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Development of computer-aided maintenance resources planning (CAMRP): A case of multiple CNC machining centers

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Abstract

Total productive maintenance (TPM), total maintenance assurance, preventive maintenance, reliability-centered maintenance (RCM), and many other innovative approaches to maintenance problems all aim at enhancing the effectiveness of machines to ultimately improve productivity. Each of these concepts demands a unique decision support system for maintenance resources planning, and implementing each of them requires a radical restructuring of work. Introducing computer-aided maintenance resources planning (CAMRP) system is a major challenge because the maintenance operations environment is usually traditional and unfavorable to change. This paper presents a computer-aided planning system for a maintenance business unit that serves a number of manufacturing facilities, each consisting of a set of high-precision CNC machining centers. The workforce in the maintenance business unit is responsible for preventive as well as corrective maintenance activities of all CNC machines within the different manufacturing sites. The newly developed decision support tool embodies a set of structured heuristics methods for the coordination of tasks among maintenance crews which will help conduct different maintenance activities of manufacturing units in a more synchronized way. Through what-if-analyses, the tool generates well-founded decisions for capacity planning are; synchronizes maintenance activities to predict maintenance start and expected finishing times, thereby leads to lower costs.

Keywords: Maintenance; Resources planning; Theory of constraints

1. Introduction

With the increasing degree of manufacturing automation, and the application of lean, agile, production systems, not only has machine sophistication been increased, but also the need for shorter lead-times has also surged. This demands higher availability of production systems to have a cost-effective distribution of fixed assets, and to minimize manufacturing delays due to machine failures caused by unplanned downtimes. Unplanned downtime increases the maintenance costs and reduces productivity. Examples are advanced manufacturing companies, like electronics and car manufacturers, which have increased their levels of automation by continuously upgrading their production facilities. To sustain a competitive place in the market, for such companies it is critical to have a sound decision support system for maintenance management, which can properly plan the maintenance activities and bring the maintenance costs under control, increasing the overall productivity.

The cost of maintenance is usually quantified by labor and hardware costs; however, there are also opportunity costs due to failure. Identification of the latter is difficult and the costs are usually high. To optimize the use of maintenance resources, one needs appropriate maintenance (optimization) policies and relevant system performance measures, all embedded in a decision support framework. These are typically brought together in what is called computerized maintenance management systems (CMMS). Our objective was to develop a computer-aided maintenance resources planning (CAMRP) module within a CMMS. This software solution generates (optimal) maintenance plans in order to reduce both the maintenance and the opportunity costs. This paper reports on a CAMRP system that has been developed and implemented

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in an independent maintenance business unit which is outsourced by a number of high-tech manufacturing companies, all belonging to one corporation in the Netherlands.

1.1. Historical perspective

The evolution of maintenance management runs parallel with the development of Just-in-Time, Lean, Agile, and Flexible manufacturing concepts. In fact one of the second corner stones of JIT, process (re-) design, suggests reduction of setup times and elimination of all non-productive activities, including those ''fire fighting'' activities such as corrective maintenance. This brought about the notion of preventive maintenance (PM) in manufacturing environment in 1970s. PM is the first generation of formal approaches to maintenance problems and is characterized by trying to maintain machines in accordance with the manufacturer's guidelines. Machine capability is maintained to the ''like new'' standard. This keeps machines' capabilities at the highest production standards. The drawback with this approach is that what is truly required of the machines, for production is not a factor in determining maintenance requirements. Thus, extra capabilities which are not used would be maintained. The second generation of maintenance management initiatives proposed in 1980s are called predictive maintenance (PDM) and condition-based aintenance (CBM). These concepts promote measurements aimed at the early detection of machine degradation, thereby allowing the degradation to be understood and eliminated or controlled, before significant physical deterioration of the machine. The third generation, reliability-centered maintenance (RCM) and total productive maintenance (TPM) are the concepts devised in late 1980s and 1990s [1,2]. These concepts require the maintenance and production departments to work together to discern potential problems. Again this development was truly in line with further developments of thoughts in production management of Lean and Agile Manufacturing systems. To reduce manufacturing lead-times and increase flexibility, RCM and TPM concepts suggest that the maintenance resources plan must be based on desired outcome requirements. This is a fundamental departure from the earlier thoughts that maintenance principles were machine-based standards. Such concepts allow the maintenance objective to be focused on production needs. All of these developments led to a new modern concept called profit-centered maintenance (PCM) [3]. In PCM, there is a wide range of maintenance function optimization capabilities that improve asset reliability and improve the administration of maintenance. The major activity required for its implementation is optimization of all maintenance resources. The major components of PCM are (adapted from [3]):

- the insistence on creating maximum value over the least costs (the effectiveness of production).
- a range of maintenance optimization capabilities, which is a blend of condition based, reliability based, and other maintenance resources planning concepts aimed at generating maximum value.
- a maintenance administration reengineering process that eliminates non-value adding activities and waste; and
- a continuous improvement program with a well-designed set of key performance indicators (KPI's), for training the work force, for advancing the maintenance information management system, and for reducing maintenance cost.

