages. Outages are always in the center of attention because they are the biggest reason of plant non-availability, and significant portion of operational and maintenance (O&M) budget has to be spent over this time. In the past one or two decades, significant changes in the electricity generation industry and the markets have been taken place. Privatization and market deregulation have led to a competition among plants and generation technologies. The business drivers are: safety, reliability and cost-effectiveness. This situation increasingly enforces plant and maintenance managers to reduce their O&M budget and sometimes also the number of their staff, to increase plant availability while continuously meeting the more and more rigorous safety requirements. Many NPPs introduced indicators to measure the effectiveness of their maintenance process taking into account various aspects associated with it.

The need to collect relevant experience and suggest a consolidated system of indicators to measure the maintenance effectiveness was recognized by the Institute for Energy EC-JRC and research conducted aimed to suggest such a system. The research was conducted in two stages:

(3) The first stage (completed in 2006) resulted in the development of MPIs system, and

(4) The second stage (completed in 2007) focused on benchmarking the suggested MPI system.

The research results of the first stage were documented in the form of a formal report (see Ref. [1]). The proposed framework for MPIs is composed of the three hierarchical levels and covers eight key aspects of maintenance. The framework included a combination of MPIs that reflect actual performance (lagging indicators), and those that provide an early warning of declining performance (leading indicators). Details of this classification are discussed further. In total, 52 specific quantitative MPIs were selected and grouped to establish the maintenance performance monitoring framework. Brief summary information from Ref. [1] is reproduced further in this report (Section 2.2); for more information regarding the definitions of the MPIs and other details, Ref. [1] should be consulted.

At the second stage of the research, the framework suggested in Ref. [1] was benchmarked at selected NPPs by means of conducting a survey and processing the results as documented in Ref. [2]. Summary information on the benchmarking exercise is provided further in this report (Section 2.3); for more information and details, Ref. [2] should be consulted.

A summary of the results and insights from the research conducted, as well as the recommendations for modifications to the framework for MPIs and the recommendations for further research and development are highlighted in Sections 2.4-2.6.

2.2 Framework for maintenance performance indicators

2.2.1 Maintenance monitoring concept and structure of the MPI framework

As a first step in the development of the maintenance performance monitoring framework, the definition of the maintenance monitoring concept was considered. It was assumed that the maintenance monitoring system is established at the NPP with the aim to achieve the maintenance excellence, by removing the existing or potential deficiencies.

The proposed approach to monitoring the maintenance performance is presented in Fig. 2.1.

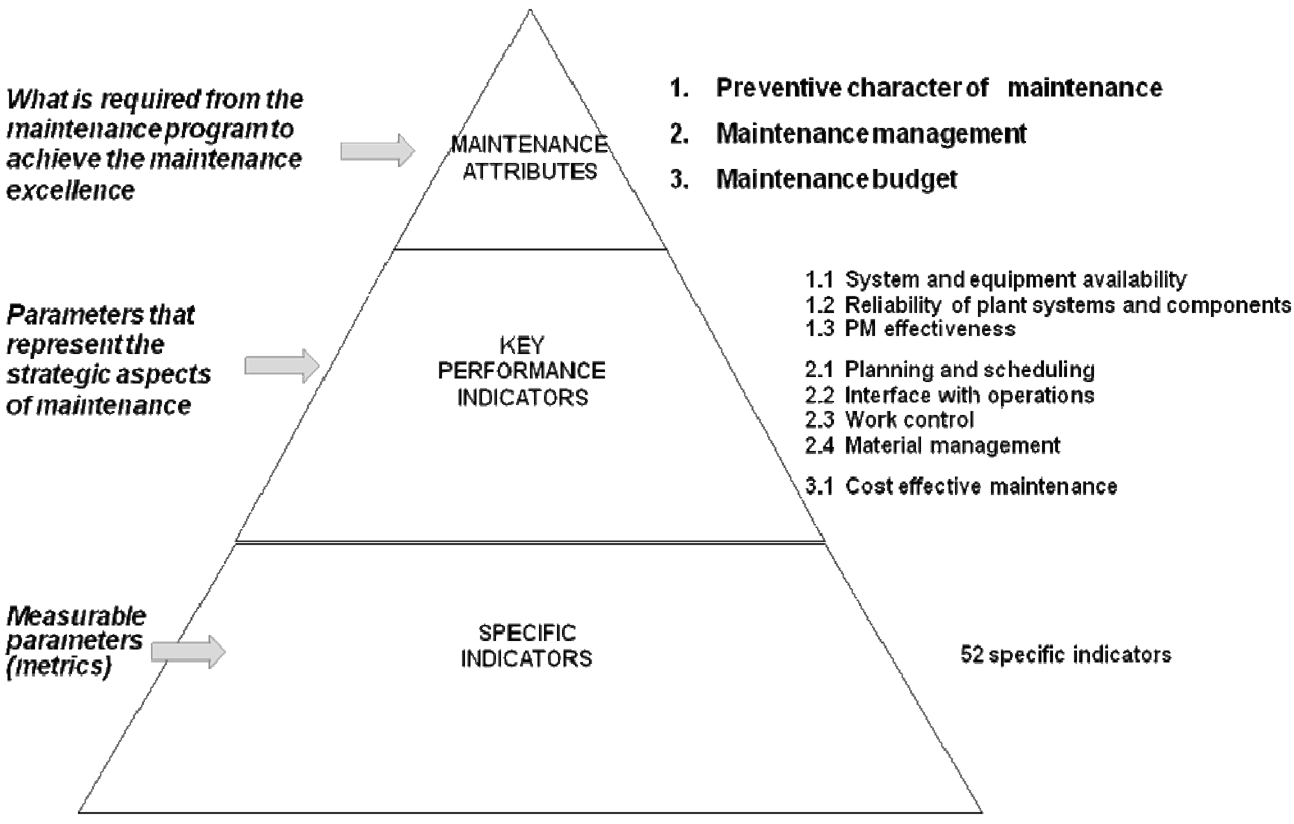

Fig. 2.1 An approach to the monitoring of maintenance performance

On the top of the maintenance performance hierarchical structure, there is Maintenance Excellence, from which three maintenance attributes are developed; these are associated with the excellence of the maintenance programme:

1) Preventive character of maintenance (including predictive maintenance);
2) Maintenance management;
3) Maintenance budget.

The three attributes are not assessable directly; therefore, the maintenance performance indicators structure was expanded until the level of easily measurable quantitative metrics. Using the attributes as a starting point for the indicators system development, a set of maintenance performance indicators was proposed. Below each attribute, key performance indicators (KPIs) were established. In turn, each key performance indicator is supported by a set of specific maintenance indicators (SMIs), some of which are already in use in the industry. The suggested structure of MPI framework till the level of key performance indicators is illustrated in Fig. 2.2.

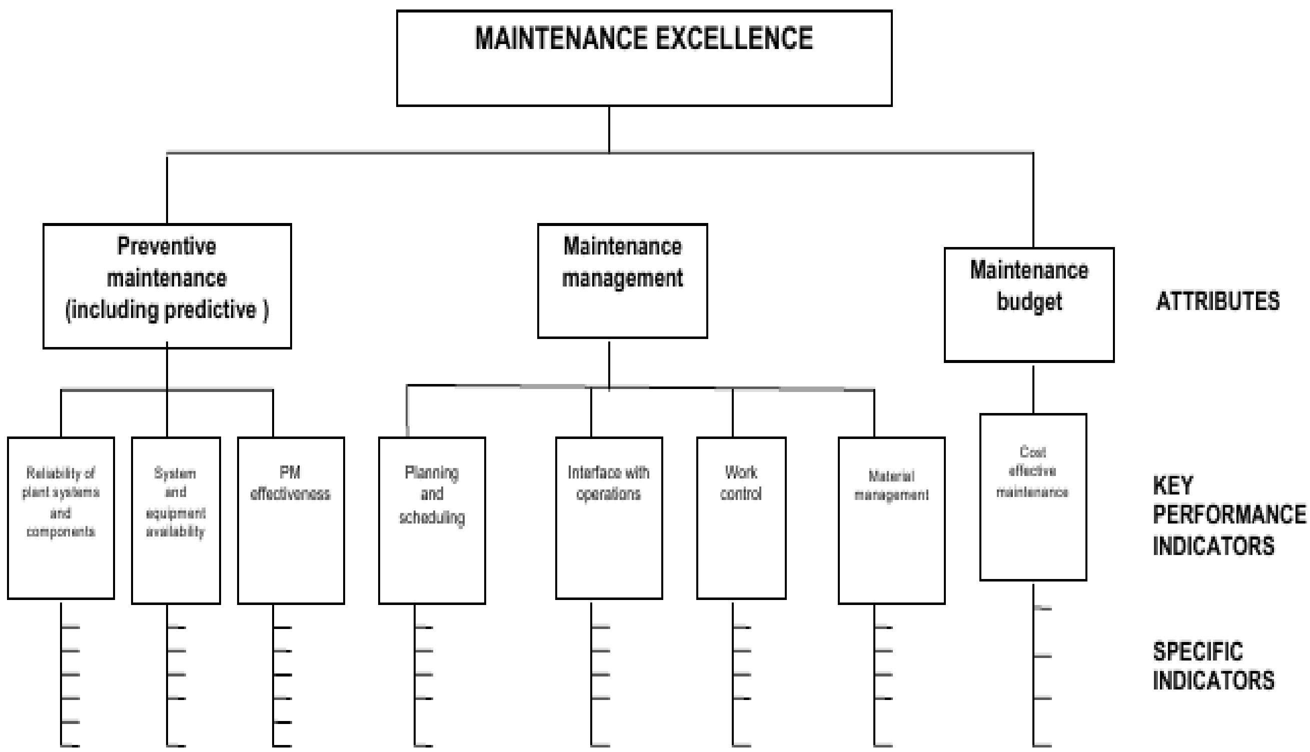

Fig. 2.2 Structure of MPI framework

2.2.2 Leading and lagging performance indicators

Depending on values of performance indicators they can be classified as either leading or lagging indicators. Most conventional quantitative indicators measure historical performance (they are often referred to as 'output' or 'lagging' indicators) and thus their predictive capacity arise from extrapolation of trends or comparisons with past performance. The WANO performance indicators are typical examples of lagging indicators.

The leading indicators are forward looking indicators which measure positive efforts to improve performance. Leading indicators are metrics that are task-specific. They respond faster than results metrics and are selected to indicate progress towards long term objectives. Leading indicators are indicators that measure and track performance before a problem arises. They are particularly valuable, although they are recognized as being more difficult to develop and measure objectively.

The best performance measurement systems contain a mix of lagging and leading indicators. Some indicators can be either leading or lagging depending on the context of their application. One example of such indicators is the schedule compliance. It is a lagging indicator of the efficiency of the scheduling process and a leading indicator for Wrench time.

2.2.3 Listing of maintenance performance indicators

In order to provide a concise overview of the system of MPIs suggested in Ref. [1], Table 2.1 was specifically developed and included in the current report to provide a complete listing of MPIs in a more structured way. The list of MPIs is directly taken from Ref. [1]. In order to facilitate further referencing and discussion, the numbering system was introduced as shown in Table 2.1 that allows attributing each specific maintenance indicator to the associated key performance indicator and the maintenance attribute. For definitions and other supporting information on the use of the MPIs, Ref. [1] should be consulted.

Table 2.1 Listing of MPIs suggested in Ref. [1]

<table>
<tr><th>Maintenance attribute</th><th>KPI</th><th>Specific indicator</th></tr>
<tr><td rowspan="10">1. PREVENTIVE CHARACTER OF MAINTENANCE (INCLUDING PREDICTIVE MEASURES)</td><td rowspan="6">1.1 System and equipment availability</td><td>1.1.1 Component and system unavailability</td></tr>
<tr><td>1.1.2 Total downtime</td></tr>
<tr><td>1.1.3 Scheduled downtime</td></tr>
<tr><td>1.1.4 Unscheduled downtime</td></tr>
<tr><td>1.1.5 Number of forced power reductions or outages because of maintenance causes</td></tr>
<tr><td>1.1.6 Mean time between maintenance (MTBM)</td></tr>
<tr><td rowspan="4">1.2 Reliability of systems and components</td><td>1.2.1 Number of corrective work orders issued</td></tr>
<tr><td>1.2.2 Number of failures in safety related systems</td></tr>
<tr><td>1.2.3 Mean time between failures (MTBF)</td></tr>
<tr><td>1.2.4 Mean time to repair (MTTR)</td></tr>
</table>

Maintenance attribute	KPI	Specific indicator
	1.3 Effectiveness of preventive maintenance	1.3.1 Preventive maintenance compliance
		1.3.2 Ratio of corrective work resulted from PM activities
		1.3.3 PM work order backlog trend
		1.3.4 Ratio of PM activities to all maintenance activities
		1.3.5 Percentage of deficiencies discovered by surveillance, testing and inspections
		1.3.6 Overdue of PM activities
2. MAINTENANCE MANAGEMENT	2.1 Planning and scheduling	2.1.1 Ratio of unplanned to planned working orders
		2.1.2 Planning compliance
		2.1.3 Schedule compliance
		2.1.4 Ratio of corrective work orders executed to work orders programmed
		2.1.5 Number of outstanding backlogs (number of urgent orders)
		2.1.6 Planner to craft work ratio
		2.1.7 Number of jobs planned but not performed
		2.1.8 Number of jobs not started as planned
		2.1.9 Actual versus planned man-hours (per job or totals).
	2.2 Interface with operations	2.2.1 Number of workarounds
		2.2.2 Number of temporary modifications
		2.2.3 Ratio of downtime to allowed outage time
		2.2.4 Number of MCR instruments out of service
	2.3 Work control	2.3.1 Duration of repair
		2.3.2 Repair time of components subject to the Technical Specifications
		2.3.3 Wrench time
		2.3.4 Crew efficiency
		2.3.5 Amount of maintenance rework
		2.3.6 Supervisor to craft worker ratio
		2.3.7 Response time to call
		2.3.8 Overtime maintenance hours
	2.4 Material management	2.4.1 Stores service level
		2.4.2 Number of work requests pending for spare parts
		2.4.3 Stock inventory turns
		2.4.4 Stocked maintenance, repair and operating materials (MRO) inventory value as a percent of replacement asset value (RAV)
		2.4.5* Average spares and tools waiting time
		2.4.6* Stocks items available but not used
		2.4.7* Inventory accuracy
		2.4.8* Spare parts and material obsolescence
		2.4.9* Vendor performance
3. MAINTENANCE BUDGET	3.1 Cost effective maintenance	3.1.1 Maintenance cost per kWh produced
		3.1.2 Overtime maintenance cost
		3.1.3 Work orders complete within the determined costs (10-20%)
		3.1.4 Unplanned costs as percentage of total maintenance costs
		3.1.5 Ratio of replacement asset value (RAV) to craft/wage head count
		3.1.6 Annual maintenance cost as a percent of replacement asset value (RAV)

* - Regarded as “Other indicators’ in Ref. [1]; the definitions of these indicators may vary from utility to utility in accordance with the specific approaches and needs of the utilities.

