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Teaching maintenance plan development in a learning factory environment

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Abstract

The use of learning factories for education in maintenance concepts is limited, despite the important role maintenance plays in the effective operation of organizational assets. A training programme in a learning factory environment is presented where a combination of gamification, classroom training and learning factory applications was used to introduce students to the concepts of maintenance plan development, asset failure characteristics and the costs associated with maintenance decision-making. The programme included a practical task to develop a maintenance plan for different advanced manufacturing machines in a learning factory setting. The programme stretched over a four-day period and demonstrated how learning factories can be effectively utilized to teach management related concepts in an interdisciplinary team context, where participants had no, or very limited, previous exposure to these concepts.

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Keywords: learning factories; maintenance plans; asset management; teaching

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1. Introduction

The discipline of asset management has gained significant traction over the past few years. Asset management is the coordinated activity of an organization to realize value from its assets [1]. Core to effective asset management is not only to acknowledge the importance of maintenance, but also the use of specific techniques such as failure mode and effects analysis as well as reliability-centered, and risk-based approaches to select appropriate maintenance tactics for the maintenance significant systems of an asset. Maintenance tactics are broadly categorized as condition-based, preventive and corrective type tasks [2]. In order to maximize the operation of an asset over its lifetime, a key consideration is the compatibility of these tactics with the maintenance significant systems. Since each maintenance significant system has its own failure characteristics, the combination of the most appropriate tactics is important. Cost plays a major role in the effective implementation of these tactics. Selecting the wrong tactic for a system could affect the overall availability of the asset and result in significant financial losses. The identification of a system's failure characteristics and the selection of the most appropriate maintenance tactic is not always obvious. Recent technological advances and digitalization brought about by Industry 4.0 have made maintenance tactic selection and the execution of the associated tasks more complex [3]. Although these same advances have introduced new opportunities to improve maintenance effectiveness using assisted systems and virtual reality technologies, new training approaches need to be identified to develop the skills and knowledge that workers require [4, 5].

This paper reports on a training programme where a combination of gamification, classroom training and applied knowledge in a learning factory environment are used to teach interdisciplinary teams of students on how to identify and select maintenance tactics, and to further develop these tactics into an overall maintenance plan.

2. Training approach

Literature is clear about how action-oriented learning environments, such as learning factories, make the transfer of knowledge more efficient [6, 7, 8]. The use of gamification in support of learning factories is also frequently used to enhance the relation to reality [9]. Learning factories are traditionally suited towards the teaching of different production systems and processes, with examples being lean management [9] and energy efficiency, [10] and they have also been used for teaching management related topics such as leadership [11]. Other operational processes, such as maintenance, which are closely related to effective production systems, can benefit from the same advantages of the learning factory's action-oriented environment. It is equally important in maintenance plan development that training should extend beyond theoretical knowledge to real world contexts. One of the challenges with maintenance plan development is to determine the failure behaviour of a system. This is typically done by studying historical failure data, which is rarely available within learning factory environments. Further, maintenance plan development involves interdisciplinary teams during the development process. It is therefore important that the training environment exposes students to the dynamics involved with forming part of interdisciplinary teams.

Against this background the learning objectives for training maintenance plan development in a learning factory environment are shown in Fig. 1. A training programme over four days was developed to support the learning objectives. The programme consists of three phases, each contributing to achieve some of the learning objectives. In the first phase, context is provided about asset management, maintenance management and the role of maintenance plan development in production environments. Students are introduced to the concepts by using gamification, where a maintenance tactic game is played to introduce the dynamics of maintenance tactic decision-making. In the second phase, theory about the processes involved in developing maintenance plans are provided in a classroom training session. Fig. 2 illustrates more details about the second phase training. In the third phase, the gained knowledge is applied, where three (depending on class size) interdisciplinary groups of students are tasked to develop a maintenance plan for a critical subsystem of an advanced manufacturing machine. In this phase the groups also present their plan and recommendations to the management of the learning factory. The next sections provide further detail about each of the programme's phases.

2.1. Maintenance Tactic Game

The Maintenance Tactic Game was developed to create a connection between the principles of maintenance tactic selection and the real-world implications of the decision-making. The choice of maintenance tactic is highly dependent on whether the occurrence of failure is hidden or detectable by condition monitoring techniques and the technical, safety and financial feasibility of applying such techniques. The game provides a multistage platform for students or industry practitioners to explore the cause and effect of their decisions on the overall cost of maintenance.

