Lecture Notes in Mechanical Engineering

Adolfo Crespo Márquez
Juan Francisco Gómez Fernández
Vicente González-Prida Díaz
Joe Amadi-Echendu *Editors*

16th WCEAM Proceedings

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Lecture Notes in Mechanical Engineering

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Foreword

The 16th World Congress on Engineering Asset Management (WCEAM) was held in Seville, Spain, from October 5 to 7, 2022. From all indications, attendees were delighted with the opportunity provided to meet in-person, especially to rekindle the warmth of face-to-face interactions and interpersonal relationships aftermath of the COVID-19 lockdowns and travel restrictions. The success of the events of 16th WCEAM provided proof of the remarkable collaboration between the International Society of Engineering Asset Management (ISEAM), the Spanish Association for the Development of Maintenance Engineering (INGEMAN), BCO Congresos Seville, and the University of Seville.

The collaborating entities are grateful to the city of Seville and the hosting partners for the access granted to visit cultural and heritage sites, privileges granted to use the city's facilities, and also for the general hospitality accorded to the 16th WCEAM delegates. Throughout the duration of the congress, the welcoming and safe environment of the city engendered enriching deliberations on 'Value-Centered and Intelligent Asset Management in the 4th Industrial Revolution Era.' The deliberations included business meetings, social engagements, and academic discourse between the participants. Much of the intellectual discussions, especially academic discourse, are summarily captured in the contents of this book of 16th WCEAM Proceedings. In this regard, the collaborating entities acknowledge the long-standing relationship between ISEAM and Springer with the primary objective of advancing education, research, training, and practice of the multidisciplinary body of knowledge in Engineering Asset Management.

November 2022

Joe Amadi-Echendu
Chair, ISEAM Board of Directors

Preface

The 16th World Congress on Engineering Asset Management (WCEAM www.wceam.com) was held in Seville, Spain, from October 5 to 7, 2022, under the auspices of the International Society of Engineering Asset Management (ISEAM www.iseam.org). The events were organized by ISEAM in collaboration with the Spanish Association for the Development of Maintenance Engineering (INGEMAN), coordinated by BCO Congresos Seville, and hosted by the University of Seville. The 16th instance of the WCEAM series took place as the global community increasingly relaxed lockdown and travel restrictions post the peak of the COVID-19 pandemic. The unprecedented and persistent effects of the pandemic, coupled with adverse influences of ongoing climate change events and geopolitical challenges, charge us to advance the principles, knowledge, and practice of the Engineering Asset Management body of knowledge within the context of 4IR technologies and the Society 5.0 ideal.

16th WCEAM 2022 provided opportunity for thought-leadership and research exchange in the multidisciplinary knowledge area of Engineering Asset Management. The Congress facilitated knowledge exchange between academics, researchers, industry practitioners, and policy makers in a friendly, multicultural, and transparent environment in Seville. The theme, ‘Value-Centered and Intelligent Asset Management in the 4th Industrial Revolution Era,’ is timely and relevant, since value-centered sustainable development is crucial for the future of human civilization. Interestingly, digitized and digitalized asset management provides new ways of looking at our world, encouraging us to utilize increasingly intelligent tools and methods to achieve more human-centric, resilient, and sustainable societies. Thus, this edition of 16th WCEAM Proceedings is a collection of high-impact discourses, serving as an important reference for Engineering Asset Management education, research, and practice.

In addition to social activities, the events of 16th WCEAM included 7 plenary sessions, 16 academic sessions, 5 industry workshop, and business sessions. Although the activities and contributions provided a transversal view of the multidisciplinary body of knowledge of Engineering Asset Management, the contents of this book are grouped into three thematic sections of '*intelligence*,' '*management*,' and '*value*' as follows:

- Section 1 on '*intelligence*' contains three parts arranged as nineteen chapters that discuss matters regarding asset management and decision support systems based on the applications of 4IR technologies such as AR and VR, machine learning, digital twinning, etc for monitoring, diagnostics, prognostics. The section particularly includes methodologies and cases applied to different operational contexts.
- Section 2 on '*management*' contains four parts arranged as twenty-three chapters that discuss asset life-cycle management, especially, human dimensions on the management of infrastructure and industry-sector assets.
- Section 3 on '*value*' contains four parts structured into twenty-five chapters that deal with the applications of international standards, local regulations and industry guidelines to risk and resilience engineering, asset operations and maintenance, condition, risk, resilience and vulnerability assessments.