2.3 Benchmarking study

This section of the report is largely based on the information provided in Ref. [2]. The aim was to provide an overview of the approach for benchmarking the suggested MPI framework, as well as the results obtained, in order to appreciate the modifications to the initial MPI framework.

2.3.1 Survey on the use of maintenance performance indicators

A questionnaire aimed to collect information on MPIs in use by NPPs and verify the suggested framework for MPIs was developed (see Ref. [2]) and widely circulated. The responses to the survey of the maintenance performance monitoring practices have been received from ten European nuclear power plants and utilities and one technical support organisation. They represent the following European countries: Belgium, Germany, Czech Republic, Hungary, Lithuania, the Netherlands, Slovakia, Sweden, UK, and Ukraine. Romania in the survey was presented by CITON, Center of Technology and Engineering for Nuclear Projects. The survey presented in Ref. [2] should be regarded as a sample of ten European NPPs, which have been selected from 62 NPPs where the questionnaire was distributed to.

The survey results show that the maintenance performance indicators are in use at all European utilities and NPPs who responded to the questionnaire. All respondents report that the maintenance performance indicators are part of the overall performance indicator system. Seven respondents explained that they have in use the monitoring system specifically dedicated to the maintenance programme. Another group of respondents explained that the maintenance monitoring is carried out within the overall asset management system.

2.3.2 General observations

There is variation in the complexity of maintenance monitoring systems. Some of them utilise single performance indicators, more advanced systems include several groups or categories of maintenance performance metrics.

Eighty percent of respondents have been using the maintenance monitoring indicators for more than 5 years, four respondents report that they use such a system for more than 10 years. In three cases the maintenance monitoring experience is between 1 and 3 years. Maintenance monitoring results are periodically reported to the utility or plant management. Annual reporting is the usual practice among the responded plants. Only in one case the reports are being produced quarterly.

Different systems for collection and interpretation of the data and the trends on the basis of processing the data are used in the nuclear utilities. Six respondents report that they use specific Data Base for the maintenance monitoring purposes. These data bases include definitions of maintenance performance indicators, goals, graphic values, references, comments and actions, responsible coordinators/ 'owners', anticipated and actual indicator values, etc. Five respondents report that the data bases are supported by specific software for the processing of collected information for the trending results and demonstration and reporting. At some power plants the graphic displays are used to show the operational safety performance indicators including definition, goal, graphic values, reference, comments and action, responsible coordinator/'owners', monthly numerical anticipated and actual values for specified time period. Majority of respondents (80%) reports that they are planning further improvements of their maintenance monitoring system. In three cases new maintenance monitoring system is planned. Almost 50% of respondents are planning to increase the number of performance indicators in their monitoring systems. The other modifications include installation of specific software and establishing or upgrading the data base to support maintenance activities.

2.3.3 Processing the survey results

The survey results on the use of specific MPIs were processed in order to clarify:

1. The list of specific performance indicators that are in use at the European nuclear utilities;
1. To what degree the maintenance performance monitoring system developed in IE/JRC is in compliance with the maintenance efficiency monitoring practices in the European nuclear utilities; and
2. Viability of the specific indicators to support certain KPI.

Based on the responses from the European utilities, an analysis was performed to evaluate how frequently the key performance indicators and specific indicators are used in practice. The task was to evaluate the weight of utilisation of the proposed indicators at the European nuclear utilities. To apply this weighting approach, a specific coefficient characterizing the, weight of utilisation of a particular key performance indicator (W) was calculated.

The weight of utilization of a key performance indicator was defined as:

$$W = \left(\sum^{n_{smi}} N_{smi} / N \times n_{smi} \right) \times 100\% \qquad (2.1)$$

W – weight of utilization of the key performance indicator;
n_{smi} – number of specific indicators within the group of certain KPI;
N_{smi} – number of respondents who use the specific maintenance performance indicator;
N – number of responses received (in our case N = 10).

The following weighting coefficients were obtained for the key performance indicators:

1. Preventive character of maintenance (including predictive maintenance)

1.1	System and equipment availability	85%
1.2	Reliability of systems and components	65%
1.3	PM effectiveness	65%

2. Maintenance management

2.1	Planning & scheduling	55%
2.2	Interface with operations	50%
2.3	Work control	30%
2.4	Material management	38%

3. Maintenance budget

3.1	Cost effective maintenance	24%

2.3.4 Analysis of the survey results

A detailed discussion on the analysis of the survey results is provided in Ref. [2]; some main points from it are summarized as follows:

- The majority of European respondents prefer the indicators that are directly related with the equipment reliability and availability (>60%). The adherence of nuclear utilities to this type of indicators is due to the fact that the final product of maintenance activities is reliability and availability of systems and equipment.

- There is a clear recognition by the European utilities of the role of preventive maintenance. The weight of utilisation of proposed indicators representing preventive character of maintenance is more than 60% (KPIs #1.1, 1.2, 1.3). Preventive maintenance programs are established to maintain equipment within design operating conditions and/or to extend equipment lifetime. Preventive maintenance allows equipment to be repaired at times that do not interfere with production schedules, thereby removing one of the largest factors from downtime cost, increasing profitability.

- Fifty-five percent of the respondents to the questionnaire use the numerical indicators to monitor quality of the planning and scheduling of their maintenance activities (KPI #2.1). Maintenance planning and scheduling is often viewed as the centre of maintenance management, since the effectiveness of other processes such as preventive maintenance, materials management, etc. are dependent on the planning and scheduling.

- Good coordination of maintenance activities in order to avoid the potential interference with normal operation of a plant is one of the attributes of good maintenance management. Significance of this attribute (i.e. KPI #2.2) was recognized by about 50% of the respondents.

- Only 30% of respondents use the complete set of proposed numerical indicators for the work control (KPI #2.3). It is supposed that the adequate work control system facilitates implementation of maintenance activities and ensures safety in the work area and prevents maintenance activities from affecting other safety relevant areas.

- The material management aspects are monitored only by 38% of respondents, despite that management of spare parts and materials is one of the key elements to support effective maintenance planning and scheduling and ensure the quality and efficiency of the maintenance process. Improved material and spare parts management may free up time for maintenance planners, maintenance supervisors, and hourly maintenance personnel.

- The maintenance budget is covered in the survey results only by 24%. The maintenance budget is an increasingly important aspect in the new economical environment in the energy market. Reducing the production costs, including the maintenance costs in particular is one of the conditions of survival in the competitive energy market.

Based on the results of the survey and observations made, a number of specific insights were drawn and revisions to the proposed framework for MPIs suggested in Ref. [2]; these are summarized in Sections 2.4 and 2.5 below.

2.4 Insights relating to the maintenance attributes

This section of the report provides a summary of the discussion on the insights and lessons learned from the analysis of the survey results provided in Ref. [2]. Adjustments to the MPI framework are highlighted for each of the three maintenance attributes. While discussing changes to the initial MPI framework presented in Table 2.1, the numbers assigned to KPIs and SMIs in Table 2.1 are used.

2.4.1 Preventive character of maintenance

The responses to the survey showed that there is confusion with the perception of the indicators:

- Mean time between maintenance (MTBM),
- Mean time between failures (MTBF), and
- Mean time to repair (MTTR).

Despite that the definitions for the above indicators have been presented in the Ref. [1], additional explanations are needed for the clarification of the role of each of the above indicators and the differences between them.

The term ‘availability’ for a system or equipment denotes the probability that the system or equipment can be used when needed. Alternatively, the term describes the fraction of the time that the service is available. The term ‘unavailability’ is defined as the probability that a system or equipment is not available when needed, or as the fraction of the time service is not available. The term ‘reliability of a system or equipment’ is defined as the probability that the system or equipment will perform its intended function without failure over a given period of time.

A commonly used measure of reliability is known as mean time between failures, which is the average expected time between failures. A maintenance service outage caused by a failure is defined as the mean time to repair. MTTR includes time required for failure detection, fault diagnosis, and actual repair. Prediction of the number of hours that a system or component will be unavailable whilst undergoing maintenance is of vital importance in reliability and availability studies.

The MTTR parameter is important in evaluating the availability of repairable systems. MTTR is usually calculated as the total amount of repair time expended in a specified period (hours) divided by number of repair events in that specified period.

Availability (A) is related to MTBF and MTTR as follows:

$$A = MTBF/(MTBF + MTTR) \qquad (2.2)$$

This relationship shows that increasing MTBF and decreasing MTTR improves availability. This means that the availability of a system or equipment can be improved by increasing the reliability of its components. Similarly, improving the reliability of its constituent elements can enhance the availability of a system or component. Changes in maintenance procedures may then be recommended allowing an increase in system availability.

Another indicator which is directly related to the equipment or system availability is the mean time between maintenance. In [3] MTBM is defined as the average length of time between one maintenance action and another for a piece of equipment or component. The metric is applied only for maintenance actions which require or result in function interruption. The mean time between maintenance includes all corrective and preventive actions (compared to MTBF which only accounts for failures). The MTBM is calculated as the total operation time divided by number of maintenance actions during the same period. This metric is useful in assessment of maintenance effectiveness. MTBM measures how many times a maintenance task is being performed on the equipment or system which interrupts the function. The objective of this indicator is to minimize the number of function interruptions by establishing an appropriate maintenance strategy and applying correct maintenance procedures.

Following the reasoning above and comments received from some of survey respondents, the grouping of the maintenance performance indicators was slightly modified. It was suggested to move MTTR as more related to the availability than to reliability under the KPI #1.1 ‘System and equipment availability’.

2.4.2 Maintenance management

It was found appropriate to re-allocate the following three SMIs from KPI #2.1 'Planning and scheduling' to KPI #1.3 'Effectiveness of preventive maintenance' as these SMIs characterize more the maintenance results than planning deficiencies:

- Number of jobs planned but not performed;
- Number of jobs not started as planned;
- Actual versus planned man-hours (per job or totals).

The survey results show that the most popular specific indicators for the Maintenance Management group are indicators 'Planning compliance', 'Schedule compliance' and 'Number of outstanding backlogs'. The indicator 'Planner to craft work ratio' (SMI #2.1.6) was not used in any of responded utilities, therefore this indicator was removed from our system.

Only one respondent reported on the use of the indicator 'Number of MCR instruments out of service' (SMI #2.2.4). It was decided to remove this indicator from the system.

The work control indicators are poorly represented in the survey results. The weight of the indicators in this group is 30%. Most popular indicators in this group are 'Amount of maintenance rework' and 'Overtime maintenance hours.' These two indicators are related to each other and the relatively high rating of these indicators witnesses that utilities acknowledge the necessity to maintain high quality of maintenance services. Based on the survey results, it was found appropriate to remove 'Crew efficiency' (SMI #2.3.4) and 'Supervisor to craft worker ratio' (SMI #2.3.6) from the MPI system.

Despite the poor representation of indicators 'Response time to call' (SMI # 2.3.7) and 'Wrench time' (SMI #2.3.3), they were retained in the MPI scheme. The indicator 'Response time to call' can be useful in connection to suggestion of some respondents to reflect in the maintenance performance monitoring system the quality of the contractor's services. A commitment to restore the system or equipment malfunctions within a specified time period requires adequate management level and good cooperation between operation and contractors. This indicator also incorporates enhanced stocks inventory management to ensure spare parts are available when needed. The SMI 'Response time to call' indicates the level of readiness of the contracted maintenance organization to respond to the urgent operational needs. Low value of the indicator witnesses the high level of the maintenance organization, including planning and coordination, resources management, material management, etc.

The 'Wrench time' indicator is frequently used in the other industries to demonstrate high efficiency of maintenance services. This metric allows one to identify the productivity of the maintenance processes in use, including planning and scheduling, supervision, and maintenance management, and is used to find opportunities for increasing productive work time. Wrench time represents the percentage of time an employee spends applying physical effort or attention to a tool, equipment, or materials in the accomplishment of assigned work. It is used to determine how efficient the plant is at planning, scheduling and executing work. It was found useful to encourage nuclear utilities to incorporate this indicator into their maintenance monitoring practice.

KPI #2.4 'Material management' deserves more attention than that shown in the survey results. In the past nuclear plant managers and operators were primarily focused on optimizing plant operating parameters, such as minimizing the duration of major maintenance and refuelling outages and achieving high availability factors, and, to a lesser extent, were concerned about efficient inventory management. Generally, materials and supplies were expected to be available whenever required and in plentiful supply. With deregulation and electricity price competition, the requirement for the careful management and tracking of nuclear plant materials and supplies inventories, as well as the maintenance of high inventory turnover rates, will be essential for efficient and competitive nuclear electricity production. Despite the majority of respondents acknowledge the role of stores service level, stocks inventory turns and the vendor performance, it was found worthwhile to encourage nuclear power plants to use the material management indicators at broader scale[2]. They are:

- Stocks items available but not used;
- Inventory accuracy;
- Spare parts and material obsolescence;
- Vendor performance.