Along the developments of maintenance management concepts, in the 1990s the expansion of software solutions for the maintenance management field was remarkable. During this period, maintenance management found new roles [4]. Many large ERP software solution providers and several specialized software houses with more specialized solutions offered a variety of maintenance software programs to assist management. Enterprise asset management (EAM) and CMMS are typical examples. However, these solutions have been either too complicated for the user to understand, or do not contain crucial elements reflecting the actual decision-making environment. Thus those who implemented these solutions use them more as a database rather than a decision support system, and as such are not proven to be effective [5]. We believe even this limited use can place management in better position to track periodic maintenance, check inventory levels of machine spare parts and also monitor the tools used.

Today, comprehensive maintenance management software solutions exist, yet to truly assist management, the generic solutions must be amended, typically at high expense or a very expensive customized software solution must be adopted. Our field experience shows that there are cases where a simple solution can be developed internally to compliment an existing generic system, reflecting the specificity of the environment, such as the one reported in this paper.

The organization of the material in this paper is as follows. Section 2 describes the case environment and related problems. In this section the literature relevant to maintenance resources planning of multi-project systems is also briefed. Section 3 gives a description of the solution concept development including a discussion on the modeling approach. Section 4 provides an overview of the resources planning tool. Section 5 presents the conclusions.

2. Case environment specifics: multi-site, multi-project systems

The case represents a machine maintenance and repair business unit (MMRBU) of a high-tech CNC machine manufacturer in the Netherlands. The CNC machines are used by other business units of the corporation or are purchased and used by other manufacturing companies (see Fig. 1). MMRBU is responsible for all after sales

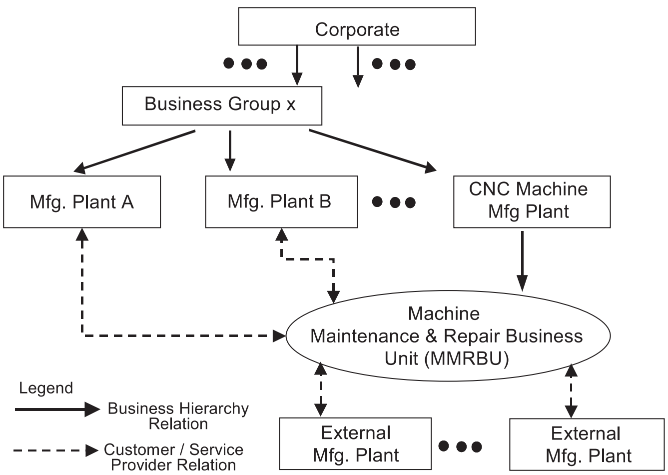

Fig. 1. Position of machine maintenance and repair business unit.

service packages, which is mainly maintenance but also includes repair of repairable parts. The specific nature of MMRBU requires them to provide maintenance services at multiple sites, each of which may have several CNC machines. The environment requires multiple concurrent maintenance projects. The projects share common characteristics (e.g. similar precedence relations among their activities), and they compete for the same set of technicians (mechanical, electrical, electronic, and IT specialists) as main resources, and other resources such as tools and spare parts.

Multi-site, multi-machine or multi-project maintenance planning usually contains a high degree of uncertainty. Although there is information on preventive maintenance projects and their timing requirements for each site and at some level for each machine, the possible delays caused by prolonged manufacturing runs also delays the start of preventive maintenance activities. The sudden breakdowns and unknown corrective maintenance times, also introduces difficulties in appropriately planning the scare resources. One of the major problems is that even when the preventive maintenance starts on time, a corrective maintenance order would require a quick response from the MMRBU, and therefore some individuals from the maintenance crew must leave to the demanding site and diagnose the faults with the broken machine(s). This means there will be a delay in completing the preventive project at hand and also a postponement in commencing of the next planned preventive project. This all brings in a new wave of uncertainties in the process.

Repairable projects have the lowest priority at MMRBU. They contain off-manufacturing site work and cover only a very small percentage of the total workload. These projects could be extended, however technicians must not be busy with other types of projects (preventive and corrective). In this study the repairable maintenance projects are considered at same levels of priority as corrective maintenance projects.

2.1. Problem discussion

Given the fact that most of the manufacturing units are currently characterized by increased diversity and complexity of their machine use because of the shift from a make-to-stock to a make-to-order policy, the environment for MMBRU has become more hectic, involving four types of uncertainties:

(a) The manufacturing units: customers cancel or delay, as it happens regularly, the preventative maintenance project days in advance.
(b) The technicians (resources) planning: may provide inadequate resource allocation for the preventive maintenance projects, which leads, in some cases, to postponing the preventive maintenance projects.
(c) Process times: the duration of maintenance projects are uncertain, because only at the beginning of a project the exact condition of the machine can be observed; and
(d) the random machine breakdown events.