The full editorial process for the WCEAM 2022 started in 2021 with the approval of the Proceedings book proposal by the publishing house Springer. Consequent upon the corresponding agreement between ISEAM and Springer, the qualification process involved two phases:

Phase 1. Conference Review:

- Initial call for papers in 2021, then a repeat call in 2022.
- Abstracts submission and review using the BCO conference management system. The abstracts were reviewed to ensure consistency with the 16th WCEAM theme and topics.
- Authors of accepted abstracts were invited to submit at least a 6-page version of their contributions formatted in accordance with the prescribed template.
- The full-paper submissions were double-blind reviewed to ensure academic rigour.

Phase 2. Editorial Review:

- The authors of selected papers were notified to extend their manuscripts from 6 to 10/12 pages, formatted according to Springer template in order to qualify as book chapters.
- The extended manuscripts were submitted and further reviewed using Springer's Online Conference System (EquinOCS).
- All reviews were conducted by the WCEAM technical review panel in accordance with ISEAM's well-established guidelines. The panel of reviewers mostly comprised Members (M) and Fellows (F) of ISEAM (i.e., F/MISEAMs)

The editors remain grateful to the global ISEAM community and INGEMAN associates for their participation during 16th WCEAM 2022. A special word of thank you to all the reviewers for ensuring the quality of the contributions published in this Proceedings.

November 2022

Adolfo Crespo Márquez
Juan F. Gómez Fernández
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16th WCEAM 2022 Editor

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Asset Management and Decision Support System

A Decision-Making Framework for Selecting an Optimum Package of Maintenance Improvement Projects in a Hospital

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Abstract. This Chapter presents a decision framework for the selection of the most satisfactory combination of projects in the maintenance department of a healthcare organisation, using a multi-criteria audit. A number of projects were designed with the aim of improving the current state of the maintenance department of a Spanish hospital. To select the optimum package of projects, a multi-criteria additive model was constructed by means of MACBETH, using two types of benefit (internal and external) and the cost of implementing each project. From the cost/benefit ratio, the resulting efficient frontier with all the possible combinations of projects to be implemented, and the particular conditions in the maintenance department under study, the first package of projects was selected.

1 Introduction

Maintenance is particularly important in healthcare organisations, since there are facilities and devices that must operate with 100% availability, safety and quality, or serious consequences will ensue for the quality of the service (patient waiting time, reprogramming of appointments, incorrect diagnoses, etc.), putting patients' safety, and even lives, at risk. For this reason, maintenance managers need to monitor the efficiency of their departments to prevent deficiencies, and then to introduce improvement projects to tackle any deficiencies found. Ideally, they should do this through a process of continuous improvement.

Project selection is a strategic decision (Liesio et al. 2007). Thus, the decision-making process is complicated, with a large number of stages, decision-making groups, and conflicting objectives, and a high risk and uncertainty (Ghasemzadeh and Archer 2000). There are many methodologies in the literature for selecting the optimal project portfolio that best aligns with the strategic priorities of the organization. For example, Bai et al. (2021) proposed a model based on the past record of the projects. Dou et al. (2019) gave two methodologies, one based on a single objective, and another on multiple objectives, to choose the set that maximises the values of these objectives. Kornfeld and Kara (2013) used lean and six sigma for their project ranking methodology. However, these approaches are not always suitable, as pointed out by Pérez et al. (2018): a) The strategy should regulate the criteria for selecting the project porfolio, but a defective

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choice of criteria may make it hard to introduce the portfolio in such a way as to make the strategy work; b) there may be complex synergies between the candidate projects that might not be accounted for. The best project to select individually may not form part of the best set of projects when a decision is taken with respect to a group of projects. Thus, Zhang and An (2016) show that, if a project has the highest degree of synergy, it should be preferred to the others; to calculate the degree of synergy, they applied a scoring method based on expert opinions.