SMI #2.4.5 'Average spares and tools waiting time' was removed from the MPI framework as being not supported by the respondents.

2.4.3 Maintenance budget

Despite that the maintenance budget is an increasingly important aspect in the new economical environment in the energy market, the budgetary indicators were poorly presented in the survey results. The objective of the plant management of nuclear generating utility is to maximize production of electricity at the lowest cost, the highest quality and within the established safety standards. Reducing the production costs, including the maintenance costs in particular is the condition of survival in the competitive energy market.

The majority of the respondents recognize the maintenance cost per kWh produced and unplanned maintenance costs as the most important budgetary indicators. The other indicators are not frequently used in the maintenance monitoring practices. Based on the survey results, it was found reasonable to remove the SMI #3.1.5 'Ratio of replacement asset value (RAV) to craft/wage head count' from the proposed framework.

[2] These indicators were regarded as 'Other indicators' in Ref. [1].

2.5 Specific insights relating to the MPI framework

This section of the report summarizes information on the areas for further research and development identified from the analysis of the questionnaire and documented in Ref. [2]:

- *Definitions of the selected indicators:* The definitions of the specific indicators should be tailored in accordance with the plant specific needs. The experience showed that the initial definitions may undergo changes during the indicator evaluation phase at the specific plant.
- *Predictive character of preventive maintenance*: More emphasis should be put on the results derived from the condition based monitoring and the predictive character of maintenance actions.
- *Efficiency of the contractors' services*: Increased used of contractor services in maintenance necessitates rigid control and monitoring of contractor's performance.

It was also found out that some maintenance monitoring aspects need additional clarification. These include interrelation between preventive and predictive maintenance, the coverage of maintenance management aspects in the maintenance monitoring framework, monitoring of contractor's performance. The following sub-sections provide details on these issues.

2.5.1 Definitions of the selected indicators

The following specific points dealing with the definitions of MPIs were emphasized by the respondents to the survey:

1) The definition for the indicator 'Schedule compliance' should be modified to emphasize the need to comply with the deadline for returning the equipment to service taking into account the time needed to prepare appropriate documentation on the maintenance performed and after-maintenance test accomplished. This is to make sure that operations department would timely accept the equipment back to service.
2) Clear and unambiguous definitions should be assigned to all MPIs. When selecting indicators for specific power plant it is recommended to review the definition of each indicator and modify it in accordance with the plant-specific definition, if appropriate.
3) The low level indicators are often highly dependent upon site-specific definitions and data collection systems established at the plants, thus preventing viable comparisons on a plant-to-plant basis. Therefore, a care should be exercised when comparing the MPIs across the plants. Some MPIs may need to be adapted to allow for a meaningful comparison.
4) Several respondents commented that not all management aspects critical for the maintenance performance are adequately presented in the proposed maintenance monitoring system. The following aspects were proposed for inclusion in the maintenance monitoring system:

- Failure to return the equipment into service, following maintenance activities, at the first presentation;
- Non compliance with the maintenance procedures;
- Control of contractor's efficiency.

2.5.2 Preventive versus predictive maintenance

Preventive maintenance (PM) can be defined as a series of systematically planned and scheduled actions performed for the purpose of preventing equipment, system, or facility failure. Preventive character of maintenance was selected as one of the three attributes of maintenance excellence. Preventive maintenance programs are established at the majority of nuclear facilities to maintain equipment within design operating conditions and/or to extend equipment life. Preventive maintenance includes the lubrication programme, routine inspections, and adjustments.

Some respondents to the survey commented that the attribute 'Preventive' should be supplemented with the 'Predictive' (Pd) to make this attribute more comprehensive. It was found appropriate to explore more on what is 'Preventive' and what is 'Predictive' maintenance and what is interrelation between these two maintenance types.

In many cases the preventive maintenance is not a proper remedy to increase the equipment reliability and availability and to avoid the recurring equipment breakdowns. If the preventive maintenance programme is time-based and follows only the manufacturers' suggestions and recommendations, it may not be sufficient to correct potential problems before they occur.

There are different views on the interrelation between the preventive and predictive maintenance. One of them is that the predictive maintenance (PdM) is a subset of preventive maintenance. Such approach is described in 'The Complete Guide to Preventive and Predictive maintenance' by J. Levitt [6]. In accordance with this approach, the comprehensive PM programme should be also predictive in nature. It should include the predictive activities to view or examine the equipment, component or system to "predict" if the condition will cause a failure before the next inspection cycle. In this interpretation of preventive maintenance the fundamental part of the definition of the PM programme is "Detect that an equipment has had critical wear and is about to fail".

Another approach is that the predictive maintenance is a separate, independent category of maintenance. Some maintenance experts consider the predictive maintenance in the historical perspective as the more advanced maintenance strategy (Ref. [7]). In this approach the predictive maintenance is defined as a right-on-time maintenance strategy; it may be described as a process, which requires technologies and people skills, while combining and using all available diagnostic and performance data, maintenance histories, operator logs and design data to make timely decisions about maintenance requirements of major/critical equipment. It is the integration of various data, information and processes that leads to the success of a PdM program. It analyzes the trend of measured physical parameters against known engineering limits for the purpose of detecting, analyzing and correcting a problem before a failure occurs. A maintenance plan is made based on the prediction results derived from condition-based monitoring. This can cost more up front than PM because of the additional monitoring hardware and software investing, manning, tooling, and education required to establish a predictive maintenance program. However, it offers increased equipment reliability and a sufficient advance in information to improve planning, thereby reducing unexpected downtime and operating costs, which is very important for the nuclear industry.

In the MPI framework suggested by JRC-IE, the predictive maintenance is considered as a part of preventive maintenance and can be characterized as 'Advanced preventive maintenance'.

2.5.3 Monitoring contractor performance

Several respondents to the survey proposed to include in the MPI framework the indicators to monitor the contractor efficiency. In particular, these proposals came from the countries where in the recent past the complete in-house maintenance staffing was the traditional approach. This approach was typical at all nuclear power plants in the former Soviet Union and East European countries operating Russian design NPPs.

Economic deregulation of electricity markets in many countries has placed NPPs in a new competitive environment where capital, operating and maintenance costs must be minimized. Downsizing and cutting down on staff numbers is the common feature when companies try to rationalize in the new economic environment. Outsourcing or increased use of contractor services is one way to achieve downsizing. Use of contractors for periodic, occasional, or one-time tasks can provide for enhanced efficiency, since the required staffing levels and/or expertise need not be maintained within the plant organization when they are not needed. The majority of nuclear utilities in new economic environment are using downsizing as one aspect of their strategy for dealing with deregulation. However, use of contractors may be more appropriate for some tasks than others. Typical examples of outsourcing in nuclear industry include maintenance, engineering services, computer services, training of operating staff and archive functions. Downsizing and outsourcing of services, in particular maintenance services lead to increased use of contractors for safety-related work and arose challenges in oversight of the contractor's activities.

The use of contractors has, in some cases, increased the risk of incidents at nuclear utilities. This may be due to the fact that the contractors do not have sufficient knowledge or training in the safety policy and procedures, or there is not sufficient co-ordination with the regular staff. A basic principle should be that the contracted workforce receives the proper training for the installation, and should work under the same conditions as would employees, applying the normal utility's safety policy and procedures.

Generic safety aspects associated with contract maintenance is the operator's ability to keep and develop enough competence within its organization to be able to maintain full control over safety-related maintenance activities in the short and long perspective. To ensure that contractors comply with the same safety requirements, policies, and procedures, as employees the appropriate contractor performance management system should be applied.

In order to control the quality of contractors and consultants a system of authorization is sometimes used. If this is done, the assessment of the contractors should include a demonstration of the financial, technical, material and organizational preconditions, including a quality system. Proof of specialist qualifications should also be included in the assessment. In some countries an authorization for outsourced work is a subject to regulatory control on the same basis as the licensee.

Contractor Performance Management (CPM) is the process that enables both parties to a contract to meet their obligations in order to deliver the objectives required from the contract. It also involves building a good working relationship between the utility and its Contractors. It is expected that the contracted maintenance services are performed safely, efficiently, effectively and economically. Effectiveness is the measure of the extent to which the objectives have been achieved, efficiency is the comparison of output with the input required to produce it and finally the economy is concerned with obtaining the same results more cheaply.

Following the respondents' comments and proposals, the available experience in energy sector and other industries on monitoring the contractor performance was analyzed. It was found out that the following examples of the contractor performance measures can be selected for consideration:

- Availability of equipment the contractor has performed maintenance on;
- Quality assurance audit;
- Maintenance rework activities;
- Number of outstanding defects;
- Injuries;
- Schedule adherence;
- Improvement of opportunities identified;
- Number of late deliveries of equipment;
- Response time to call.

2.6 Conclusions and recommendations

The survey presented in Ref. [2] should be regarded as a sample of ten European nuclear power plants which have been selected from 62 nuclear power plants where the questionnaire was distributed to. The following items summarize main conclusions:

1) It was learned from the survey results that the maintenance performance monitoring is the integral part of the overall maintenance management system at all utilities responded to the survey.
2) The scope and completeness of the maintenance monitoring systems vary from those that use single maintenance performance indicators to more sophisticated systems that are part of the plant's asset management system and include several groups and categories of maintenance performance metrics.
3) Despite of the fact that the majority of maintenance monitoring practices are focused on those indicators that are direct measure of equipment reliability and availability, there is a clear recognition by the European utilities of the role of preventive maintenance. Following the remarks of several respondents, the predictive component of the preventive maintenance has been emphasized more in Ref.[2]; this was reflected in the title of the first maintenance attribute (i.e. 'Preventive character of maintenance (including predictive maintenance'). In addition, a discussion on interrelation of preventive and predictive was included in the report.
4) Maintenance monitoring results are periodically reported to the utility or plant management. This information is useful management tool to measure progress in achieving goals and objectives and monitoring current performance problems and identifying areas requiring management attention. Annual reporting is the usual practice among the responded plants.
5) Different systems for collection and interpretation of the data and the trends on the basis of processing the data are used in the nuclear utilities. Dedicated Data Bases and the specific software for the data processing are implemented at some European utilities for the maintenance monitoring purposes. At some power plants the graphic displays are used to show the maintenance performance indicators including definition, goal, graphic values, reference, comments and action, responsible coordinator/'owners', monthly numerical anticipated and actual values, etc. for specified time period.
6) The survey results were also used for checking the validity of selected specific indicators. It was found out that the majority of the MPIs included in the suggested framework are in use at European nuclear power plants, despite that the weight of their use is different. Some of them are extensively used, while others are not widely practiced. Taking into account the survey results and proposals of some respondents (see Section 2.4), the original framework for MPIs suggested in Ref. [1] and reproduced in Table 2.1 was modified. The modifications were the following:
    a. Removed SMIs:
        i. Planner to craft work ratio
        ii. Number of MCR instruments out of service
        iii. Crew efficiency
        iv. Supervisor to craft worker ratio
        v. Average spares and tools waiting time
        vi. Ratio of replacement asset value (RAV) to craft/wage head count
    b. The SMIs re-allocated from KPI #2.1 'Planning and scheduling' to KPI

#1.3 'Effectiveness of PM':

i. Number of jobs planned but not performed
ii. Number of jobs not started as planned
iii. Actual versus planned man-hours (per job or totals)

c. The SPI #1.2.4 'Mean time to repair' reallocated from KPI #1.2 'Reliability of systems and components' to KPI #1.1 'System and equipment availability'.

The modified list of MPIs comprising 46 specific maintenance indicators is presented in Table 2.2.

7) The specific insights relating to the MPI framework and discussed in Section 2.5 were left for future consideration. In particular, the survey results identified the following areas of interest for further research:

- Representation of the predictive character of maintenance in the maintenance monitoring system;
- Monitoring of contractor performance;
- Material management monitoring (inventory, spare parts, vendors);
- Maintenance budget.

In addition, the implementation process and practices in relation to the maintenance effectiveness monitoring process were found to be of interest to many nuclear power utilities:

- Data collection for the indicators;
- Establishing indicator definitions (plant specific);
- Identification of goals;
- Indicators trending;
- Data display and interpretation;
- Database and software.

Table 2.2 Adjusted listing of MPIs presented in Ref. [2]

Maintenance attribute	KPI	Specific indicator
1. PREVENTIVE CHARACTER OF MAINTENANCE (INCLUDING PREDICTIVE MEASURES)	1.1 System and equipment availability	1.1.1 Component and system unavailability
		1.1.2 Total downtime
		1.1.3 Scheduled downtime
		1.1.4 Unscheduled downtime
		1.1.5 Number of forced power reductions or outages because of maintenance causes
		1.1.6 Mean time between maintenance (MTBM)
		1.1.7 Mean time to repair (MTTR)
	1.2 Reliability of systems and components	1.2.1 Number of corrective work orders issued
		1.2.2 Number of failures in safety related systems
		1.2.3 Mean time between failures (MTBF)
	1.3 Effectiveness of preventive maintenance	1.3.1 Preventive maintenance compliance
		1.3.2 Ratio of corrective work resulted from PM activities
		1.3.3 PM work order backlog trend
		1.3.4 Percentage of deficiencies discovered by surveillance, testing and inspections
		1.3.5 Ratio of PM activities to all maintenance activities
		1.3.6 Overdue of PM activities
		1.3.7 Number of jobs planned but not performed
		1.3.8 Number of jobs not started as planned
		1.3.9 Actual versus planned man-hours (per job or totals)
2. MAINTENANCE MANAGEMENT	2.1 Planning and scheduling	2.1.1 Ratio of unplanned to planned working orders
		2.1.2 Planning compliance
		2.1.3 Schedule compliance
		2.1.4 Ratio of corrective work orders executed to work orders programmed
		2.1.5 Number of outstanding backlogs (number of urgent orders)
	2.2 Interface with operations	2.2.1 Number of workarounds
		2.2.2 Number of temporary modifications
		2.2.3 Ratio of downtime to allowed outage time
	2.3 Work control	2.3.1 Duration of repair
		2.3.2 Repair time of components subject to the Technical Specifications
		2.3.3 Wrench time
		2.3.4 Amount of maintenance rework
		2.3.5 Response time to call
		2.3.6 Overtime maintenance hours
	2.4 Material management	2.4.1 Stores service level
		2.4.2 Number of work requests pending for spare parts
		2.4.3 Stock inventory turns
		2.4.4 Stocked maintenance, repair and operating materials (MRO) inventory value as a percent of replacement asset value (RAV)
		2.4.5 Stocks items available but not used
		2.4.6 Inventory accuracy
		2.4.7 Spare parts and material obsolescence
		2.4.8 Vendor performance
3. MAINTENANCE BUDGET	3.1 Cost effective maintenance	3.1.1 Maintenance cost per kWh produced
		3.1.2 Unplanned costs as percentage of total maintenance costs
		3.1.3 Overtime maintenance costs
		3.1.4 Work orders complete within the determined costs (10-20%)
		3.1.5 Annual maintenance cost as a percent of replacement asset value (RAV)

3.1 Description of changes to the MPI framework

The initial MPI framework [1] that has been adjusted taking into account the points discussed in Section 2.4 and presented in Ref. [2] and Table 2.2 of this report was taken as a starting point to further modify the system of maintenance performance indicators with the aim to address the points discussed in Sections 2.5 and 2.6 and other available information. The latest modifications to the MPI framework are summarized in Table 3.1. The table provides a description of changes and information on how they have been implemented in the MPI framework, as well as references to the sources recommending the specific change.