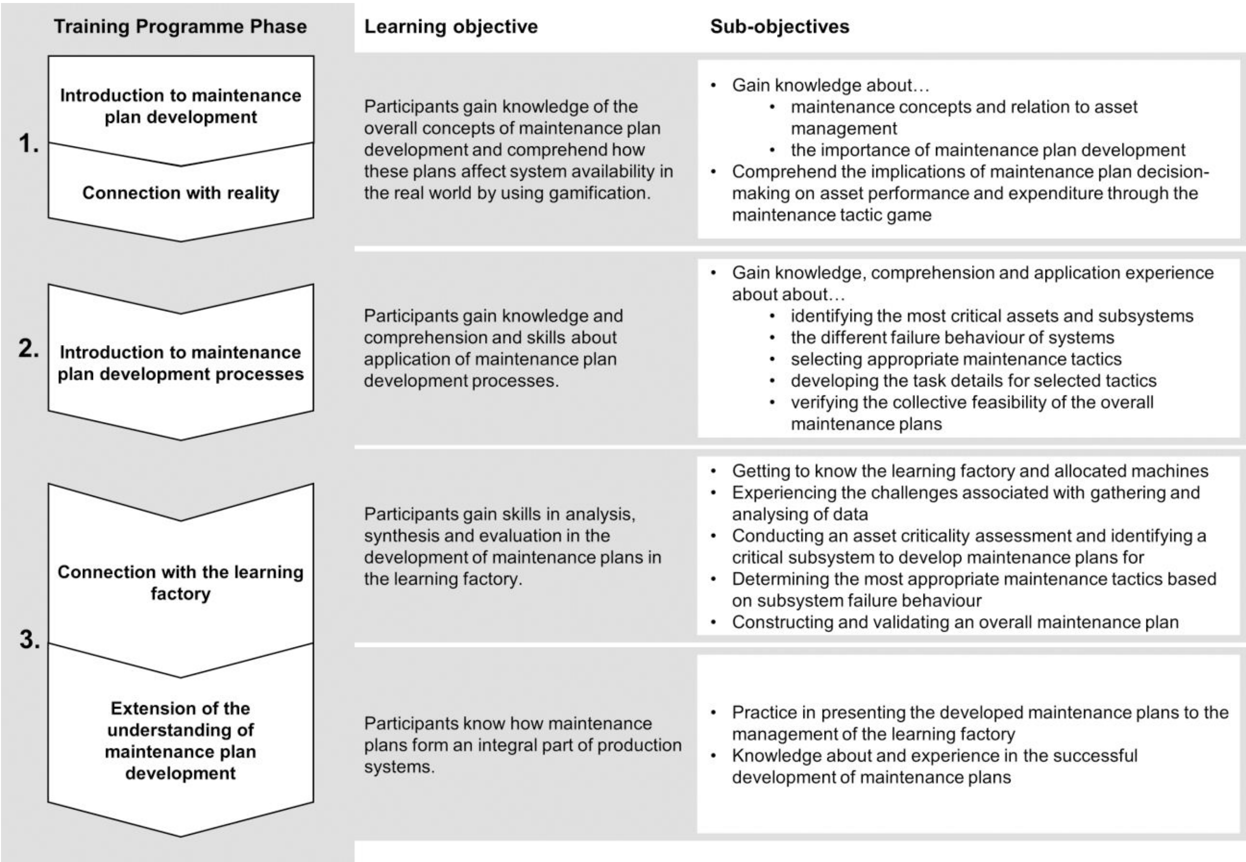

Fig. 1. Training program phases and learning objectives.

The game set is a production line producing ceramic products, which consists of three maintenance significant systems. Each has a different failure behaviour, which is unknown to the participants. The first system is a set of bearings for which the failure is determined by a statistical distribution with a mean life of six gameplay periods, but with outliers, resulting in large variations. Condition monitoring of the bearings is inexpensive and a good tactical choice. The second system is a set of oven fire bricks for which the failure behaviour is also determined by a statistical distribution with a mean life of five and a half gameplay periods, with low variation. Although condition monitoring can be decided on, it is expensive compared to preventive replacement. The third system is a shaft which fails randomly, determined by the throw of a die. Teams compete to maintain their production line of three systems at the lowest cost over an undisclosed number of iterations (gameplay periods). Teams are provided with historical and cost information for each of the systems, where for instance, failure data includes opportunity costs which makes repair more expensive than proactive condition monitoring or preventive replacement costs. At the beginning of a round, teams decide on a maintenance tactic – either doing nothing, purchasing condition monitoring information from the facilitator, or deciding on preventive replacement. Following each team's decisions and recording of the associated costs, the facilitator reveals for each team which of their production line systems are still operational and which have incurred a failure. In the case of failure, repair and opportunity costs are recorded, before another round of decisions is made by the teams.