These uncertainties in the maintenance planning process, complicated by the limited number of maintenance personnel, the level of expertize involved for each operation, the nature of maintenance operations, and the inflexible production planning of different manufacturing units, has confronted MMRBU with major problems. These problems are: late completion of maintenance operations, resulting in more than 80% corrective maintenance and 20% preventive, which has generated huge operating costs like overtime, lost production for other manufacturing business units and sometimes paying penalties for external manufacturing units. The cost of maintenance personnel constitutes the largest block in the costs of the MMBRU. To reduce these increasing costs of maintenance, it is important to establish an accurate personnel capacity requirement in MMRBU, while different maintenance activities are planned intelligently.

2.2. Literature overview

Most of the literature on maintenance deals with maintenance management concepts, development and selection of a maintenance strategy [6–9]. The other bulk of research describes machine maintenance modeling and scheduling. The books edited by Duffua and Raouf [10] and Ben-Daya and Duffuaa [11] contain many papers and review of this nature. Another area of research concerns reliability theory, replacement theory, and inspection frequency determination. Examples here are [12–16] among many others. Other researchers use simulations for measurement of a maintenance system like Duffua et al. [17].

There are very limited studies dealing with multi-site, multi project resource planning. They include Demeulemeester [18], De Boer [19], Luczak H., Mjema [20], and

Mjema [21], who specifically discuss capacity resources planning.

The most relevant literature for our study can be sought under the theme of project management and capacity planning in production management. The latter, however, does not fully represent our case environment specifics. The literature on project management is rich. We use both resources-driven and time-driven (see definitions in modeling approach) methodologies. Resources-driven studies include Hans et al. [22], who discuss multi-project planning under uncertainty and report additional literature in this area. Another related study is the work Mourtzis [23] on managing ship repair operations.

The literature on time-driven project management has become richer since 1997, when Goldratt [24] discussed critical chain project management (CCPM) from theory of constraints (TOC) point of view. In many published articles and books on project management there is discussion on how to use Goldratt's proposed methodologies and related potential shortcomings [25–37].

3. Solution concept development

A computer-aided integrated approach was developed for the MMRBU management system that would enhance and optimize the maintenance process, ensuring that maintenance projects' load would receive a consistent level of maintenance resources, reducing overall delays and costs.

To establish a CAMRP system, the RCM is considered the driving point. Fig. 2 shows different components of this approach, including the strategies required for maintenance resources planning optimization. RCM is somewhat fluid concept, defined differently in various sources (Backlund [38]). Classical RCM is not only condition monitoring, the process involves identifying the maintenance projects to be studied, their critical functions and critical components, functional failures, failure modes, failure causes, categorization of failure effects, and the maintenance task selection. The RCM approach considered here is very empirical, it is analysis of need and priorities. Using a series of classical quality control (QC) tools implemented in Delphi, it allows the MMRBU to properly articulate and adjust its and balance preventive, predictive, and corrective maintenance strategies.

The most critical part of this approach is the planning of scare maintenance resources, which affects the overall performance of the MMRBU. In other words, we need to determine a plan that measures the consequences of breakdown projects on the preventive maintenance projects, while critical customers and the machines leading to extra loads on resources are identified through predictive measures. All machines of different manufacturing units need to be analyzed, and the most critical pieces of machines should be determined. We also need to understand the different manufacturing units (customers) needs in terms of reliability, service lead-times, cost, etc. These attributes can be then weighted to determine the best maintenance policy to deal with each manufacturing unit.

In order to optimize the maintenance resources plan, all relevant information must be collected to most effectively initiate, schedule, track, record, and analyze maintenance tasks of different projects. An open communication protocol that enables various monitoring devices (of the internal as well as external manufacturing units) to talk with MMRBU would best suit the needs of such a computer-aided approach which uses various data sources from other software solutions.