The first change (see Item #1 in Table 3.1) is dealing with adjusting the definition of the SMI ‘Schedule compliance’ to emphasize the need to comply with the deadline for returning the equipment to service.

Two changes (see Items #2 and 3 in Table 3.1) are dealing with introducing new SMIs to provide a better support to the evaluation of the effectiveness of maintenance management.

There was a recommendation to include a new SMI aimed to show the number of injuries received during maintenance. To introduce this specific indicator, a new KPI #2.5 was included in the MPI framework under Attribute #2 ‘Maintenance management’. The new KPI is entitled ‘Safety during maintenance’ (see Item #4 in Table 3.1). This KPI is aimed at providing information to plant and maintenance department management on various aspects of safety during maintenance, including safety of personnel, fire-related safety, and plant configuration control. Under the new KPI, two SMIs (see Items #5 and 6 in Table 3.1) were introduced aimed at monitoring safety of personnel and fire-related safety.

There have been several recommendations to provide SMIs to support the evaluation of the contractor’s efficiency (see Ref. [2] and Section 2.5). However, it was found out that many of the SMIs already included in the MPI framework can be used specifically to address the issue. The most relevant are the following:

- 2.1.3 Schedule compliance
- 2.3.1 Duration of repair
- 2.3.4 Amount of maintenance rework
- 2.3.5 Response time to call
- 2.3.6 Overtime maintenance hours
- 2.3.7 Non-compliance with the maintenance procedures
- 2.2.4 Number of failures to return the equipment into service, following maintenance activities, at the first presentation
- 2.5.1 Number of injuries

The definitions for these SMIs were adjusted to specifically highlight their ability to evaluate the contractor’s performance (see Item #7 in Table 3.1). It should be noted that depending on the specific needs, other SMIs can also be applicable to the evaluation of contactor performance.

There are also changes (see Items #8-10 in Table 3.1) dealing with introducing new SMIs aimed at monitoring safety during maintenance activities using data from Risk Monitor, if the latter is installed and used at the NPP. Comprehensive information on the use of Risk Monitors is provided in the report of the IAEA and OECD/NEA entitled 'Risk Monitors: The State of the Art in their Development and Use at Nuclear Power Plants' [10]. Several SMIs using Risk Monitor data are suggested to address recommendations provided in Refs [3] and [4], as well as by the recent PECO Workshop [11].

Table 3.1 Modifications to the MPI framework

#	Description of modification	Implementation	Reference/ comment
1	The definition for the SMI 'Schedule compliance' was modified to emphasize the need to comply with the deadline for returning the equipment to service taking into account the time needed to prepare appropriate documentation on the maintenance performed and after-maintenance test accomplished. This is to make sure that operations department would timely accept the equipment back to service. The new definition is formulated as follows: *'Schedule compliance' is a percentage of the scheduled work accomplished (hours) including the time needed for preparing documentation on maintenance performed and after-maintenance test to the total work time available to the schedule.*	The new definition is included in the final listing of MPIs, see Table 3.2, SMI #2.1.3	Recommended in Ref. [2] & Section 2.5
2	A new SMI is included in the MPI framework; it is aimed at emphasizing the effectiveness of maintenance management process and interface with operations department: *2.2.4 Number of failures to return the equipment into service, following maintenance activities, at the first presentation*	SMI #2.2.4 is included under KPI #2.2 'Interface with operations', see Table 3.2	Recommended in Ref. [2] & Section 2.5
3	A new SMI is included in the MPI framework; it is aimed at emphasizing the effectiveness of maintenance management process and work control: *2.3.7 Non-compliance with the maintenance procedures*	SMI #2.3.7 is included under KPI #2.3 'Work control', see Table 3.2	Recommended in Ref. [2] & Section 2.5
4	A new KPI is included in the MPI framework; it is aimed at emphasizing the safety during maintenance: *2.5 Safety during maintenance*	KPI #2.5 is included under Maintenance Attribute #2 'Maintenance management'	Recommended in Ref. [2] & Section 2.5 and PECO Workshop
5	A new SMI is included in the MPI framework; it is aimed at emphasizing the safety of maintenance personnel: *2.5.1 Number of injuries*	SMI #2.5.1 is included under KPI #2.5 'Safety during maintenance', see Table 3.2	Recommended in Ref. [2] & Section 2.5
6	A new SMI is included in the MPI framework; it is aimed at emphasizing the fire-related safety during maintenance: *2.5.2 Number of events involving an inflammation/fire*	SMI #2.5.2 is included under KPI #2.5 'Safety during maintenance', see Table 3.2	

#	Description of modification	Implementation	Reference/ comment
7	The definitions for the SMIs presented below were adjusted to specifically emphasize their ability to evaluate the contractor's performance: *2.1.3 Schedule compliance* *2.2.4 Number of failures to return the equipment into service, following maintenance activities, at the first presentation* *2.3.1 Duration of repair* *2.3.4 Amount of maintenance rework* *2.3.5 Response time to call* *2.3.6 Overtime maintenance hours* *2.3.7 Non-compliance with the maintenance procedures* *2.5.1 Number of injuries* The following note was included in the definitions of these SMIs: "*Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services*".	Definitions for the SMIs: #1.1.1 #2.1.3 #2.2.4 #2.3.1 #2.3.4 #2.3.5 #2.3.6 #2.3.7 #2.5.1 were adjusted, see Table 3.2	Recommended in Ref. [2] & Section 2.5
8	A new SMI is included in the MPI framework; it is aimed at emphasizing the plant configuration safety during maintenance: *2.5.3 Number of times the plant was operating with elevated risk* This SMI uses the data available from Risk Monitor.	SMI #2.5.3 is included under KPI #2.5 'Safety during maintenance', see Table 3.2	Recommended by PECO Workshop
9	A new SMI is included in the MPI framework; it is aimed at emphasizing the plant configuration safety during maintenance: *2.5.4 Time the plant was operating with elevated risk* This SMI uses the data available from Risk Monitor.	SMI #2.5.4 is included under KPI #2.5 'Safety during maintenance', see Table 3.2	Recommended by PECO Workshop
10	A new SMI is included in the MPI framework; it is aimed at emphasizing the plant configuration safety during maintenance: *2.5.5 Ratio of time the plant was operating with elevated risk* This SMI uses the data available from Risk Monitor.	SMI #2.5.5 is included under KPI #2.5 'Safety during maintenance', see Table 3.2	Recommended by PECO Workshop

3.2 Final list of maintenance performance indicators

The final framework for MPIs includes 3 Maintenance Attributes, 9 Key Performance Indicators, and 53 Specific Maintenance Indicators. The final MPI framework is illustrated in Fig. 3.1.

In order to provide a concise overview of the final proposal for the MPIs framework with the relevant characteristics of MPIs, Table 3.2 was developed. It is largely based on information provided in Ref. [1]. Table 3.2 provides a complete listing of MPIs along with their definitions, expressions for calculation, and other characteristics (i.e. whether the indicator is lagging or leading). The list of MPIs and their characteristics is based on the list provided in Ref. [1] with the modifications suggested in Ref. [2] and Section 3.1 of this report.

1. PREVENTIVE CHARACTER OF MAINTENANCE (INCLUDING PREDICTIVE MEASURES)	**1.1 System and equipment availability**	1.1.1 Component and system unavailability 1.1.2 Total downtime 1.1.3 Scheduled downtime 1.1.4 Unscheduled downtime 1.1.5 Number of forced power reductions or outages because of maintenance causes 1.1.6 Mean time between maintenance 1.1.7 Mean time to repair
	1.2 Reliability of systems and components	1.2.1 Number of corrective work orders issued 1.2.2 Number of failures in safety related systems 1.2.3 Mean time between failures
	1.3 Effectiveness of preventive maintenance	1.3.1 Preventive maintenance compliance 1.3.2 Ratio of corrective work resulted from PM activities 1.3.3 PM work order backlog trend 1.3.4 Percentage of deficiencies discovered by surveillance, testing and inspections 1.3.5 Ratio of PM activities to all maintenance activities 1.3.6 Overdue of PM activities 1.3.7 Number of jobs planned but not performed 1.3.8 Number of jobs not started as planned 1.3.9 Actual versus planned man-hours (per job or totals)
2. MAINTENANCE MANAGEMENT	**2.1 Planning and scheduling**	2.1.1 Ratio of unplanned to planned working orders 2.1.2 Planning compliance 2.1.3 Schedule compliance 2.1.4 Ratio of corrective work orders executed to work orders programmed 2.1.5 Number of outstanding backlogs (number of urgent orders)
	2.2 Interface with operations	2.2.1 Number of workarounds 2.2.2 Number of temporary modifications 2.2.3 Ratio of downtime to allowed outage time 2.2.4 Number of failures to return the equipment into service, following maintenance activities, at the first presentation
	2.3 Work control	2.3.1 Duration of repair 2.3.2 Repair time of components subject to the Technical Specifications 2.3.3 Wrench time 2.3.4 Amount of maintenance rework 2.3.5 Response time to call 2.3.6 Overtime maintenance hours 2.3.7 Non-compliance with the maintenance procedures
	2.4 Material management	2.4.1 Stores service level 2.4.2 Number of work requests pending for spare parts 2.4.3 Stock inventory turns 2.4.4 Stocked maintenance, repair and operating materials MRO inventory value as a percent of RAV 2.4.5 Stocks items available but not used 2.4.6 Inventory accuracy 2.4.7 Spare parts and material obsolescence 2.4.8 Vendor performance
	2.5 Safety during maintenance	2.5.1 Number of injuries 2.5.2 Number of events involving inflammation/ fire 2.5.3 Number of times the plant was operating with elevated risk 2.5.4 Time the plant was operating with elevated risk 2.5.5 Ratio of time the plant was operating with elevated risk
3. MAINTENANCE BUDGET	**3.1 Cost effective maintenance**	3.1.1 Maintenance cost per kWh produced 3.1.2 Unplanned costs as percentage of total maintenance costs 3.1.3 Overtime maintenance costs 3.1.4 Work orders complete within the determined costs (10-20%) 3.1.5 Annual maintenance cost as a percent of RAV

Fig. 3.1 Final MPI framework

Table 3.2 Final list of MPIs

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
1. PREVENTIVE CHARACTER OF MAINTENANCE (INCLUDING PREDICTIVE MEASURES)	**1.1 System and equipment availability**	1.1.1 Component and system unavailability	Fraction of time that component is unable to perform its intended function when it is required to be available for service Usually expressed as a number of times/hours a safety system is unavailable over a specified observation time Note: This indicator can be split further into three more specific indicators: total downtime, scheduled downtime, unscheduled downtime.	**CSU,** 1/To[3]; h/To	Lagging	Monitoring the effectiveness of maintenance practices	At some NPPs this indicator is defined as unavailability of safety system performance caused by maintenance, surveillance, or inspection.
		1.1.2 Total downtime	Amount of time a system is not capable of running over a specified observation time It is the sum of scheduled downtime and unscheduled downtime. This metrics allows one to evaluate the total amount of time the system or equipment has not been capable of running.	**DT,** h/To	Lagging	Identifying problematic areas and/or potential capacity in order to minimize downtime	
		1.1.3 Scheduled downtime	Amount of time an equipment or system is not capable of running due to scheduled downtime, i.e., work that is on the established maintenance schedule, over a specified observation time	**DS,** h/To	Lagging	Understanding the impact of scheduled work on capacity and to minimize downtime	
		1.1.4 Unscheduled downtime	Amount of time when equipment or system is not capable of running due to unscheduled repairs, i.e., repairs not on the approved maintenance schedule, over a specified observation time Can be expressed as a sum of equipment downtime elements not identified on the maintenance schedule	**DUS,** h/To	Lagging	Understanding the impact of unscheduled work on capacity and maintenance productivity in order to minimize downtime	
		1.1.5 Number of forced power reductions or outages because of maintenance causes	The number of forced power reductions and outages due to maintenance causes over a specified observation time	**FPR,** 1/To	Lagging	Monitoring the overall quality of plant maintenance	