Optimal project selection depends on many factors, and therefore the multi-criteria technique could be very useful in the evaluation of different criteria simultaneously. Although project selection by means of multi-criteria techniques has been analysed in the literature (Ghasemzadeh and Archer 2000; Salo et al. 2004; Bana e Costa et al. 2005; Mohanty et al. 2005; Phillips and Bana e Costa 2007; Singh et al. 2021), in the area of maintenance, the use of analytical techniques has historically been rare, and is even rarer in hospitals, despite the important potential repercussions for patient care. Consequently, this research combines different techniques, including maintenance audits, Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), and the Taguchi loss function, with the aim of continuous improvement in a hospital maintenance department. In order to apply it, it is thus necessary first to carry out a multi-criteria audit, based on the judgements of experts, to weight each subject and fundamental point of view to be considered. On the other hand, the evaluation of each project is objective, providing a methodology that guarantees the objectivity of the solutions produced.

The structure of this Chapter is as follows. Section 2 examines the characteristics of the internal audit carried out. Section 3 discusses the criteria used to select the most suitable packages of maintenance projects. Section 4 describes the procedure for building the efficient frontier for the selection of the first project package. The Chapter ends with the reference section.

2 Maintenance Multi-criteria Audit

The maintenance audit is structured into the following subjects: maintenance strategy, attitude of maintenance staff and other hospital personnel, resources and installations, human resources, records, planning, scheduling, work orders, purchases, warehouse stock, maintenance documentation, calibration, technical aspects, effectiveness and control. Each subject comprises a number of Fundamental Points of View (FPV). A FPV is an aspect that is relevant to the evaluation of the alternatives. The FPVs group into a hierarchical structure, and each is associated with a descriptor. The descriptor is a set of impact levels that can measure, either quantitatively or qualitatively, the level of compliance of an FPV (Bana e Costa and Carvalho 2002). The audit is based on Bana e Costa et al. (2012). Table 1 shows, as an example, the FPVs "Quality control of spare parts, tools and machinery that enter a warehouse, measures to prevent stock breakage and obsolescence check" in the subject Warehouse in the audit carried out. The descriptors in this audit are constructed and generally qualitative, although some are quantitative. Descriptors usually have five scale levels (L_1–L_5), among which the reference level is known as "Neutral" and the best level is known as "Good".

Table 1. FPV Quality control of spare parts, tools and machinery that enter a warehouse, measures to prevent stock breakage and obsolescence check.

Scale level	Description
L_1 (Good)	Quality control is carried out on each spare part, tool or machine that enters the warehouse. Action protocols are in place in the event of stock breakage to guarantee optimum availability of hospital facilities as a function of their criticity. Obsolescence checks are carried out periodically
L_2	Quality control is carried out on each spare part, tool or machine that enters warehouse. Action protocols are in place in the event of stock breakage. Obsolescence checks are carried out periodically
L_3 (Neutral)	Quality control is carried out on each spare part, tool or machine that enters the warehouse. Action protocols are in place in the event of stock breakage. Obsolescence checks are not carried out periodically
L_4	Quality control is carried out on machines that enter the warehouse. No action protocols are in place in the event of stock breakage. Obsolescence checks are not carried out
L_5	No quality control is carried out on machines that enter the warehouse. No action protocols are in place in the event of stock breakage. Obsolescence checks are not carried out

For each FPV a matrix of MACBETH judgements must be built. The matrices built are all consistent. Then a numerical scale is constructed based on the qualitative judgements with value scores of 100 and 0 arbitrarily assigned to the Neutral and Good reference levels, respectively (Bana e Costa and Chagas 2004). Figure 1 shows the numerical scale and the value function corresponding to the FPV "Classification of spare parts according to criticity". To obtain the weights for the FPVs in each subject, the following procedure is adopted. First, the possibility of an alternative with all criteria or FPVs at a Neutral level is considered. The system calculates how much a swing from Neutral to Good in all FPVs would improve the preference of this alternative, using the semantic categories of MACBETH. This ranks the FPVs in the matrix of judgements. Then, the system compares how much more preferable would a swing from Neutral to Good be in the first FPV in comparison to in the second FPV. The comparison repeats for the first FPV and the third FPV, and so on. This process continues row-by-row until the matrix of judgements is complete.