At the time of the study most of the manufacturing units had some machine diagnostic test procedures in place. Those units had also computerized the generation of maintenance work orders including retaining maintenance histories for their machines. However, the proper communication, integration and analysis of all of this information

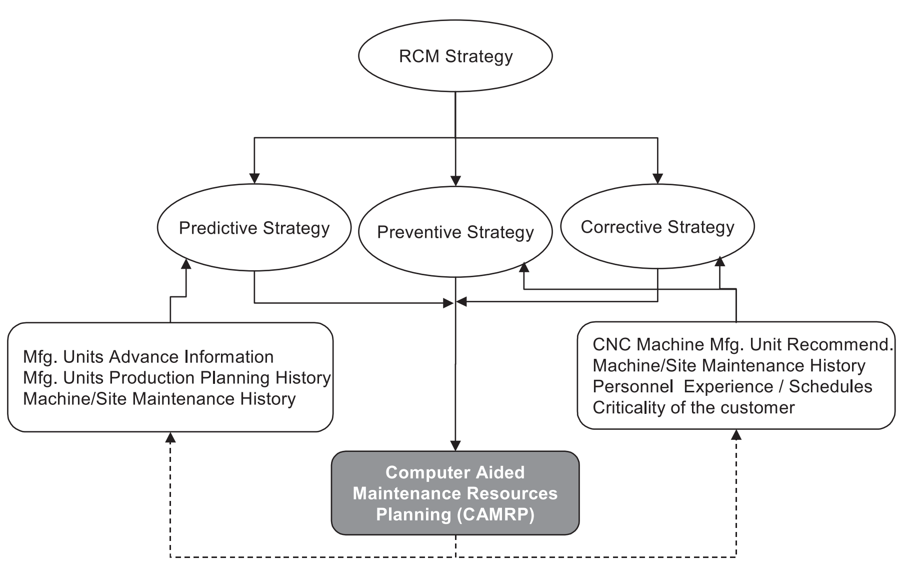

Fig. 2. Computer-aided maintenance resources planning supporting blocks.

Table 1
Maintenance task and responsibilities

What→		
Who↓	Objectives	Tasks and responsibilities
I. Corporate	*Support maintenance operation strategically and financially.*	Communicate with plants board or senior management team Supply support in business relations matters Offer and support an adequate management system
II. Plant/production managers (internal and external)	Lead a maintenance requirement planning for receiving maintenance services from MMRBU *Initiate a special project group to consider special maintenance improvements*	Communicate with MMRBU manager, or senior representatives *Report to corporate office* *Develop plant maintenance strategies together with MMRBU* Lead in matters involving business relations with MMRBU *Follow-up metrics on TPM performance, reporting on* all financial matters
III. Machine maintenance and repair business unit (MMRBU) manager	*Optimize the maintenance resources* Coordinate maintenance projects Plan spare parts requirements to ensure maximum machine utilizations	*Develop and communicate the maintenance business system of the unit and the strategies* *Communicate with plant/production managers over PM effectiveness* Review work orders and PM's orders *Optimize resources utilization* Coordinate different work orders Identification of necessary operators' skills/training needed *Develop CAMRP for TPM*
IV. Maintenance Teams	Operate in a manner guaranteed to supply quality support in the maintenance of machines in different plants	Carry out assigned tasks as planned and requested by maintenance manager Maintain a register of all of their tasks (logbook) *Develop/Update ABC check sheets for inspections* *Information services to support new addition to CAMRP*
V. Procurement officer	Support maintenance teams in the supply of all spare parts and materials required to effectively maintain the machines in different plants	Determine necessary spare parts Identify availability of spares *Reduce costs of inventory* Purchase materials, spare at the best prices available Coordinate delivery to areas *Standardize procurement methods* *Reduce number of suppliers* *Consult plant/production about future machine purchases* *Information services to support new addition to CAMRP*
VI. Support staff	Provide all additional support	Supply any support required by the maintenance teams *Record-related statistical information and plot trends* *Reports to contain:* • *reaction time* • *trouble report generation* • *completion of tasks on a project* Standardized checking procedures for machines and tools *Information services to support new addition to CAMRP*

The italics text suggests specific improvement areas.

within the MMBRU as suggested by our approach would result in more accurate recommendations concerning when to perform a preventive maintenance and/or how to predict a failure at a specific site.

A thorough study was conducted to identify the main factors affecting the maintenance resources planning and extra procedures were designed to guarantee the collection of data required for the computer-aided planning system. To collect the right information, the roles and responsibilities of different players were reviewed by meeting with those individuals. Table 1 presents the information collected from the interviews. Six areas are summarized in the table and the italics text suggests specific improvement areas in the division of roles and responsibilities to help gather and process the essential data for the successful application of computer-aided planning.

Since the development of the resources planning tool is the core concern of this paper, the remaining sections are dedicated to this discussion.

3.1. The modeling approach

The objective of this research is the realization of a computerized maintenance resources planning tool. Roughly speaking, the planning tool should plan the preventive maintenance projects, whereas the uncertainties of the corrective maintenance projects are taken into account. The tool should also allow what-if scenario analysis of the possible future events. The preventive maintenance projects are planned with a simple algorithm, which is based on a time-driven rough-cut capacity planning (RCCP) problem. For this algorithm a preventive maintenance project is disaggregated in one or more task packages. A task package is a set of activities. For each task package, the type of resources required and the minimum duration is known. Each task package represents the type of technicians (specialists) required, and the number of task packages will be equal to the number of required resources. When these task packages are planned, the uncertainties of the past corrective maintenance projects are measured and used to plan buffer times. The buffer times are exclusively used for uncertainties; no preventive maintenance project can be planned during these time intervals.