[3] To – observation time; it may be a month (To=m), a quarter of the year (To=q), a year (To=y), or another time unit. For failures in safety systems, using one month as the observation time is not indicative because failures in safety systems are relatively rare.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		1.1.6 Mean time between maintenance	Average length of time between one maintenance action and another for an asset or component Calculated as the total operation time divided by number of maintenance actions during the same period Note: MTBM includes all corrective and preventive actions.	**MTBM,** h	Leading	Minimizing the number of function interruptions by establishing an appropriate maintenance strategy and applying correct maintenance procedures	The metric is applied only for maintenance actions which require or result in component function interruption.
		1.1.7 Mean time to repair	Average number of hours that a system or component will be unavailable whilst undergoing maintenance Calculated as a total amount of repair time expended in a specified period (hours) divided by number of repair events in that specified period	**MTTR,** h	Leading	Identification of areas of poor maintainability leading to reduced system availability	The MTTR parameter is important in evaluating the availability of repairable systems.
	1.2 **Reliability of systems and components**	1.2.1 Number of corrective work orders issued	Number of corrective work orders over a specified observation time	**NCW,** 1/To	Leading	Revealing maintenance deficiencies or reliability problems	A high number of corrective work orders issued for safety or safety related systems may reflect potential reliability problems, but also maintenance deficiencies. High number of corrective work orders may directly affect overall plant performance and unit capability factor.
		1.2.2 Number of failures in safety related systems	Number of failures in safety related systems over a specified observation time	**NF,** 1/To	Lagging	Monitoring the reliability of safety related systems	It is desirable to monitor each system with its own indicator, or at least each group of systems (e.g. ECCS, emergency diesel generators, emergency feed water system, etc.)
		1.2.3 Mean time between failures	Average time (expressed in hours) that a component works without failure Calculated as the hours under observation divided by the number of failures The other definition presents MTBF as an indicator of expected system reliability calculated on a statistical basis from the known failure rates of various components of the system. Usually MTBF is expressed in hours.	**MTBF,** h	Lagging	Managing repairable assets of similar type	MTBF is an excellent characteristic for determining how many spare parts are needed to support 1000 similar equipment items but a poor characteristic for guiding on when to replace the component to avoid a crash of a system.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
	1.3 Effectiveness of preventive maintenance	1.3.1 Preventive maintenance compliance	Percentage of the PM orders executed on time to the total amount of the working order on a monthly or quarterly basis	**PMC,** unit-less	Leading	Providing a management summary of PM work order execution and completion compliance	To be reviewed on a monthly or quarterly basis High values for executed on time and completed on time works indicate high level of maintenance planning and execution.
		1.3.2 Ratio of corrective work resulted from PM activities	The preventive maintenance effectiveness can be expressed as the amount of corrective work that is identified when performing PM work compared to the amount of PM work being done. Note: The indicator should be calculated as an average for a large maintenance department. It should not be applied to a single PM task or single item.	**RCW,** unit-less	Leading	Evaluating of how well preventive maintenance is identifying potential failures before they occur	This indicator is only one of the measures of the effectiveness of a PM programme. The best indicator of the effectiveness of PM work is the reliability of equipment. The target value for R1 should be a mid range. Very low or very high numbers would be a cause for investigation. In all cases the measure should be considered with the equipment reliability. In addition the total amount of PM work being done should be considered when evaluating the effectiveness of PM activities.
		1.3.3 PM work order backlog trend	All active PM work orders are segregated into categories 'Overdue', 'Current' and 'Future', according to a predetermined calendar based formula, and plotted as a function of time. The graphical representation allows the maintenance manager to identify trends in non-compliance and effectiveness of backlog reviews.	**PMB,** unit-less	Leading	Managing PM work order backlog	The PMB indicator is a measure of all active PM work orders in the system. It is historically trended using the required by date of the work order and comparing this to today's date +/- 14 days.
		1.3.4 Percentage of deficiencies discovered by surveillance, testing and inspections	Ratio of the deficiencies discovered during the planned surveillance activities to the total amount of the deficiencies discovered on the annual basis	**RDD,** unit-less (defined on yearly basis)	Lagging	Monitoring the effectiveness of surveillance programme at the plant	RDD is a measure of the effectiveness of the preventive activities in identifying equipment problems before this equipment is required in real situation.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		1.3.5 Ratio of PM activities to all maintenance activities	1) Ratio of preventive maintenance work orders to total maintenance work orders 2) Another version of this indicator is the ratio of PM activities to CM activities.	**RPM,** unit-less	Leading	1) Measuring of shift towards planned maintenance and away from emergency maintenance 2) Optimizing the equipment replacement interval before equipment fails	1) This metrics indicates the prevailing maintenance strategy. It is expected that the use of this indicator will increase PM activities as a percentage of maintenance work. Since inadequate scheduled maintenance results in unscheduled failures/downtime, it is expected that increased PM activities will eventually decrease emergency/ unscheduled repair work orders. 2) Analysis of the effect of the corrective/preventive cost ratio on the optimum replacement interval shows that as the cost ratio increases, the optimum replacement interval decreases. This is an expected result because the corrective replacement costs are much greater than the preventive replacement costs. Therefore, it becomes more cost effective to replace the component more frequently before it fails.
		1.3.6 Overdue of PM activities	The indicator is a measure of PM work orders that are past the required by date (i.e., overdue). It can be expressed as a percentage: PM work orders overdue (%) = [(Today's date – Required by date) / PM frequency (days)] x 100	**PMO,** unit-less	Leading	Helping plant management to prioritize work execution opportunities	The PM work orders that are determined to be overdue can be rank ordered to determine those work orders that are the most overdue, and which can be focused on for corrective action. High number of overdue PM work is evidence of poor planning or inadequate attitude of plant management.
		1.3.7 Number of jobs planned but not performed	Number of jobs planned but not performed over a specified observation time	**NJNP,** 1/To	Leading	Assessing the maintenance effectiveness	
		1.3.8 Number of jobs not started as planned	Number of jobs not started as planned over a specified observation time	**NJNS,** 1/To	Leading	Assessing the maintenance effectiveness	

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		1.3.9 Actual versus planned man-hours (per job or totals)	Ratio of actual versus planned man-hours Can be calculated either on per-job or totals basis	**APMH,** unit-less	Leading	Assessing the maintenance effectiveness	
2. MAINTENANCE MANAGEMENT	**2.1 Planning and scheduling**	2.1.1 Ratio of unplanned to planned working orders	Ratio of unplanned working orders to planned working orders	**RUP,** unit-less	Leading	Providing balance in establishing the periodicity of preventive maintenance actions	Low level of this indicator indicates good preventive maintenance management at the plant.
		2.1.2 Planning compliance	The ratio of total labour hours planned divided by total labour hours scheduled	**PC,** unit-less	Lagging	Indication of the effectiveness of maintenance programme	The high number in this indicator indicates an effective maintenance programme and thus gives confidence that the equipment is adequately being looked after.
		2.1.3 Schedule compliance	Can be expressed as a percentage of the scheduled work accomplished (hours) including the time needed for preparing documentation on maintenance performed and after-maintenance test to the total work time available to the schedule. Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**SC,** unit-less	Lagging	• Measuring the effectiveness of the work scheduling process and indication of adherence to the maintenance schedule • Useful for the maintenance management to look for reserves for efficiency improvements	SC is usually calculated on either a daily or a weekly basis, and is based on hours. SC is the example when the same indicator can be leading and lagging. It is a lagging indicator of the efficiency of the scheduling process and a leading indicator for wrench time. Despite that this indicator is attributed to the Planning and Scheduling this indicator can be equally placed under the Work Management since schedule compliance in most part is dependent of the good work management and control.
		2.1.4 Ratio of corrective work orders executed to work orders programmed	The ratio of corrective work orders executed to the total number of corrective work orders	**RWE,** unit-less	Leading	Indication of the effectiveness of maintenance programme	A high number of this indicator indicates an effective maintenance programme and gives confidence that the equipment is adequately being looked after.
		2.1.5 Number of outstanding backlogs (number of urgent orders)	The number of work orders that are pending for specified time period (e.g. one month, one quarter)	**NOB,** 1/To	Lagging	Indication of the ineffectiveness of maintenance programme	A high number in this indicator indicates an inefficient maintenance programme and thus gives an alarm that equipment is not being adequately looked after.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
	2.2 Interface with operations	2.2.1 Number of workarounds	A workaround is a bypass of a recognized problem in a system or equipment. A workaround is typically a temporary fix that implies that a genuine solution to the problem is needed. Number of workarounds accumulated to the date	**WA,** 1/plant	Leading	Indication of poor maintenance practices	Frequently workarounds are as creative as true solutions, involving high intellectual potential in their creation. A workaround is a temporary solution used to bypass, mask or otherwise avoid a problem in some system. Some power plants often find themselves living with workarounds for long periods of time rather than getting a problem solution as a result of the appropriate maintenance action. High number of workarounds is an indicator of poor maintenance practices, inadequate coordination between the operations and maintenance or inadequate engineering resources to properly resolve an existing problem.
		2.2.2 Number of temporary modifications	Measure of the number of problems that have been temporarily solved; indirectly assesses the effectiveness in providing a permanent or definitive solution Number of temporary modifications accumulated to the date	**TM,** 1/plant	Leading	Indication of potential lack of resources or degradation of equipment and/or maintenance system as a whole	Temporary modifications are the common practice in NPPs. Proper control of the temporary changes ensures keeping power plant within the design envelope. However, the trend in increase of the number of temporary modifications is indicator that some problems may exist at a power plant. Those problems may be related to the lack of resources to transfer the temporary modification into the permanent establishment or lack of proper attitude from the plant management. The high level of temporary 'fixings' may be an early indicator of degradation of plant systems and equipment and the maintenance system as a whole.
		2.2.3 Ratio of downtime to allowed outage time	The ratio of the time the system is out of service for maintenance to the allowed outage time	**RDA,** unit-less	Leading	Measuring the effectiveness of managerial processes and controls and coordination between the operations and maintenance	This indicator can also be interpreted as the percentage of the actual time the system is in TS limiting conditions for operation (LCO) to the prescribed LCO time.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		2.2.4 Number of failures to return the equipment into service, following maintenance activities, at the first presentation	Ratio of failures to return the equipment into service, following maintenance activities, at the first presentation to total number of returning equipment into service Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**NFRS,** unit-less	Leading	Measuring the effectiveness of managerial processes and controls and coordination between the operations and maintenance	
	2.3 **Work control**	2.3.1 Duration of repair	Direct measuring of the duration of the repair of the same type Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**DR,** h	Lagging	Revealing deficiencies in the skills and the qualification of the maintenance personnel or inadequacy of the maintenance management or the material management	
		2.3.2 Repair time of components subject to the Technical Specifications	The measure of the average repair time of failures causing unavailability of components defined in the Tech. Specs. (the indicator can be expressed as an average of the repair times of all failure repairs). Calculated as sum of repair times divided by the number of failures	**RTTS,** h	Lagging	Revealing deficiencies in the skills and the qualification of the maintenance personnel or inadequacy of the maintenance management or the material management for components subjected to TS	
		2.3.3 Wrench time	Wrench time represents the percentage of time an employee spends applying physical effort or attention to a tool, equipment, or materials in the accomplishment of assigned work The indicator can be expressed in the following way: Wrench time (%) = [Productive work time/ Total work time scheduled] * 100%	**WT,** unit-less	Lagging	Determining how efficient the plant is at planning, scheduling and executing the work	WT allows one to identify the productivity of the maintenance processes in use, including planning and scheduling, supervision, and maintenance management, and is used to find opportunities for increasing productive work time.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		2.3.4 Amount of maintenance rework	This metric is useful to monitor the amount of work that is carried out repeatedly since the results of the previous work are inadequate. Rework can be calculated as a percentage of the corrective work identified as rework (in man-hours) to the total work (in man - hours). Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**AMR,** unit-less	Leading	Identifying what corrective actions are needed to minimize or eliminate rework	This indicator witnesses the quality of the maintenance performed. AMR provides also a measure to show if the corrective measures are effective.
		2.3.5 Response time to call	Often a nuclear power plant requires immediate reactive services of call-to-repair support. Call-to-repair support provides coverage across the normal working hours as well as at any time such support is needed. A commitment to restore the system or equipment malfunctions within a specified time period requires adequate management level in several services, in particular good management of resources, both, manpower and material. This service should incorporate enhanced stocks inventory management to ensure spare parts are available when needed. It is time, expressed in hours, from revealing the failure until maintenance activities start. Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**RTC,** h	Leading	Indication of the level of readiness of the maintenance organization to respond to the urgent operational needs	Low call- to-repair indicator witnesses the high level of the maintenance organization, including planning and coordination, resources management, material management, etc.
		2.3.6 Overtime maintenance hours	This metric assists in determining whether the permanent maintenance workforce is appropriately staffed and within guidelines for safety concerns and operational issues. The indicator is defined as a number of overtime maintenance labour hours used to maintain equipment, divided by the total maintenance labour hours to maintain equipment, expressed as a percentage. Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**OMH,** unit-less	Lagging	Indication of a poor wrench time and/or inadequate staffing	A high overtime percentage could be also a result of poor wrench time and/or inadequate staffing.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		2.3.7 Non-compliance with the maintenance procedures	Number of cases when non-compliance with the maintenance procedures have been identified over a specified observation time Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**NCMP,** 1/To	Lagging	Indication of degradation of safety culture at maintenance	
	2.4 Material management	2.4.1 Stores service level	This indicator can be calculated as how many times person comes to check out a part and receives a stock item divided by the number of times a person comes to the storeroom to check out a stocked item and item is not available. The indicator can be also expressed in percent of number of inventory requests with stock out to the total number of inventory requests.	**SSL,** unit-less	Lagging	Minimizing the waste associated with excess inventory	By reducing inventory value while maintaining an appropriate level of stock outs, an efficient work force with minimum inventory can be assured. By analysing the information provided by stock outs, management can identify planning problems, vendor supply issues, potential over stocking, and changes in equipment reliability.
		2.4.2 Number of work requests pending for spare parts	The indicator can be expressed either as the total amount of work requests or as the percentage of pending work requests to the total amount of work requests.	**NWSP,** unit-less	Leading	Monitoring the ability of power plant to ensure the necessary material resources that are needed for the smooth maintenance process.	