As part of the programme, the game is played first, before students are exposed to any decision-making processes related to maintenance tactic selection. Therefore, the purpose and main learning objective is to introduce a fictional production environment providing the students the opportunity to experience the results and consequent cost implications associated with the choice of their maintenance decisions. Ultimately this experience creates awareness about the fundamental considerations forming part of maintenance strategy decision making. The main learning outcomes of the game are:

- Introduction to different types of maintenance tactics.
- Importance of analyzing historical data to identify failure characteristics.
- Cost implications associated with maintenance tactic selection.
- Differences between failure behaviour of systems.
- Necessity of applying the correct tactic to the corresponding failure behaviour.

High demand is placed on the facilitator of the game, especially in the case where the content is new to participants. Initial briefing before the start and final debriefing of the results after the game are of utmost importance. Further, the correct recording of the results during each round and the tracking of each team's condition monitoring and replacement decisions are essential to ensure the credibility of the results. The facilitator therefore is required to have a profound understanding of the learning content and to provide credibility by having the game under control throughout the duration of the gameplay.

2.2. Classroom Training

The classroom training phase of the programme consists of seven modules (Fig. 2) which are based on Reliability Centered Maintenance principles from the SAE JA1011 standard and the seminal works by Moubray and Nolan and Heap [12, 13, 14]. The development of the modules was based on the Analysis, Design, Development, Implementation and Evaluation (ADDIE) model and the content has been previously piloted with groups of under- and postgraduate student groups [15]. The modules' content provides for learning on the knowledge, comprehension and application levels of Bloom's taxonomy [16]. Each module fundamentally covers the subprocesses to follow for establishing maintenance plans. During the training, reference to the failure behavior and tactics of the systems in the game, should be used to facilitate learning retention. Further, each module begins with a set of open-ended leading questions, which provides the students the opportunity to participate and aligning their attention on the module content to follow. Further, group and individual exercises are included for establishing comprehension and application skills. Finally, the students are provided the opportunity to develop skills on the *analyze*, *synthesis* and *evaluation* levels of Bloom's taxonomy in a learning factory environment by developing maintenance plans for three of the factory's advanced manufacturing machines.

2.3. Maintenance Plan Development in the Stellenbosch Learning Factory

The Stellenbosch Learning Factory (SLF) was initiated in 2015 in collaboration with the European Network of Innovative Learning Factories (NIL) for supporting undergraduate teaching in production system design and management methods. At the same time the Stellenbosch Technology Centre – Laboratory for Advanced Manufacturing (STC-LAM) was established to conduct research and provide services and training to industry in advanced manufacturing and tooling engineering. The STC-LAM is integrated into the SLF, providing facilities for action-based learning in an industrial environment, while still retaining its commercial services business to industry. The knowledge in maintenance plan development that students obtained during the game and training activities was practically applied at the STC-LAM.

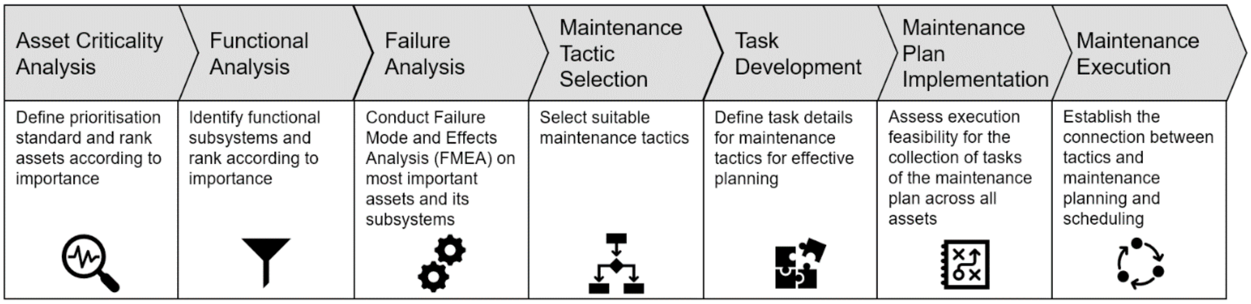

Fig. 2. Modules of the maintenance plan development training.