The developed decision support tool embodies a new methodology for coordination of cross-expertise exchange among maintenance crews in order to conduct different maintenance activities of manufacturing units in a more synchronized way. Through what-if-analyses, the tool at the strategic level can generate well-founded decisions for a possible expansion of the maintenance personnel capacity, and/or for acquiring possible new jobs. At the tactical level, the tool is helpful for synchronizing maintenance activities with the production plans of different manufacturing units, and to make promises regarding (guaranteed) maintenance operation start time, and expected durations. On the aggregate level, the model generates a maintenance plan that smoothens the personnel capacity utilization over the planning horizon, which results in lower costs. It also guarantees a feasible operational plan that takes into account relevant working times.

4. Computer aided resource planning framework

Uncertainty that is brought by the projects can be reduced when the strategic, tactical, and operational resources planning are tackled differently. Thereby the task packages and the activities must be handled at different levels of aggregation at each level of planning. Various resource planning levels can be distinguished as follows:

I. Long-term capacity resource planning (strategic): Here arrival moments and volumes of maintenance orders of certain types are unknown and characterized statistically. Here the expected number and estimated duration of projects based on historical data, adjusted with new maintenance policies, are used for capacity planning.

II. Resource loading (tactical), the Order Acceptance Stage: This assigns due dates to maintenance orders, different task packages are confirmed according to recent data collected from manufacturing sites and the history of maintenance at each site. On the tactical level, in general, a rough estimate of the capacity required and specifications of the critical components (spare parts) are made. The method that is used for the planning of the task packages at this level is RCCP. The method used will be more closely commented upon further below.

III. Scheduling (operational): This level is referred to as Engineering and Process planning stage. Information about different activities are detailed. These include the more reliable duration estimates of the activities and the possible preference relations between the activities. The method that is used for the planning of activities is the resource-constrained project scheduling (RCPS). This method does not come up for discussion in this report as readily available software solutions can handle the planning at this level.

The adopted RCCP planning method is the key component of the CAMRP, which allows both what-if strategic capacity analysis and planning of the maintenance orders for every resource. Two types of capacity are considered here: (a) *regular capacity that is present within MMRBU, the regular time and the regular staff*. (b) *Irregular capacity that includes overtime, subcontracting, and hiring extra staff*. Flexibility in the scope of the staff can be created by means of subcontracting. This is the last resort when the potential overtime hours are fully utilized.

There are two approaches for solving RCCP problems: resource driven and time driven. The resource resource-driven RCCP minimizes the maximum lateness (i.e. the late processing of a task package) concerning all task packages, thereby (only) using the available quantity regular capacity. The time-driven RCCP considers the due dates of the task packages as strict deadlines. Within a time-driven RCCP, non-regular capacity used is minimized. Depending on the circumstance, the planning tool developed makes use of either approach.

The methodology developed consists of two steps. The first step is the planning of the preventive maintenance projects. To a large degree of certainty, the preventive maintenance projects could be planned in advance. This step has been subdivided in two parts: the planning of the task packages with start time, and the planning of the task packages without start time. At the second step the uncertainties of the corrective maintenance projects are taken into account by using buffer times (capacity provisions).

The framework models distinguish six types of resources:

- Technical service team 1 (TST1): This service team consists of four technicians who have specialist knowledge in the field of a restricted group of CNC machines.

These machines are very important for the customers and are used in key processes and are usually the bottleneck machines. In case of insufficient work, these technicians can be also deployed on other machines.

- Technical service team 2 (TST2): This team job is similar to team 1, except they are specialists for another set of CNC machines.
- Technical service team 3 (TST3): These technicians are mechanical technicians who are mainly available for work on conventional machines.
- Technical service team 4 (TST4): This is the team of electric technicians. They are responsible for the wiring in and around the machines.
- Technical service team 5 (TST5): This is the team of electronic/IT technicians. They are responsible, among other things, to maintain onboard programmable numerical control devices.
- Technical service team 6 (TST6): These technicians conduct the situation appraisal of the machines.

For each resource (technical service team), a plan is made. This plan is presented in Gant chart format that indicates the preventative activities to be carried out and free buffer times for corrective maintenance orders.

4.1. Step I: preventive maintenance planning

In the first part of the algorithm, the task packages with a known strict start time are planned. In consultation with general managers, it has been agreed upon that these task packages must be completed first within the deadline. This is a time-driven RCCP mentioned earlier. For solving time-driven RCCP problem, we implemented a modified version of incremental capacity planning algorithm (ICPA) (De Boer [19]). The modified ICPA heuristic has three differences, first instead of earliest due date (EDD) priority rule, we use earliest start time as the priority rule since the task package exact durations are unknown and we only have a lower bound. Second, the irregular capacity is divided into overtime and subcontracting capacity, and third, the collection of predecessors are ignored as in our case 90% of the preventive orders contained only one task package.