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		2.4.3 Stock inventory turns	The stock turnover rate is the rate at which the average inventory is replaced or turned over, throughout a pre-defined standard operating period, typically one year. Inventory turns identifies how quickly specific types of inventory are flowing through the inventory system. For the calculations of this indicator it is reasonable to divide the stocks inventory into two groups: 1) operating supplies that are supposed to turn frequently, and 2) spare parts which will usually have a lower turnover [14]. Inventory turns is calculated as follows: Inventory turns = Value of Stock Purchased / Value of Stock on Hand	**SIT,** unit-less	Lagging	Managing a facility's inventory to ensure proper stock levels	SIT can be used in conjunction with the metrics 'stock service level' to verify that the inventory levels are adequate to the operational needs. A stock service level and inventory turn ratio should be used to balance the inventory levels, and to manage risk to an acceptable level, on both operating supplies and spare parts. The optimum turn ratio will be different for different types of equipment, and is dependent of the amount of risk a facility can take. The reliability and availability requirements of the safety related equipment and systems should be taken into consideration when reducing the inventory levels. A high turn ratio on spare parts could indicate a reliability issue that needs to be addressed.
		2.4.4 Stocked maintenance, repair and operating materials (MRO) inventory value as a percent of replacement asset value (RAV)	The metric is the value of maintenance, repair and operating materials (MRO) and spare parts stocked at the site to support maintenance, divided by the replacement asset value (RAV) of the assets being maintained at the plant, expressed as a percentage. This indicator allows one to compare the value of stocked maintenance inventory on site with other plants of varying size and value, as well as to benchmarks. The RAV as the denominator is used to normalize the measurement given that different plants vary in size and value.	**MROM,** unit-less	Lagging	Useful for the corporate managers to compare plants but also can be used by plant managers in relation to maintenance activities	The best plants with high asset utilization and high equipment reliability in most industries have less stocked inventory value because of a more predictable need for materials. This indicator should be used cautiously because lower stocked inventory value does not necessarily equate to best in class. This indicator should be balanced with stock-outs (which should be low) and other indicators related to the stocked inventory.
		2.4.5 Stocks items available but not used	The number of stock items available not but not used over as specified observation time	**SINU,** 1/To	Lagging	Evaluation of effectiveness of material management	
		2.4.6 Inventory accuracy	Ratio of identified cases of non-properly documented (or missed) inventory items to total number of inventory items	**IA,** unit-less	Lagging	Evaluation of effectiveness of material management	

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
		2.4.7 Spare parts and material obsolescence	Ratio of identified obsolete spare parts and material items to total number of inventory items	**SPMO,** unit-less	Lagging	Evaluation of effectiveness of material management	
		2.4.8 Vendor performance	Number of identified cases of non-compliance with the delivery schedule over a specified observation time or Number of deviations from expected performance of delivered spare part and material items over a specified observation time	**VP,** 1/To	Lagging	Evaluating of vendor performance	
	2.5 **Safety during maintenance**	2.5.1 Number of injuries	Number of injuries received during maintenance over a specified observation time Note: For the evaluation of contractor performance, the data used should include only the data related to the contractor excluding the data related to in-plant maintenance services.	**NI,** 1/To	Leading	Monitoring safety during maintenance	
		2.5.2 Number of events involving inflammation/ fire	Number of events involving inflammation or fire over a specified observation time	**NIF,** 1/To	Lagging	Monitoring fire safety during maintenance	
		2.5.3 Number of times the plant was operating with elevated risk	This indicator assumes retrospective use of plant Risk Monitor. Number of cases over a specified observation time when the plant entered the configuration corresponding to the orange or red thresholds of elevated risk shown by Risk Monitor due to simultaneous taking out of service components important to safety	**NER,** 1/To	Leading	Monitoring operational safety during maintenance	It is assumed the plant Risk Monitor is installed at NPP and used to support plant operation.
		2.5.4 Time the plant was operating with elevated risk	This indicator assumes retrospective use of plant Risk Monitor. Cumulative time over a specified observation time when the plant entered the configuration corresponding to the orange or red thresholds of elevated risk shown by Risk Monitor due to simultaneous taking out of service components important to safety	**TER,** h/To	Leading	Monitoring operational safety during maintenance	It is assumed the plant Risk Monitor is installed at NPP and used to support plant operation.
		2.5.5 Ratio of time the plant was operating with elevated risk	This indicator assumes retrospective use of plant Risk Monitor. Ratio of cumulative time when the plant was operating with elevated risk shown by Risk Monitor to the total operating time	**TER,** unit-less	Lagging	Monitoring operational safety during maintenance	This indicator uses the data from plant Risk Monitor, if the latter is available.

Attribute	KPI	Specific indicator	Definition / expression	ID, unit	Lagging or leading	Purpose / use	Comments
3. MAINTENANCE BUDGET	**3.1 Cost effective maintenance**	3.1.1 Maintenance cost per kWh produced	Most of maintenance cost is a fixed amount per year for the regular service of the systems and components, but some utilities prefer to use a fixed amount per kWh of output in their calculations. The reasoning behind this method is that tear-and-wear of the equipment increases with the life time of the power plant. Total cost of maintenance divided by kWh produced	**CKWH,** EUR/ kWh	Lagging	Evaluation of the maintenance efficiency	The indicator is sensitive to the overall maintenance management and its strategy.
		3.1.2 Unplanned costs as percentage of total maintenance costs	The adequate maintenance planning at nuclear facility should take into account all the maintenance aspects that can affect the maintenance effectiveness including the maintenance costs within the planned budget. Ratio of unplanned costs to total maintenance costs	**UC,** unit-less	Leading	Indication of either poor planning, decreased reliability of the plant systems, or the deficiencies in the work execution	Departure from the budgeting forecast may indicate either poor planning, decreased reliability of the plant systems or the deficiencies in the work execution. All these aspects should be thoroughly analyzed when facing the increase in the unplanned maintenance costs.
		3.1.3 Overtime maintenance costs	Total cost of overtime maintenance activities over a specified observation time	**OMC,** EUR/ To	Lagging	Indication of the maintenance inefficiency	
		3.1.4 Work orders complete within the determined costs (10-20%)	This indicator is useful in monitoring the maintenance budget discipline. The indicator can be expressed as percentage of work orders that are accomplished beyond the planned costs. The ratio of the number of work orders that are accomplished beyond the planned costs to the total number of work orders	**WOC,** unit-less	Lagging	Indication of shortages in the maintenance planning and work control	Increased value of this indicator may witness shortages in the maintenance planning and work control.
		3.1.5 Annual maintenance cost as a percent of replacement asset value (RAV)	The metric is the amount of money spent annually maintaining assets, divided by the Replacement Asset Value (RAV) of the assets being maintained, expressed as a percentage. The RAV as the denominator is used to normalize the measurement given that different plants vary in size and value.	**AMC,** unit-less	Lagging	Assisting in comparison of expenditures for maintenance with other plants	This metric allows comparing the expenditures for maintenance with other plants of varying size and value, as well as to benchmarks.

4 DISCUSSION ON MAINTENACE EFFECTIVENESS ENHANCEMENT USING MPIs

4.1 Determination of the thresholds for MPIs

One of the important and also difficult tasks dealing with the effective use of the MPI framework is the definition of thresholds for SMIs. The data are often confidential and are not publicly available. Often, instead of a threshold, below which the maintenance practice is considered unacceptable, a target value (sometimes also called 'World class target level') is used that is regarded to be the goal to achieve. Some examples of these values (for non-nuclear industry) provided in Refs [15] – [17] are displayed below:

Ratio of PM activities to all maintenance activities	75-80%
Number of jobs not started as planned	5%
Schedule compliance	90%
Wrench time	65%
Amount of maintenance rework	2-3%
Work orders complete within the determined costs (10-20%)	90%

The specific thresholds and target values for MPIs may be developed using an expert elicitation process. In this process a special questionnaire have to be developed to collect expert judgement on specific values for the thresholds; then the results will be statistically processed and averaged. In many cases the thresholds for MPIs will depend on plant-specific formulation of the respective MPI; therefore the results should be processed carefully to avoid wrong interpretation.

4.2 Representation of MPIs and providing a feedback

Each KPI contains a set of SMIs that should be considered together to provide a meaningful picture of the maintenance effectiveness. Generally, there may be an incentive to integrate SMIs in a single measure using a weighted aggregation approach; the perception may be that this would give a final unambiguous number for a KPI. However, such way of thinking is discouraged due to the fact that the final result obtained may be misleading and rather meaningless. Instead, a combined representation of the MPIs could be recommended that keeps each individual SMI separately but at the same time allows to assess and meaningfully represent the composite entries of each KPI. This approach is discussed further.

Generally, there are many different approaches for representation of MPIs using various diagrams (Refs [13], [15] – [17]). However, in order to represent a KPI that includes several SMIs measured in different units, a relative measure for each SMI can be calculated that would characterize the percent of deviation from the threshold value or the percent towards the target value.

4.2.1 Deviation from the threshold

The percent of deviation from the threshold will characterize what is the margin to unacceptable performance that can also be negative (in this case underperformance is immediately identified). The following formula can be applied:

$$D = 100 * (SMI_{actual} – THRES) / THRES \qquad (4.1)$$

Where:

D	- the percentage of deviation from the threshold value;
SMI_{actual}	- the actual value of the specific maintenance indicator;
THRES	- the threshold value for the SMI, below which the performance is unacceptable.

For the purpose of visual representation of MPIs that can be used by plant managers to facilitate the review and analysis of the maintenance effectiveness using the system of performance indicators, the results of the analysis of deviation from the threshold can be presented in the form of the diagram shown in Fig. 4.1. In this diagram, the X-axis represents the threshold, and the percent of deviation for each SMI is represented by a corresponding bar, either positive (meaning that the threshold is exceeded by the SMI by the corresponding percent), or negative (meaning that the SMI is below the threshold by the corresponding percent). The SMIs are grouped into the sets based on their belonging to a particular KPI (these SMIs are uniformly coloured). The negative entries are marked by red colour.

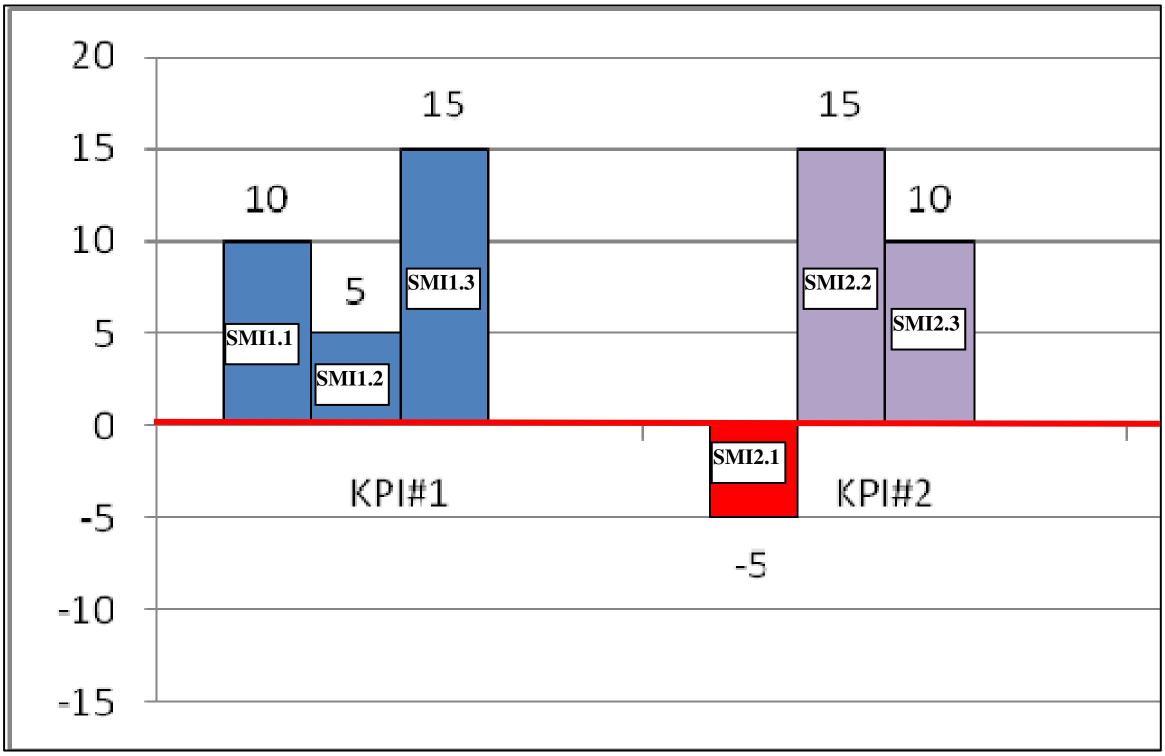

Fig. 4.1 Representation of the deviation of MPIs from the thresholds

4.2.2 Gap to the target

The indicator of the percent towards the target value will characterize what is the gap between the current and target performance. The following formula can be applied:

$$A = 100 * (TARGET - SMI_{actual}) / TARGET \qquad (4.2)$$

Where:

A - the indicator of achieving the target (in percent);

TARGET - the target value for the SMI;

SMIactual - the actual value of the specific maintenance indicator.

Using the measure of gap to the target, the results of the assessment could be plotted by means of the diagram represented in Fig. 4.2. In this figure, each set of SMIs included in the KPI is represented by a set of bars uniformly coloured with the indication of the status of each SMI relative to its target. In this diagram, the Y-axis represents the target line, and the percent of the gap for each SMI is represented by the corresponding bar meaning that the SMI is away from the target by this percent. The entries exactly matching the target (or very close to it) are marked by green labels.