Each subject can be in one of the following states: excellent, satisfactory, acceptable, poor and very poor. In addition, the states "All excellent" and "All very poor" define the best and worst possible states of each subject. The limits between each pair of states in a subject are defined as: Excellent/Satisfactory limit; Satisfactory/Acceptable limit; Acceptable/Poor limit; and Poor/Very poor limit. The current state of the hospital maintenance department is labelled "current state". The methodology for establishing the limits between states by subject is a variation on the bottom-up and top-down procedures described in Bana e Costa and Carvalho (2002). The limits between states obtained using these procedures may differ, in which case the limits are reanalysed. Table 2 shows the final limits obtained by the subject, and the current state of the maintenance department assessed (in a quantitative and qualitative manner).

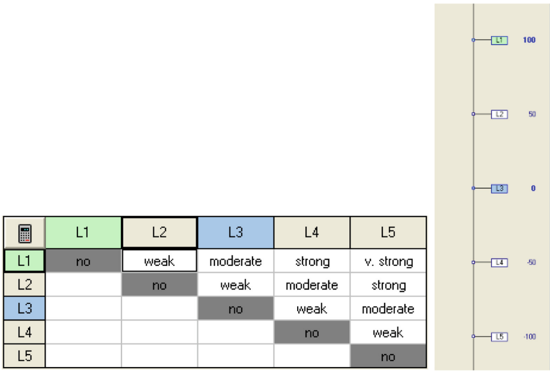

Fig. 1. Judgement matrix, scale and value function for FPV "Classification of spare parts according to criticity".

3 Decision Framework for Selection of Optimum Package of Maintenance Improvement Projects

The objective is to calculate an efficient frontier with packages of maintenance projects offering the optimum cost-benefit relation. In order to identify the most efficient investment in the whole portfolio, all projects must be considered simultaneously. This produces an envelope graph that shows every possible combination of investments. The upper line in the graph is known as the efficient frontier. This line represents the investment portfolios that generate the most benefit at a particular cost.

An area is built by grouping the investment opportunities into projects. The areas defined are: undergraduate projects, outsourcing, and internal development. Only one project can come from each area to form any one package due to the time constraints of the head of the hospital's maintenance department, who has to manage or control each project adopted in the maintenance department.

Table 2. Limits between states by subject and current state of Maintenance Department.

Subject	Excellent/satisfactory limit	Satisfactory/acceptable limit	Acceptable poor limit	Poor/very poor limit	Current state
Strategy	50.00	19.23	−11.54	−50.00	38.46 (Satisfactory)
Attitude	50.00	25.00	−12.50	−28.13	12.50 (Acceptable)

(*continued*)

Table 2. (*continued*)

Subject	Excellent/satisfactory limit	Satisfactory/acceptable limit	Acceptable poor limit	Poor/very poor limit	Current state
Resources	61.11	19.45	−2.78	−50.00	−38.89 (Poor)
Human Resources	53.66	31.70	−31.71	−53.66	−36.59 (Poor)
Records	71.79	28.20	−53.85	−97.44	−10.26 (Acceptable)
Planning	63.64	33.33	−6.06	−39.40	18.18 (Acceptable)
Scheduling	38.46	15.38	−34.62	−61.54	−23.08 (Acceptable)
Work orders	65.38	36.54	−3.85	−46.16	71.43 (Excellent)
Purchases	50.00	22.23	−11.11	−50.00	61.11 (Excellent)
Warehouse	65.38	36.54	−3.85	−46.16	−30.77 (Poor)
Maintenance documentation	54.16	18.75	−20.84	−39.59	−33.33 (Poor)
Calibration	58.14	25.58	−32.56	−62.79	−18.60 (Acceptable)
Technical aspects	64.28	35.71	−28.57	−75.00	−21.43 (Acceptable)
Effectiveness	51.91	23.02	−20.24	−40.40	9.52 (Acceptable)
Control	50.00	23.96	−16.67	−43.75	10.42 (Acceptable)

The criteria are the elements for evaluating each project: cost and benefit. The benefit criterion has the sub-criteria (for a detailed explanation see Phillips (2004)):