In the second part of this step the preventive task packages without start time are planned. These task packages are planned between the task packages already planned. Here we use a serial method to plan these preventive jobs, in order to balance the workload and avoid a surge in capacity requirement, which usually would be the case if these jobs are planned in parallel to those with a known start time. A pairwise switching procedure is developed to make the algorithm workable when a serial solution is infeasible.

The planning interval is set on half working days (i.e. 4-h). When a task package is, for example, 22 or 15 h, the required time is rounded up. This assumption makes planning simpler and more synoptic. The planning horizon is equal to the critical path time, which will be explained further below.

4.2. Step II: corrective maintenance planning

To plan the corrective maintenance projects properly, using the historical data we measure a median estimate for the duration of corrective tasks for each period (Goldratt [24], Goldratt & MaKay [25]). Some literature suggests the use of average estimates instead of the median (see [26,32,33,37]). However, we use median to represent a more reasonable picture of random behavior of corrective jobs.

Based on these estimates, using the latest inter-arrival distribution of corrective jobs, a set of corrective maintenance jobs are generated. Using TOC, the *Critical Chain* for the generated set of corrective and already planned preventive orders is identified. Here, the critical chain is a chain of dependent tasks, which minimizes the estimate duration of all task completed, thereby takes into account the precedent relations and the resource dependencies.

The critical chain project duration is equal to the largest completion time of any resource (technical service team), say, for example, for one service team to complete all task packages it would take 24 working days and this is the largest among all resources, (i.e. CCP horizon is 5 weeks). Now suppose seven task packages involving k resources are planned, for every resource a separate chart is devised. A planning chart reflects the cumulated required capacity per day concerning the whole planning horizon. An example of a planning chart for a resource is shown in Fig. 3. In this figure Ji stands for task package (job) i. Empty slots in this figure represent free time.

The free time for unknown corrective maintenance jobs is now used as a project buffer and a fifth of it (a free day) is placed at the end of each week. These buffers can be exclusively used for unforeseen activities. On this day, therefore, no preventive maintenance project is planned. Based on these buffers, using the algorithm developed, a new resource plan is made for preventive maintenance tasks. (see Fig. 4, where the buffers have been reflected at the end of each week by cross). Fig. 3 shows the best-case scenario and Fig. 4 serves as a worst-case scenario. These plans can be used for negotiation with the involved manufacturing units and confirming the preventive maintenance schedules.

The buffer times, which are also referred to as shock absorbers, would minimize delays (Newbold [32]). According to TOC, there are three distinguished buffers types to be planned:

1. *The project buffer:* This buffer has been devised to protect the customer against the variability in duration of the tasks on the critical chain. In other words, this buffer must protect the deadline of the project. The project buffer is added at the end of the critical chain. When a task of a project takes away more time than the estimate, then this buffer can be used. If the duration of

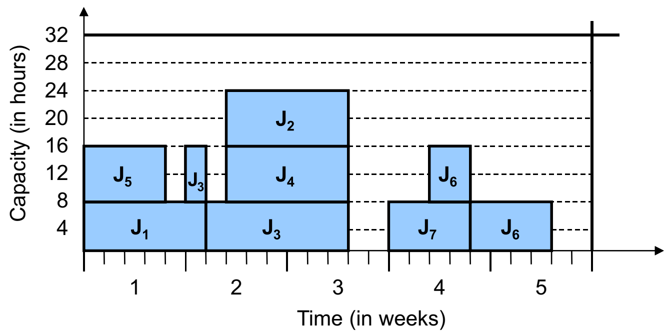

Fig. 3. Example of a planning chart.

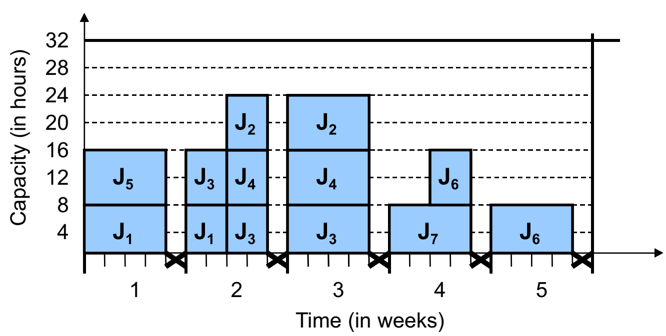

Fig. 4. Example of a worst-case scenario.

the task is shorter than the estimate, then this must be communicated, so the following task in the critical chain (if possible) can start.