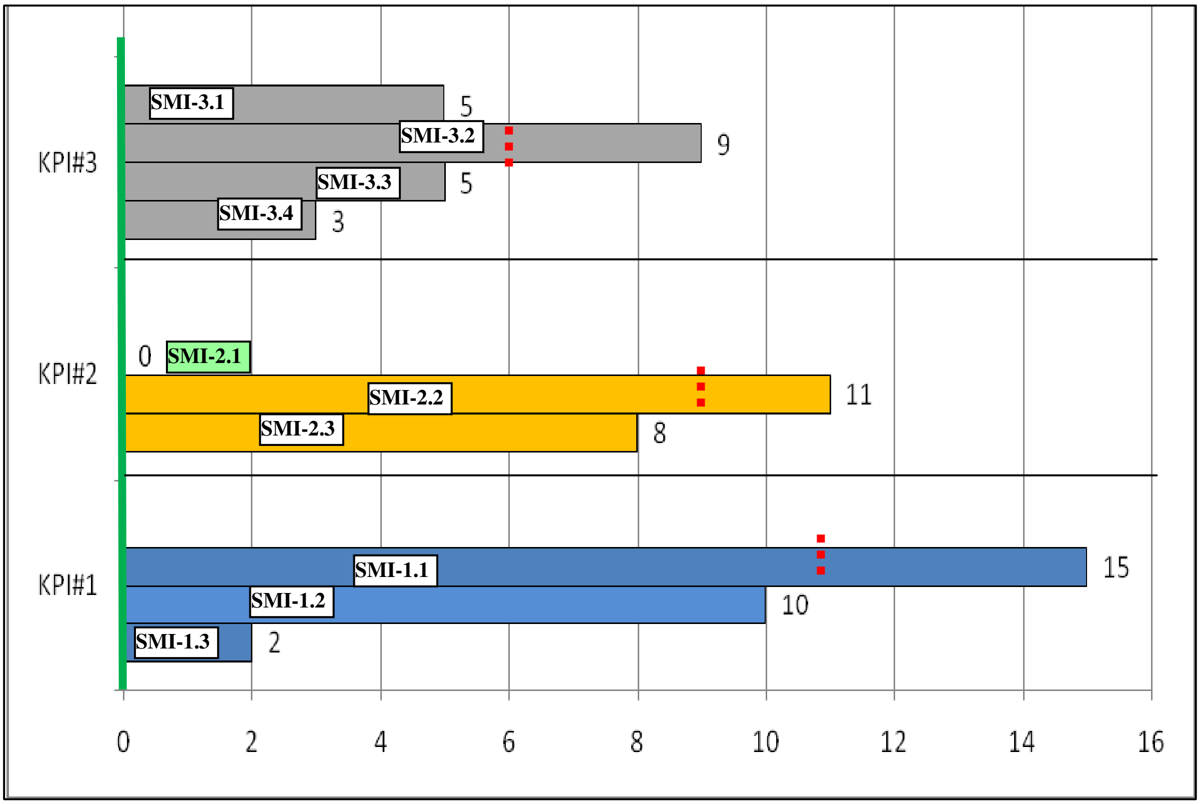

Fig. 4.2 Representation of the MPI's gap to the target

The diagram presented in Fig. 4.2 can be further enhanced by incorporation of the thresholds relative to the target values for those SMIs, for which both target values and thresholds have been defined (this is shown by the dashed red line on the corresponding bars in Fig. 4.2). In this case the thresholds should be formulated as percent of the gap from the target value:

$$THRES_0 = 100 * (TARGET - THRES) / TARGET \quad (4.3)$$

Where:

$THRES_0$ - the threshold expressed as percent of the gap between the threshold and the target value;

TARGET - the target value for the SMI;

THRES - the threshold value for the SMI, below which the performance is unacceptable.

4.2.3 Backfitting analysis

After defining the indicators D and/or A (see Formulas 4.1 and 4.2 respectively) for all SMIs included in the KPI, they can be plotted and reviewed from the perspective of achieving the maintenance excellence goals:

- If there is a negative D indicator, an immediate action is needed to improve the situation.
- If all D indicators are positive, no immediate action is needed, but a low value for a particular SMI should be considered for potential recovery actions to break the negative trend.
- If an A indicator is quite large, actions may be considered to improve the situation and reduce the gap to the target value.

The indicators A and D can also be used for trending purposes to evaluate the effectiveness of management actions aimed at enhancing the maintenance efficiency. Several thresholds corresponding to the yellow (warning) and red (unsatisfactory performance) status could be established. For the trending analysis of a particular SMI, the direct comparison with the thresholds and target values can be used. A useful representation in this case would be a standard comparative bar chart representing the change of the SMI with time.

For the backfitting purposes, an analysis of compliance with the thresholds and requirements should be performed. In case of a declining performance, a detailed analysis of the causes of unsatisfactory performance should be performed and documented. One of the possible ways of documenting the analysis for backfitting action definition is presented in Fig. 4.3. In this example, each actual SMI is represented along with its ideal value, the range within which the indicator is still acceptable, and the corresponding threshold that is considered as an alarm for unacceptable degraded performance. Each line has a check-off box that is ticked in the cell corresponding to the actual performance. Such a table can be easily developed using broadly available standard software, such as EXCEL. It should also be noted that there are many commercial software pages available in the market that provide a possibility to compute and analyze different MPIs. Some of the software packages also provide a possibility to maintain maintenance records system that serves as a source of initial data for the calculation of MPIs.

Name of indicator	Actual value	Ideal value	Amber threshold	Red threshold	Recommended action
SMI1	Actual calculated value of the SMI1	IV $_{SMI1}$	Range 1 (SMI1 is still acceptable if within the range)	Threshold for the acceptability for SMI1	Action recommended to improve the situation, if relevant, or blank
		☐	☐	☐	
SMI2	Actual calculated value of the SMI1	IV $_{SMI2}$	Range 2 (SMI2 is still acceptable if within the range)	Threshold for the acceptability for SMI2	Action recommended to improve the situation, if relevant, or blank
		☐	☐	☐	
. . .					

Fig. 4.3 Example template for documentation of the SMI analysis for backfitting purposes

Another representation of the status of MPIs can be done using colour code scheme; an example is shown in Figure 4.4. In this representation, three regions should be defined for each SMI:

(a) an acceptable region ('green'),

(b) a border line region ('yellow' or 'orange'), and

(c) an unacceptable region ('red')

Using the representations of the MPI system shown in Figures 4.1-4.4, the SMIs needing attention or backbiting measures could be identified. For example, let the value of the SMI #2.1.1 'Ratio of unplanned to planned working orders' be higher than the defined threshold, this will be an indication of either deficiencies in planning or degradation in maintenance quality. In order to better understand the reasons, other indicators could be checked to decide what backfitting measures would be useful. In this example, if the SMI #1.3.5 'Ratio of PM activities to all maintenance activities' is decreased, this would mean that more corrective maintenance emerged, thus signalling that maintenance procedures and quality should be checked and adjusted, if appropriate.

The MPI system requires that a follow-up and backfitting mechanisms are established and implemented. These are seen to be plant-specific.

1. PREVENTIVE CHARACTER OF MAINTENANCE (INCLUDING PREDICTIVE MEASURES)

1.1 System and equipment availability						
1.1.1 Component and system unavailability	1.1.2 Total downtime	1.1.3 Scheduled downtime	1.1.4 Unscheduled downtime	1.1.5 Number of forced power reductions or outages because of maintenance causes	1.1.6 Mean time between maintenance	1.1.7 Mean time to repair

1.2 Reliability of systems and components		
1.2.1 Number of corrective work orders issued	1.2.2 Number of failures in safety related systems	1.2.3 Mean time between failures

1.3 Effectiveness of preventive maintenance								
1.3.1 Preventive maintenance compliance	1.3.2 Ratio of corrective work resulted from PM activities	1.3.3 PM work order backlog trend	1.3.4 Percentage of deficiencies discovered by surveillance, testing and inspections	1.3.5 Ratio of PM activities to all maintenance activities	1.3.6 Overdue of PM activities	1.3.7 Number of jobs planned but not performed	1.3.8 Number of jobs not started as planned	1.3.9 Actual versus planned man-hours (per job or totals)

Fig. 4.4 Example of representation of the status of MPIs using a colour code scheme

4.2.4 Interpretation of the SMIs using Risk Monitor

Many NPPs in EU countries and around the world develop and make full use of plant-specific Risk Monitors to further enhance safety during maintenance and support maintenance planning activities from the view point of the plant configuration control. Reference [10] provides a comprehensive overview of the issues dealing with the development and use of Risk Monitors internationally. The Risk Monitor option is being pursued by many countries in US to comply with the US NRC Maintenance Rule (Ref. [18]).

A prerequisite for the Risk Monitor is a detailed plant-specific PSA that is developed taking into account the specific features like symmetric of the model, the possibility to disregard the basic events representing the averaged component unavailabilities due to maintenance, etc.; relevant information is provided in Refs [10] and [12].

From the information received from the Member States, it is apparent that the main reason for developing the Living PSA into a Risk Monitor is to have a PSA tool that can be used to provide risk information as an input into the day-to-day management of operational safety. In particular, it can be used as an input into maintenance planning to ensure that these activities are scheduled in such a way that high peaks in the risk are avoided or their duration is minimised wherever possible. The Risk Monitor also provides information on which components should be returned to service before particular maintenance activities are carried out and which components are the most important for ensuring plant safety during specific maintenance outages.

The introduction of a Risk Monitor is also seen as providing greater flexibility in operation. In particular, it can be used to provide justification that more maintenance can be carried out on-line without increasing the overall risk. The introduction of a Risk Monitor has been seen as a way of addressing the US NRC Maintenance Rule (a)(4) which went into service in the USA on 28th November 2000 and has also been applied in other Member States. This requires that nuclear power plant operators should assess and manage the risk associated with maintenance activities.

The Risk Monitor, along with the cumulative risk, provides information on instantaneous risk that allows observing the risk profile over a specified time period. This is illustrated in Fig. 4.5. The Risk Monitor can be used prospectively, on-line, and retrospectively. The Risk Monitor model allows disabling the basic events representing specific plant components; thus it is possible to model and evaluate risk associated with specific plant configurations caused by taking out of service components for maintenance.

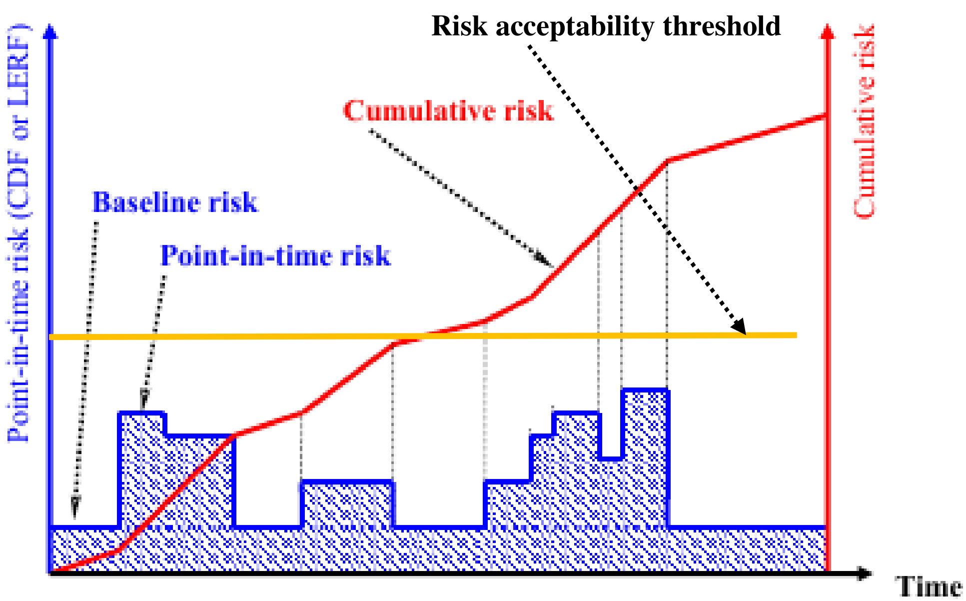

Fig. 4.5 Example of plant risk profile provided by Risk Monitor

Three SMIs using the data provided by Risk Monitor are suggested to support the new KPI #'2.5 'Safety during maintenance' (see Table 3.2):

2.5.3 Number of times the plant was operating with elevated risk

2.5.4 Time the plant was operating with elevated risk

2.5.5 Ratio of time the plant was operating with elevated risk

Definitions for the three SMIs are provided in Table 3.2. The first two indicators are classified as 'leading' because they may be obtained immediately from the analysis of the data from Risk Monitor; this is illustrated in Fig. 4.5. The number of cases and the cumulative time the plant was operating with elevated risk exceeding the established threshold can be easily retrieved from the Risk Monitor. These indicators, being considered over a prolonged time, can also be used as lagging indicators. The aim should be these two indicators are zero.

If SMI #2.5.3 provides information that some instances of operation with elevated risk have taken place, the causes for this should be investigated, and dangerous plant configurations in terms of components taken out of service identified and avoided while planning future maintenance activities.

If SMI #2.5.4 provides information that within a relatively substantial time the plant is being operated with elevated risk then the prioritization of maintenance activities is adjusted in such a way that the critical components are returned into service as soon as possible to avoid the dangerous plant configuration. In this case, the Risk Monitor is used off-line to evaluate the risk associated with returning different components to service.

SMI #2.5.5 is a lagging indicator signalling that a substantial fraction of the time over a specified time interval the plant was operating with elevated risk. In this case a retrospective analysis of the plant configurations and causes for them should be performed. The causes may include planning mistakes, substantial reactive maintenance activities overlapping with preventive maintenance, lack of interfaces with operations, etc. For instance, if SMI #2.5.5 shows a degradation and at the same time SMI #2.2.4 'Number of failures to return the equipment into service, following maintenance activities, at the first presentation' shows a declination, the procedures for maintenance documentation and acceptance of equipment into operation from maintenance should be checked and adjusted, if appropriate.

It is important that the PSA used for Risk Monitor should be of an appropriate scope and technical quality; to observe this, available PSA Standards should be used, e.g. Refs [12], [19], and [20].

4.3 Steps to establish the MPI framework

The followings general steps are deemed appropriate in pursuing maintenance effectiveness enhancement using the MPI framework:

STEP (1) State the goals of introducing the MPI system.