- Internal benefit. This benefit is related with the different FPVs analysed in the multi-criteria audit. In each maintenance project, the potential benefit is estimated by considering the change in the scale level of one or various FPVs in one subject of the audit. Figure 2 shows the internal benefits of the projects in each area, which are calculated from the estimated value of a subject after implementing the project less the current value of the subject.
- External benefit. This benefit is related to the quality of the service provided, in other words, how a project can improve the satisfaction of the hospital's patients and healthcare staff. This increase in satisfaction is due to improvements attributable to the project in maintenance aspects that have a direct or indirect effect on quality of healthcare (e.g., decrease in breakdowns of a medical device, with a consequent

decrease in customer waiting time for a diagnostic test). The external quality relates to modifications in the opportunity costs, defined as the losses as a result of the failure of machinery and medical devices to carry out their functions properly. The Taguchi loss function (see Eq. 1) is used to evaluate the external quality of the maintenance department. $L(y)$ is the benefit for the quality of healthcare expected from the implementation of a project, k the effect on the quality of healthcare of the improvements in the maintenance department, y the current value obtained from the maintenance audit in the subject, and τ the target value in the subject desired for a project.

$$L(y) = k(y - \tau)^2 \tag{1}$$

This study uses an additive model, following Eq. (2), where v_{ij} is the value associated with alternative i in criterion j, and w_j is the weight of criterion j.

$$V_i = \sum_j w_j v_{ij} \tag{2}$$

As a result of the double weighting, the additive model takes on the form of Eq. 3, where w_{jk} is the within-criterion weight, v_{ijk} the value of alternative i in criterion j in area k, and w_j is the weight of criterion j. The multiplication by 10 is so that the weighted values obtained are above 1000, rather than 100 as in the starting data. The final value V_{ik} of a project is the sum of the scores of alternative i in all criteria (Phillips 2004).

$$V_{ik} = \sum_j 10(w_j w_{jk} v_{ijk})/(\sum_j \sum_k w_j w_{jk}) \tag{3}$$

The cost-benefit ratio r_{ik} is then calculated by dividing the difference of values between one level and the next by the difference in costs, as shown in Eq. 4.

$$r_{ik} = (V_{ik} - V_{(i-1)k})/(C_{ik} - C_{(i-1)k}) \tag{4}$$

The doubly-weighted mean of the two benefit scales means that each project is characterised by two numbers: the cost, and one single benefit. This enables the calculation of the cost and total benefit of all the combinations or packages of projects. The efficient frontier is the curve of the best set of investments or most beneficial package of projects for each level of total cost. The shaded area in the graph represents all the possible combinations of packages (each one consisting of three projects).

4 Selection of Projects for Maintenance Department

Looking at the results of the multi-criteria audit carried out reveals which subjects or PFVs are in a worse situation. Fourteen projects were proposed to improve the subjects of the internal audit carried out. The projects fall into the following areas: Undergraduate projects, Outsourcing, and Internal development, as shown in Fig. 2.