2. *The feeding buffer:* This buffer has been devised to safeguard the critical chain against delays on non-critical paths. This buffer is placed on each point where a task on non-critical chain meets a task on the critical chain. The feeding buffers determine the start time for the first activities that lie on the non-critical chains. These buffers are also natural points to measure the project's progression on the feeding paths, while keeping a focus on the critical chain (Leach [34]).
3. *The resource buffer:* This buffer (or protective capacity) is used to insure that the resources would be available to carry out the tasks on the critical chain on time, or earlier (Bolander & Taylor [27], Umble & Umble [35]). Resource buffers can be implemented in two manners (Umble [35]):
   - As a wake-up call: The resource buffer ensures that the resources receive regular updates over the expected start times of the planned task on the critical chain, or mobilize resources for the next activity.
   - As a buffer to absorb all existing inactive times: The buffer can be considered as a type protecting capacity. This provides an even larger guarantee that a resource is available at the correct time.

In this case we placed a heavy emphasis on resource buffers, because when a task is completed early, the next one can immediately be continued. This can lead to a shorter project duration. A too early completion can smooth out a too late completion, and as such the project can terminate on time.

The buffers ensure the completion of the preventive maintenance projects. The buffer placement is crucial, and interested readers are referred to the literature on critical chain.

4.3. The software

The resource-planning concept was implemented in Delphi software. To setup the program, data are stored in Microsoft Access; some are directly keyboarded and some uploaded from the existing systems. Simplicity and inter-portability were the main reasons for this choice. The data have been classified as follows:

1. The available capacity matrix per resource in terms of: regular capacity in hours (multiple of 4 h), and over time for whole planning horizon (i.e. 5 weeks).
2. Task package information.
3. The historical data on each machine at each manufacturing site.
4. Log of previous corrective maintenance faults and durations per site per machine; and
5. a serious of key performance indicators to track for different maintenance projects.

The information collected can be easily read in the Delphi program. Through very interactive screens the user is assisted to generate planning alternatives or re-plan an existing one due to unforeseen events.

5. Conclusion

This paper described a planning tool which was designed to manage a very hectic preventive and corrective maintenance environment of MMRBU. The tool constructs a "good" and "feasible" plan of preventive maintenance projects, taking into account the uncertainties of the corrective maintenance projects. In about 9 months after implementation, the tool allowed the company to double the number of executed preventive maintenances.

For the planning tool to function properly, it is expected that MMRBU improve current system by:

- Centralizing the planning and control of the maintenance, preferably, in this case, at the service management level.
- Concluding contracts with customers so that it can also start effectively on time, reducing the uncertainty regarding the preventive projects.
- Improving communication between the customers, the service manager, the purchasing managers and the technicians' teams.

- Creating a database where all information about required data and history of maintenance is tracked, collected, and updated; and
- setting up a balance score card for the unit to be able to continuously improve the processes.

The implementation of these improvement points provides a clearer overview of the true remained resources capacities, increases the percentage of preventive maintenance projects, and reduces the corrective ones.

Modern maintenance practices necessitate computer-aided tools to assist service managers. The critical item in the implementation is the information system. This issue was raised many times during the course of conducting this research, and was continuously communicated to parties involved.

Maintenance resource planning improvement is not achieved by simply setting up a computerized program, it is achieved by a company-wide effort which includes many people, sets obligations upon management, and requires commitment from both manufacturing units and maintenance unit. We have also found that while improvement is feasible for MMRBU in certain areas, the development of a maintenance improvement strategy that appreciates the needs of different customers (manufacturing units) is indispensable. Maintenance improvement strategy relates to policy, anticipation of problems, responsiveness of people and monitoring outcomes. The data analysis associated with this exercise is intended to provide a focus on what must be improved. A careful audit will provide a foundation to plan the necessary organizational changes.

References

[1] Peters RW. Maintenance benchmarking and best practices, 1st ed. USA: McGraw-Hill; 2006.

[2] Moubray JM. Reliability-centered maintenance. 2nd ed. New York, NY: Industrial Press; 1997.

[3] Bond TH. Implementing profit centered maintenance, P/PM Technology, December 1994.

[4] Takata1 S, Kimura F, van Houten FJAM, Westkämper E. Maintenance: changing role in life cycle management. Ann CRIP 2004;53(2):643–55.

[5] Cholasuke C, Bhardwa R, Antony J. The status of maintenance management in UK manufacturing organizations: results from a pilot survey. J Qual Maintenance Eng 2004;10(1):5–15.

[6] Horner RMW, El-Haram MA, Munns AK. Building maintenance strategy: a new management approach. J Qual Maintenance Eng 1997;3(4):273–80.

[7] Tsang AHC. A strategic approach to managing maintenance performance. J Qual Maintenance Eng 1998;4(2):87–94.

[8] Bevilacqua M, Braglia M. The analytic hierarchy process applied to maintenance strategy selection. Reliab Eng Syst Safe 2000;70: 71–83.