STEP (2) Provide plant management support.

STEP (3) Dedicate manpower and provide organizational framework for the development and introducing the MPI framework in plant operational practices.

STEP (4) Select a set of KPIs and SMIs from the suggested framework (see Table 3.2). In this process, the plant specific influencing factors should be taken into consideration, e.g. existing maintenance practices, maintenance data collection systems, organizational structures, production goals, etc.

STEP (5) Select and purchase in the market commercially available software or develop a computerized system to support computation and representation of the selected MPI framework (for details, see Section 4.2).

STEP (6) Establish thresholds and target values for the SMIs (this could be done, for instance, through an expert elicitation process, see Section 4.1).

STEP (7) Establish a procedure for the analysis of the MPIs and taking corrective actions, when appropriate (for details, see Section 4.2).

STEP (8) Establish a procedure for providing a feedback and enhancement of the MPI framework.

4.4 Benefit from implementation of the advanced maintenance strategies

4.4.1 Summary of different maintenance approaches

A brief discussion on preventive and predictive maintenance has been provided in Section 2.5.2 of the report. This section is aimed at summarizing benefits and disadvantages of the preventive, predictive, and reactive maintenance in order to provide a complete picture of the capability of different maintenance strategies; this information is presented in Table 4.1.

4.4.2 Benefit from enhancement of maintenance strategies

Preventive and predictive maintenance are prevailing strategies in NPP maintenance; these can only be efficiently pursued through introduction of well-developed MPI framework. The emerging trend is dealing with emphasizing the predictive component. Benefits from introducing the predictive maintenance are the following:

- Safety - Predictive maintenance would allow potential problems to be fixed before failure occurs, which would create safer driving conditions for consumers as well as a safer vehicle for shops to service.
- Increased revenue - With less maintenance on good components and quicker repair of faulty components, repairs can be more effectively handled, thereby reducing repair time.
- Increased efficiency of employee time - By identifying the precise repair task needed to correct deficiencies, as well as the parts, tools and support needed to correct the problem. PdM has the potential to dramatically increase effective "wrench time."

Information available including non-nuclear sector (see Ref. [21]) reports that effective use of preventive maintenance, including predictive technologies, could eliminate from 33% to 50% of maintenance expenditures that are wasted by most manufacturing and production plants.

Based on historical data in the USA, the initial savings generated by effective preventive/predictive maintenance programs fall into the following areas:

1) Elimination of unscheduled downtime caused by equipment or system failures: Typically, reductions of 40% to 60% are achieved within the first two years and up to 90% reductions have been achieved and sustained within five years.

2) Increased manpower utilisation: Statistically, the average "wrench-time" of a maintenance craftsperson is 24.5% or about 2 hours per shift. By identifying the precise repair task needed to correct deficiencies within a plant asset, as well as the parts, tools and support needed to rectify the problem, preventive/predictive maintenance can dramatically increase effective "wrench-time". Most plants have been able to achieve and sustain 75% to 85% effective utilisation.

3) Increased capacity: The primary benefit of effective preventive/ predictive maintenance programs is an increase in the throughput or production capacity of the plant. Short term, i.e. 1-to-3 years, increases in sustainable capacity have ranged between 15% and 40%. Long-term improvements of 75% to 80% have been achieved.

4) Reduction of maintenance expenditures: In some cases, actual maintenance expenditures will increase during the first year following implementation of an effective preventive/predictive program. This increase, typically 10% to 15%, is caused by the inherent reliability problems discovered by the use of predictive technologies. When these problems are eliminated, the typical result is a reduction in labour and material cost of between 35% and 60%.

Table 4.1 Summary of different maintenance strategies

Type of maintenance	Definition	Advantages	Disadvantages
Preventive	Preventive maintenance refers to a series of actions that are performed on either a time-based schedule or a schedule based on that of machine-run time. These actions are designed to detect, preclude, or mitigate degradation of a system (or its components). The goal of a preventive maintenance approach is to minimize system and component degradation and thus sustain or extend the useful life of the equipment. Preventive maintenance is time-based. Activities such as changing lubricant are based on time, like calendar time or equipment run time.	• Is cost effective in many capital intensive processes and equipment • Provides flexibility for the adjustment of maintenance periodicity • Increases component life cycle • Generates energy savings • Reduces equipment and/or process failures • Results in an estimated 12% to 18% cost savings over that found in a reactive maintenance program	• Does not eliminate catastrophic failures • Is more labour intensive
Predictive	A predictive maintenance approach strives to detect the onset of equipment degradation and to address the problems as they are identified. This allows casual stressors to be eliminated or controlled, prior to any significant deterioration in the physical state of the component or equipment. This leads to both current and future functional capabilities. Basically, predictive maintenance differs from preventive maintenance by basing maintenance needs on the actual condition of the equipment, rather than on some predetermined schedule.	• Provides increased component operational life and availability • Allows for pre-emptive corrective actions • Results in decrease in equipment and/or process downtime • Lowers costs for parts and labour • Provides better product quality • Improves worker and environmental safety • Raises worker morale • Increases energy savings • Results in an estimated 8% to 12% cost savings over which might result from a predictive maintenance program	• Increases investment in diagnostic equipment • Increases investment in staff training • Savings potential is readily seen by management
Reactive	Reactive maintenance is basically the "run it till it breaks" maintenance mode. No actions or efforts are taken to maintain the equipment as the designer originally intended, either to prevent failure or to ensure that the designed life of the equipment is reached.	• Has lower initial costs • Requires fewer staff	• Increases costs due to unplanned downtime of equipment • Increases labour costs, especially if overtime is needed for untimely repairs or replacement • May increase costs associated with repair or replacement of equipment • May result in possible secondary equipment or process damage from equipment failures • Is an inefficient use of staff resources

5) Increased useful life: Typically, the useful operating life of plant assets will be extended by 33% to 60%. Detecting incipient problems or deviations from optimum operating conditions before damage to equipment occurs derives this benefit. Making minor adjustments or repairs and not permitting a minor deficiency from becoming a serious problem can extend the effective useful life extended almost indefinitely.

The down side of using a predictive maintenance approach is its initial costs. The up-front costs of starting this type of program can be expensive. Another issue is that training of in-plant personnel to effectively utilize predictive maintenance technologies and practices will require substantial additional funding. In addition, beginning a predictive maintenance program requires an understanding of the facility's predictive maintenance needs and the approaches which need to be undertaken. It is also essential to have a firm commitment, by management and all facility staff and organizations, to make it work.

5 CONCLUSIONS AND RECOMMENDATIONS

The MPI framework developed by JRC-IE (Ref. [1]) has been further enhanced by addressing the recommendations provided in Ref. [2] and reproduced in Sections 2.4-2.6 of this report. The final listing of MPIs in a user-friendly form comprising the definitions, purpose, and other characteristics of MPIs was compiled and presented in Table 3.2. One additional KPI ‘Safety during maintenance’ was included in the MPI framework. Several new SMIs were included to support the latter KPI, as well other KPIs as documented in Section 3. The issues of indicators’ representation and backfitting were discussed and an approach for the analysis of compliance with the thresholds was suggested in Section 4. A discussion on the use of data from plant Risk Monitor to support computation of newly introduced SMIs was provided.

The updated framework for MPIs suggested by JRC-IE comprehensively covers the various aspects of maintenance-related activities and allows easy reference and use of the MPI system in the maintenance performance monitoring process. However, for a meaningful use and efficient implementation of the MPI framework, further efforts should be pursued; these are to be concentrated on the development of thresholds and/or target values for the SMIs. This can be done through an expert elicitation process.

Other issues that deserve attention in the future research activities dealing with enhancing the maintenance effectiveness include the following:

- Collect and disseminate information on advanced experience regarding using multipurpose in-plant data collection systems to support calculation of SMIs;
- Promote the development and use of advanced databases and software tools to support data collection and MPI computation;
- Collect and disseminate advanced experience on the use of Risk Monitors to provide safety during maintenance (e.g. maintenance activities prioritization, control of plant configuration, planning);
- Conduct a survey to evaluate the impact of the regulatory framework on the feasibility to implement changes to the existing maintenance strategies (i.e. safety related components);
- Conduct a survey to evaluate the benefit from the implementation of the MPI framework and predictive maintenance approaches.

6 REFERENCES

[1] EUR Report 22602 EN, Povilas Vaisnys, Paolo Contri, Claude Rieg, Michel Bieth, “Monitoring the Effectiveness of Maintenance Programs Through the Use of Performance Indicators”, SENUF, JRC/IE, 2006.

[2] EUR 23230 EN, Povilas Vaisnys, Paolo Contri, Michel Bieth, “Benchmarking Study of Maintenance Performance Monitoring Practices”, SONIS, JRC/IE, 2007.

[3] EUR 22604 EN, Vesselina Ranguelova, Paolo Contri, Irina Kuzmina, Summary Report, “IAEA/EC-JRC Regional Workshop on Advanced Methods for Safety Assessment and Optimization of NPP Maintenance held on 2-5 October 2006,” SENUF Series, DG JRC – Institute for Energy, Petten, The Netherlands, November 2006.

[4] EUR 22603 EN, Paolo Contri, Workshop on “Maintenance Rules: Improving Maintenance Effectiveness” organized by EC/JRC (SENUF), Iberdrola, Soluziona, Tecnatom, UNESA & EPRI, on 19-22 June 2006, at UNESA, Madrid, SENUF Series, DG JRC – Institute for Energy, November 2006.

[5] “Maintenance Optimization of NPPs; Nuclear Power Plant Maintenance in the CIS and CEEC, A Brief Evaluation Report,” SENUF, DG JRC – Institute for Energy, 2004.

[6] Levitt. J, “Complete Guide to Preventive and Predictive Maintenance,” Industrial Press, New York, 2003.

[7] Hai Qiu and Jay Lee, “Near-zero downtime: Overview and Trends,” the University of Cincinnati, USA, 2007.

[8] IAEA-TECDOC-1551, “Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants”, IAEA, Vienna, 2007.

[9] IAEA-TECDOC-1590, “Guidelines on Application of Reliability Centred Maintenance to Optimize Operation and Maintenance in Nuclear Power Plants,” IAEA, Vienna, 2007.

[10 IAEA and OECD NUCLEAR ENERGY AGENCY, “Risk Monitors: The State of the Art in their Development and Use at Nuclear Power Plants,” WG-Risk, NEA/CSNI/R(2004)20, OECD/NEA, Paris, 2004.

[11] Workshop Material on CD, JRC Enlargement and Integration Workshop IE-W06 "Optimization of Maintenance Programs at NPPs with Consideration of Safety and Economical Aspects“, 13-14 November 2008, JRC-Institute for Energy, Petten, The Netherlands.

[12] IAEA-TECDOC-1511, “Determining the Quality of Probabilistic Safety

Assessment (PSA) for Applications in Nuclear Power Plants," IAEA, Vienna, 2006.

[13] IAEA-TECDOC-1509, "Integrated Approach to Optimize Operation and Maintenance Costs for Operating Nuclear Power Plants", IAEA, Vienna, 2006.

[14] IAEA Safety Reports Series No.42, "Safety Culture in the Maintenance of Nuclear Power Plants," IAEA, Vienna, 2005.

[15] Ricky Smith, R. Keith Mobley, "Rules of Thumb for Maintenance and Reliability Engineers," Butterworth-Heinemann, 2007.

[16] John P. Cook, "Proactive approach studies corrective maintenance orders on components in the PM program," http://www.maintenanceworld.com/Articles

[17] Ralph D. Hedding, "Measuring maintenance effectiveness: The bulls and the bears," http://www.maintenanceworld.com/Articles.

[18] Assessing and Managing Risk Before Maintenance Activities at Nuclear Power Plants; Regulatory Guide 1.182; US Nuclear Regulatory Commission; May 2000.

[19] Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications; ASME RA-S-2002; American Society of Mechanical Engineers; April 2002, and Addendum to ASME RA-S-2002; ASME RA-Sa-2003; American Society of Mechanical Engineers; December 2003.

[20] IAEA Safety Guide 'Performance and Application of Level-1 PSA for NPPs', Final Draft DS394, IAEA, Vienna, December 2008.

[21] http://www.ferret.com.au/n/The-basics-of-predictive-preventive-maintenance-n693449

7 LIST OF ACRONYMS AND ABBREVIATIONS

CPM	Contractor Performance Management
EC	European Commission
EU	European Union
IAEA	International Atomic Energy Agency
JRC-IE	Joint Research Centre – Institute for Energy
KPI	Key Performance Indicator
MPI	Maintenance Performance Indicator
MRO	Repair and Operating Materials
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Repair
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OECD	Organization for Economic Co-Operation and Development
PdM	Predictive Maintenance
PM	Preventive Maintenance
RAV	Replacement Asset Value
SENUF	Safety of European Nuclear Facilities
SMI	Specific Maintenance Indicator
SONIS	Safe Operation of Nuclear Installations
US NRC	United States Nuclear Regulatory Commission
WANO	World Association of Nuclear Operators

European Commission

**EUR-23751 EN – Joint Research Centre – Institute for Energy - SONIS Action n. 52103-
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Plants - Technical Report**
Author Paolo Contri – EC/JRC-IE

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Abstract

This Report summarizes the results of a research carried out in the year 2007 and 2008 under the SONIS (Safety of Nuclear Installations) programme, Task 1.1.1, Maintenance effectiveness indicators and risk monitors. The research is based on the survey of the experience of European nuclear utilities in the use of maintenance performance indicators at selected European nuclear utilities. The survey results proved the validity of the specific maintenance performance indicators selected for the maintenance performance monitoring framework proposed by IE/JRC and published in the EU Report 22230. The updated framework for MPIs suggested in this report comprehensively covers the various aspects of maintenance-related activities and promotes easy reference and use of the MPI system in the maintenance performance monitoring process. The results obtained provide good basis for the further development and implementation of the proposed maintenance monitoring system at the EU plants.

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