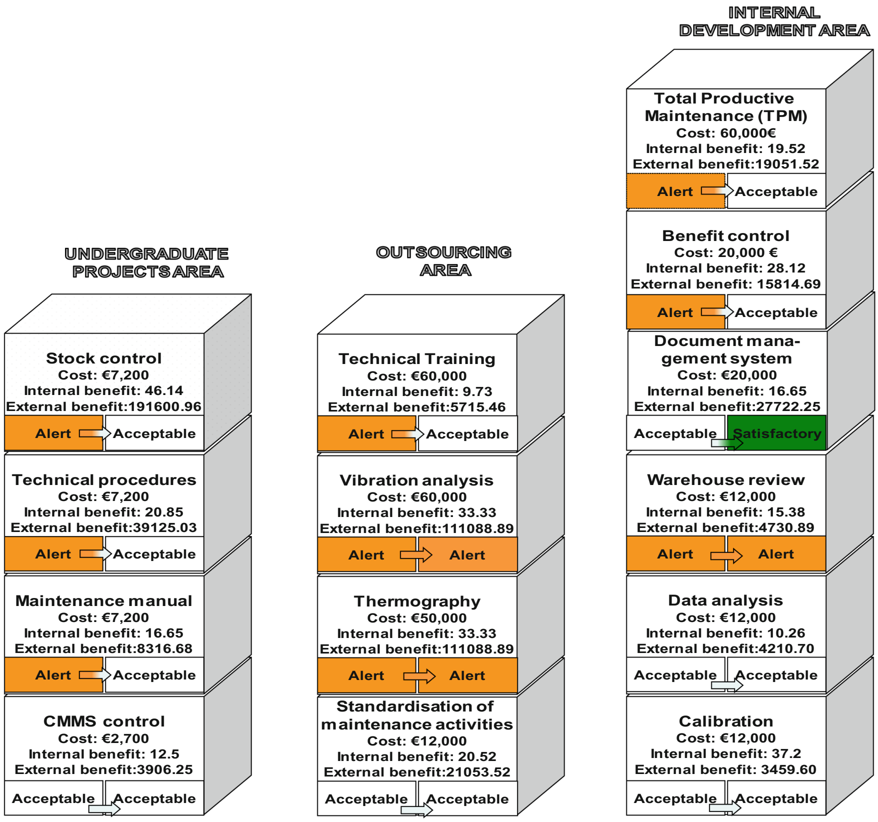

Fig. 2. Maintenance improvement projects by areas (adapted from Carnero 2015).

Projects offering the most benefits generally also have the highest costs. But because of the particular characteristics of the maintenance area, in this study a number of the projects proposed here are exceptions to this rule, having very low costs despite potentially offering considerable benefits. Each combination of projects aiming to improve maintenance is called a package and consists of three projects, one from each area. Each project aims to improve only one single subject, and in some cases only a single FPV in that subject. The number of potentially buildable packages is $4 \times 4 \times 6 = 96$. Figure 2 shows the projects in each area, the costs and internal and external benefits of each project, and the qualitative current state of the subject in which the project would be implemented before (left cell) and after (right cell) its implementation. To obtain the total benefits of each project a multi-criteria additive model considering internal and external benefits has been produced. Relative scales are used ranging from 0 to 100; thus, for internal benefits, the undergraduate projects area becomes 100, 70.15 for outsourcing and 53.09 for internal development, and for external benefits 100, 55.91 and 12.87 respectively.

The internal benefits obtained with each project are estimated in the audit. For example, implementing the project Stock control leads to an improvement in the descriptor for the FPV "Inventory policy for each spare part and periodic review" from Neutral to Good, and in the descriptor for the FPV "Classification of spare parts according to criticity" from L_5 to Good. With this, Warehouse would improve from the current state of -30.77 (Poor) to 15.37 (Acceptable) (see Table 2). Thus the potential internal benefit of this project is 46.14. To obtain the external benefits, the current state of the subject is obtained in the audit. A target value for each project is determined. The value of the loss coefficient is estimated using the Smart method. Using this method, the influence of the projects on healthcare is obtained via swing weights. A swing weight of 100 is assigned to the project that is most important to swing from its least preferred level to its most preferred level with respect to healthcare quality. The levels of influence of each project on healthcare quality are: none, low, medium and high. Lower weights are assigned to the projects on the basis of the relative importance of swinging them in comparison to the most important project. Figure 2 shows the costs and internal and external benefits attributable to each project. The figure also shows the current state of the subject in which the project would be implemented (left cell) and the estimated final state after implementing the project (right cell). To obtain the total benefits of each project, a multi-criteria additive model that considers the internal and external benefits has been produced. Relative scales are used, so the values of the projects in each area and in each type of benefit are converted into scales ranging from 0 to 100. That is, the value 100 is assigned to the project with the most internal (or external) benefit in each area, and 0 to the project with the least benefit. The rest of the projects in each area are assigned values corresponding to a linear conversion between 0 and 100. To calculate the within-criterion weights, the difference between the projects with the best and worst internal benefit in each area is evaluated. For the Undergraduate projects area, this calculation is $46.14 - 12.50 = 33.64$; for the Outsourcing area, $33.33 - 9.73 = 22.54$; and for the Internal development area, $28.12 - 10.26 = 17.86$. Subsequently, the area with the biggest difference between projects is assigned 100, with the other two areas being assigned values in proportion. Thus for the internal benefits the value 33.64 becomes 100, while the value becomes 70.15 for Outsourcing and 53.09 for Internal development. For external benefits a similar procedure results in 100 for the Undergraduate projects area, 55.91 for Outsourcing and 12.87 for Internal development.