[9] Cooke FL. Plant maintenance strategy: evidence from four british manufacturing firms. J Qual Maintenance Eng 2003;9(3): 239–49.

[10] Duffuaa SO, Raouf A, Campbell JD. Planning and control of maintenance systems: modeling and analysis. New York: Wiley; 1999.

[11] Ben-Daya M, Duffuaa SO, Raouf A. Maintenance, modeling and optimization. Dordrecht: Kluwer Academic Pub.; 2000.

[12] Birolini A. Quality and reliability of technical systems: theory – practice – management. Berlin: Springer; 1994.

[13] Knapp GM, Wang H-Pn (Ben). Automated tactical maintenance planning based on machine monitoring. Int J Prod Res 1996;34(3): 753–66.

[14] Bahrami-Ghasrchami K, Price JWH, Mathew J. Optimum inspection frequency for manufacturing systems. Int J Qual Reliab Manage 1998;15(3):250–8.

[15] Kimura F, Hata T, Kobayashi N. Reliability-centered maintenance planning based on computer-aided FMEA. In: The 35th CIRP-international seminar on manufacturing systems, Seoul, Korea, 12–15 May 2002.

[16] Funk P, Jackson M. Experience based diagnostics and condition based maintenance within production systems, (IDP), COMADEM. In: David Mba, editor. Proceedings of the 18th international congress and exhibition on condition monitoring and diagnostic engineering management, United Kingdom, August 2005, p. 7.

[17] Duffuaa SO, Ben-Daya M, Al-Sultan KS, Andijani AA. A generic conceptual simulation model for maintenance systems. J Qual Maintenance Eng 2001;7(3):207–19.

[18] Demeulemeester E. Optimal algorithms for various classes of multiple resource-constrained project scheduling problems, unpublished PhD dissertation, Universit Catholique de Louvain, Belgique, 1992.

[19] Boer R. de, Resource-constraint Multi-project Management, a Hierarchical Decision Support System. Enschede: Febodruk B.V., PhD thesis, 1998, ISBN:90-36512069.

[20] Luczak H, Mjema EAM. A quantitative analysis of the factors affecting personnel capacity requirement in maintenance department. Int J Prod Res 1999;37(17):4021–37.

[21] Mjema EAM. An analysis of personnel capacity requirement in the maintenance department by using a simulation method. J Qual Maintenance Eng 2002;8(3):253–73.

[22] Hans EW, Herroelen W, Leus R, Wullink G. A hierarchical approach to multi-project planning under uncertainty. Working paper, School of Business, Public Administration & Technology Universiteit Twente, The Netherlands, October 2003.

[23] Mourtzis D. An integrated system for managing ship repair operations. Int J Comp Integ M 2005;18(8):721–33.

[24] Goldratt EM. Critical chain. Great Barrington: The North River Press; 1997.

[25] Goldratt EM, McKay KN, Morton TE. Critical chain. I.I.E. Trans: Indus Eng Res Dev 1998;30(8):759–68.

[26] Newbold RC. Project management in the fast lane: applying the theory of constraints. Boca Raton: St. Lucie Press; 1998.

[27] Bolander SF, Taylor SG. Scheduling techniques, a comparison of logic. Production and Inventory Management Journal (First Quarter) 2000;41:5.

[28] Hoel K. Quantifying buffers for project schedules. Production and Inventory Management Journal (Second Quarter) 2000;40: 43–7.

[29] Michalski L. Applying the theory of constraints: managing multiple deadlines. Pharm Technol 2000;24:126–32.

[30] Rand GK. Critical chain: the theory of constraints applied to project management. Int J Project Manage 2000;18:173–7.

[31] Steyn H. An investigation into the fundamentals of critical chain project scheduling. Int J Project Manag 2000;19:363–9.

[32] Newbold RC. Introduction to critical chain project management. ProChain Solutions Inc., 〈http://www.prochain.com〉, 2001.

[33] Herroelen W, Leus R. On the merits and pitfalls of critical chain scheduling. J Oper Manag 2001;19:559–77.

[34] Leach LP. Project management improves project performance. Project Manage J 1999;30:39–51.

[35] Umble M, Umble E. Manage your projects for success: an application of the theory of constraints. Production and Inventory Management Journal (Second Quarter) 2000;41:27–32.
[36] Hameri A-P, Heikkilä J. Improving efficiency: time-critical interfacing of project tasks. Int J Project Manag 2002;20: 143–53.
[37] Rizzo T. A New Jersey Corporation: The Critical Chain Method. Product Development Institute Inc., 〈http://www.pdinstitute.com/tutorial〉. 2006.
[38] Backlund F. Managing RCM introduction: A literature study, Research Report 2003:2, Division of Quality and Environmental Management, Luleå, Sweden, 2003.