Three groups of four students were tasked to develop a maintenance plan for three different advanced manufacturing machines at the STC-LAM, namely a *Concept Laser M2 Cusing Machine*, a *GF AgieCharmilles CA20 wire electrical discharge machine*, and a *DMG Mori DMU65 monoBlock milling machine*. The brief also required that the plan should include a conceptual reality technology application for one of the high impact maintenance tasks in the plan. Students had access to interview operators and STC-LAM personnel, to limited historical data, and to service manuals of the machines. The groups had three days to develop the maintenance plan, show the concept application, and had to present their final plan and recommendation at a concluding session on the third day.

It was evident from the final plans and presentation of results that the programme did achieve its learning objectives. The first challenge that all the groups had to overcome was to determine a critical subsystem for development purposes, since it was not feasible to develop maintenance plans for all of the machine subsystems within the given time frame. This was no trivial task. The first group was allocated the *Concept Laser M2 Cusing Machine* and they found that no documented maintenance history or error logs exist for the machine. They developed a criticality analysis for identifying the most important subsystems of the machine (Fig. 3). With machine operators they identified four consequences in the case of machine failure. Consequences were compared pairwise to determine the final weights of each consequence. The severity for each consequence and the probability of failure (P) was rated on a high (3), medium, (2) low (1) scale with the assistance of operators. The weighted average consequence (C) was multiplied with the probability of failure (P) to calculate the final subsystem criticality (R). Based on the results the machine's technology unit and gas supply were identified as the most critical subsystems of the machine. Their development led to a plan consisting of a combination of usage-based, condition-based and corrective maintenance tactics. Usage-based tasks were based on build and calendar-based times, while sensory condition-based inspections were suggested. It was further identified that there is high occurrence of machine downtime, due to insufficient argon gas supply. In addition to the maintenance plan, organizational process improvements were suggested to address stock-outs of the gas supply. The group's conceptual reality technology application featured augmented reality of the machine subsystems in combination with the digitalized tasks from their maintenance plan.

The second group was allocated a *GF AgieCharmilles CA20 wire electrical discharge machine*, which had limited historical data available in the form of an error logfile. Through the analysis of the logfile and a criticality analysis they identified the wire and filter systems as the most critical. A combination of usage- and condition-based tasks with costing requirements were developed into their maintenance plan. The third group was assigned a *DMG Mori DMU65 monoBlock milling machine*. Like the first group, no maintenance data was available, however through interviews and criticality analysis they arrived at the coolant system as the most important. Their plan included a combination of condition-based and corrective tactics, but there was a specific focus on how to identify and rectify contaminated coolant. A novelty in their approach was a cost comparison between corrective maintenance as well as digital and manually measurable condition-based techniques and a motivation in favour of digitally monitoring the coolant pH level to detect contamination.

Subsystem Description	Consequences									x	Probability of Failure (P)	=	Subsystem Criticality (R)
	Maintenance Impact	+	Production Impact	+	Environmental Impact	+	Health and Safety Impact	=	Overall Consequence Rating (C)				
	Weight: 12.5%		Weight: 20.8%		Weight: 33.3%		Weight: 33.3%						
Technology unit	3		3		2		1		2.0		2		4.0
Gas supply	2		3		1		2		1.9		2		3.7
Processing station	1		2		2		2		1.9		1		1.9
Extraction and filter system	2		1		2		2		1.8		1		1.8
Handling station	1		1		2		2		1.7		1		1.7
Laser system	3		3		1		1		1.7		1		1.7
Switch cabinet	2		2		1		1		1.3		1		1.3
Control panel	1		2		1		1		1.2		1		1.2

Fig. 3. Example of the first group's criticality analysis that was developed during the four-day programme.

3. Evaluation and outlook

The training programme was carried out during September 2019 at the SLF, with engineering, technology and informatics students from the ESB Business School, Hochschule Reutlingen, in Germany. The students were able to comprehend the processes involved in maintenance plan development, develop and conduct a criticality analysis for identifying the most critical subsystems of an industrial machine, develop a maintenance plan, and develop a concept reality technology application. With reference to the results achieved by the three groups and according to the lecturers, research assistants, those involved and who observed the training, the programme effectively demonstrates how learning factories can be utilized to teach management related concepts in an interdisciplinary team context.

Future steps envisaged, are the inclusion of the programme into existing undergraduate modules in maintenance management. The installation of data loggers on the STC-LAM's machines is also foreseen and will allow the collection of operational and failure data, which will allow for expanding the programme to include topics on reliability engineering and machine health and prognostics.

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