The cross-criteria weights demonstrate the relative importance of one criterion with respect to another. By means of cross-criteria weights it is possible to obtain the equivalence of a scale in one criterion in comparison to another scale belonging to a different criterion. When assessing the cross-criteria weights the swing in preference from 0 to 100 is considered (this swing is considering the difference in value from the least to the most preferred level when the criteria are compared). In this study, the external benefit is assigned double the swing from 0 to 100 than the internal benefit because external benefits are closer to the ultimate aim of achieving improvement that patients and healthcare staff can appreciate. The external or internal benefit of each project resulting from the additive model is then calculated. The project Technical procedures returns an external benefit of 39125.03 and an internal benefit of 28.85. After applying the concept of relative scales these values become 19.10 and 48.60 for external and internal benefit, respectively. The weighted external benefit is:

$$10 * 19.10 * 100 * 100/(100 * 100 + 100 * 50 + 55.91 * 100 + 70.15 * 50 + 12.87 * 100 + 53.09 * 50) = 68.12$$

and the weighted internal benefit is:

$$10 * 48.60 * 100 * 50/(100 * 100 + 100 * 50 + 55.91 * 100 + 70.15 * 50 + 12.87 * 100 + 53.09 * 50) = 86.66.$$

The total benefit for this project is therefore:

$$68.12 + 86.66 = 154.78 \approx 155$$

Figure 3 shows the efficient frontier that links the packages with the greatest benefits for a given cost. These packages define the efficient frontier and will always be on the upper surface of the envelope. The shaded area of the graph represents the position of all the possible packages of projects. Equity software is used to calculate the efficient frontier. The head of the maintenance department proposed the package called P (see Fig. 3), comprising the projects Stock control, Technical training, and Document management system. These projects would improve the subjects in the Poor state: Warehouse, Human resources and Maintenance documentation, respectively, and would move them all into the Acceptable state. The cost of this package is €87,200, and the benefit 614.86. Nevertheless, a better package than the one proposed is B, which consists of the projects Stock control, Thermography and Benefit control. These projects would improve the subjects Warehouse, Resources and Control. The first two subjects are in a Poor state and would become Acceptable and Poor, respectively, while Control would improve to Satisfactory. The cost of this package is €77,200 and the benefit 977.43. Package F consists of the projects Stock control, Standardisation of maintenance activities and Benefit control. The cost is €39,200 and the benefit is 739. A cheaper package than the one proposed (C) consists of the projects Stock control, Standardisation of maintenance activities and Calibration. The cost would be €31,200 and the benefit 665.30. Both F and C would improve one subject from Poor to Acceptable. The projects with the highest cost-benefit ratio make up package B. Finally, package B is selected for implementation, since its benefits are 58.97% higher than those of the proposed project, while its cost is 11.47% less.

The head of the maintenance department considered the increase in benefit resulting from this project more important than the potential cost reductions attributable to packages F and C.

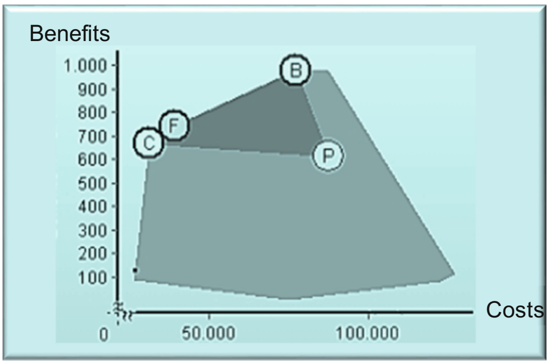

Fig. 3. Efficient frontier with packages P, B, C and F (adapted from Carnero 2015).

5 Conclusions

This Chapter describes a methodology for project portfolio selection in a hospital maintenance department. This area of application is historically lacking in contributions, and so it could be useful in service companies, and in particular, to healthcare organisations, although it could also be applied in manufacturing companies. The use of a maintenance audit via MACBETH allows objective evaluation of all the benefits potentially to be obtained from each proposed improvement project.

The limitations of the methodology set out here relate to the need to carry out a prior audit of the state (qualitative and quantitative) of maintenance in different subjects, and the need to relate each improvement project to improvements in a single subject, and in some cases only a single FPV in that subject. Furthermore, it must be borne in mind that only one project can be selected in each area, in order to make up a package. This is, however, due to constraints specific to the case study described here. Future work could consider evolving criteria, and how one project might improve a number of FPVs from different subjects in the maintenance audit.

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A Preliminary Implementation of Data-Driven TPM: A Real Case Study

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Abstract. Total Productive Maintenance (TPM) is one of the methodologies widely used to increase the availability of existing facilities reducing downtimes, stops, and defects, by improving manufacturing methods, usage, and maintenance equipment. Considering the large amount of data currently available thanks to the Industry 4.0 (I4.0) digitization processes, extending the analysis performed in TPM with the support of new techniques and tools is interesting. More in detail, in this work, Association Rule Mining (ARM) is used to identify the hidden relationships between different failure events, allowing their monitoring and prediction and improving the continuity and resilience of the production flow. The final aim pursued by the proposed approach is the development of a maintenance strategy in order to improve the Overall Equipment Effectiveness (OEE) of the selected process. An example case based on real data from an automotive company is used to present the approach and extract proper knowledge from its implementation.

1 Introduction and Background

Maintenance is nowadays considered one of the main strategic business activities for company performance improvement within Lean Production (LP) (Lucantoni et al. 2019): it is particularly useful to ensure the continuity of the production flow from a resilient perspective. Among LP practices, TPM is one of the most widely applied methodologies to increase the availability of existing facilities. Specifically, TPM has a relevant role in reducing stoppages, wastes, and defects and promoting employee participation in operation and maintenance (Au-Yong et al. 2022). TPM is usually combined with OEE assessment to find the cause of low values and provide suggestions for improvements (Sukma et al. 2022), paving the way towards perfect production. The current maintenance management systems, however, need a certain degree of personalization since their main features do not meet the requirements of each company when dealing with a wide amount of data (Lopes et al. 2016). Within TPM, Planned Maintenance is widely regarded in the literature as the main pillar (Morales Méndez and Rodriguez 2017): its main weakness can be recognized in the fact that it relies on the historical failure rate of the equipment but does not include any probability measure (Adesta et al. 2018). However, Predictive Maintenance is nowadays extensively used for failure prediction, equipment cost reduction, and performance improvement (Sahal et al. 2020). Novel data-driven techniques are required due to the large amount of data

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available for knowledge extraction (Antomarioni et al. 2021). In parallel, some authors highlighted how Lean Automation can be applied for the concomitant implementation of I4.0 technologies into LP practices, even though the complexity of IT infrastructure necessary to fully integrate I4.0 into TPM could make such adoption less desirable (Tortorella et al. 2021). In line with this perception, despite I4.0 being one of the primary paradigms of the current industrial context (Marcucci et al. 2021), the current literature appears poor on how I4.0 techniques can really support LP principles and practices (Ferreira et al. 2022) showing that more research is needed in this area. One of the few examples in the existing literature presents that data mining techniques, such as ARM, can be integrated with traditional Pareto Chart and Ishikawa diagrams or network analysis in order to assess the magnitude of the production losses and identify the related causes within TPM (Djatna and Alitu 2015; Antomarioni et al. 2022).

Considering the existing research gap and the opportunities related to the importance of this research field, the focus of the proposed application is based on relating a metric derived from the well-known Failure Modes Effects Analysis – namely, the Risk Priority Number (RPN) - and ARM: from a practical point of view, they will be used to prioritize failure events; from a theoretical point of view, the aim of the proposed research approach is bridging the existing lack of research in this area through a novel data-driven approach. More in detail, RPN is used to identify the risk associated with each failure mode, considering the current best practices implemented in the company object of the study. Through ARM, instead, the hidden relationship existing between the occurrence of different failure events will be investigated. The last goal is to propose improvement actions that benefit the TPM strategy, improving the OEE and the continuous process flow. A case study from the automotive industry has been used as a pilot project to explain the proposed research approach.

In the rest of the paper, a general explanation of the proposed approach is provided in Sect. 2, while Sect. 3 contains its application to the case study. Conclusions and future research directions are drawn in Sect. 4.

2 Data-Driven TPM Approach

In order to introduce an effective data-driven TPM strategy in manufacturing, the proposed methodology can be summarized as in Fig. 1. Three main steps can be identified in carrying out such an application, as explained in the following sub-sections.

2.1 Data Collection and Pre-processing

Data collection and pre-processing: data represent the basis for an effective maintenance strategy; thus, this module is the foundation of the developed approach. It is fundamental to be able to access data from different sources and integrate them into a unique and reliable dataset. Indeed, the quality of the whole process relies on the quality of data, and the correctness of the decision that will be made is strictly related to them.