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# Maintenance 4.0 to fulfil the demands of Industry 4.0 and Factory oftheFuture

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**ABSTRACT:** In today's high market competition, industries attempt adapt new technologies retain their market share. With technology advancement in factories, maintenance methods are developed to suit the new manufacturers' demands. Now, with the Industry 4.0, new maintenance techniques have to be developed to fulfill the new demands which we refer to as Maintenance 4.0. Each currently used maintenance technique has its own advantages and disadvantages. Until now it is unclear if these techniques are suitable for Industry 4.0. This study shows how to identify the maintenance technique that is the most suitable to be further developed for Industry 4.0. In this paper, the tasks and features of Maintenance 4.0 are identified, and the suitability of the most popular maintenance techniques is examined with respect to Industry 4.0 demands. This is done by using Multiple Attribute Decision Making combined with the Simple Additive Weight. The results show that Total Quality Maintenance(TQMain) and then Condition Based Maintenance(CBM) are the highest ranked among the examined maintenance techniques, and therefore it is concluded that these maintenance techniques could be used as a based to develop Maintenance 4.0.

**Keywords-** Maintenance 4.0, maintenance for Industry 4.0, maintenance for smart factories, maintenance techniques comparisons.

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## I. INTRODUCTION: STATE-OF- ART AND MOTIVATIONS

In today's high market competition, industries attempt to adapt new technologies to fulfill customer needs and retain their market share. Industry has experienced threerevolutionsduring the past 200 years, driven by mechanization, electrical power and the electronics & Information technology(Kagermann et al. 2013; Drath & Horch 2014; Deloitte 2015).With the recent technology advance in Cyber Physical Systems (CPS), the Internet of Things (IoT) and the internet of Services (IoS), Industry 4.0 has been announced as the 4th industrial revolution. Thisrevolution is driven by the need of shorter time to market, customized mass production and increased efficiency(Helmrich 2015).Industry 4.0 is characterized by the vertical integration of systems at different hierarchical levels of the value creation chain and the business process, as well as, by the horizontal integration of several value networks within and across the factory. This is done through end-to-end engineering across the entire value chain(Kagermann et al. 2013; Hermann et al. 2016; Stock & Seliger 2016).Hermann et al. (2016) defined Industry 4.0 as,a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT and CPS communicate and cooperate with each other and humans in real time. Via the IoS, both internal and cross- organizational services are offered and utilized by participants of the value chain. (p.11)

Itisprovenbymanyresearchersthatmaintenance plays an important role to enhance production performance (Waeyenbergh & Pintelon 2002; Al-Najjar & Alsyouf 2003; Al-Najjar 2007). With technology advancement in factories andincreased complexity n the manufacturing machines, maintenance methodsaredeveloped in order to suit thenewmanufacturers' demands.Furthermore, several commercial software solutions evolved to improve the production performance and its profitability. However, the profitability of maintenance and assessment of its pay-back is not common among maintenance commercial software. Nevertheless, it is still considered in some of the maintenance software systems such as Smart eMDSS (Smart eMaintenance Decision Support System) uses deterministic and statistical approaches) from E-maintenance Sweden ABand EXAKT (uses the probabilistic approach) from OMDEC Inc.

Now, with the Industry 4.0,new maintenance paradigm,innovative methods, tools and systems have to be developed to fulfill the new demands whichisreferredto as Maintenance 4.0.Industry 4.0 is a relatively new technology (Deloitte 2015; Qin et al. 2016) and therefore a little research is performed in the area of its maintenance. There is a lack of studies that examine the suitability of the current used maintenance techniques for Industry 4.0. Therefore, the problem addressed in this study is:How to identifythe maintenance technique that isthe most suitable to be developed for meeting the demands stated by factory of the future implementing the concept of Industry 4.0? The need of this study arises from the fact that each maintenance technique has its own features, advantages and disadvantages. However, until now it is unclear how these techniques will perform in Industry 4.0environment. This study aims to examinethe most popular maintenance techniques with respect to the maintenance features demanded by the maintenance suitable for Industry 4.0. It is necessary to give an insight to maintenance professionals that helps indeveloping proper maintenance strategy that suits Industry 4.0.

Next describes the methodology to achieve the aims of this paper. Section 3 and 4 describe and classify the most popular maintenance techniques. Then, section 5, reveals the industry demands, potential maintenance tasks and the features of the maintenance technique/system that is suitable for Industry 4.0 (i.e. Maintenance 4.0). Section 6 explains the tools to examine the suitability of the selected maintenance techniques with respect features demanded by Maintenance 4.0. Section 7 examines the maintenance techniques using the features of Maintenance 4.0, which is followed by results and discussions in section 8. Finally, conclusions will be drawn in section 9.

## II. METHODOLOGY

To achieve the objective of this study, the suitability of the most popular maintenance techniques will be explored, discussed and examined with respect to the maintenance features demanded by Industry 4.0. The examination of the maintenance techniques will be done by using Multiple Attribute Decision Making (MADM) combined with the Simple Additive Weight (SAW) in order to see the collective performance. This combination is used by several researchers (Al-Najjar & Alsyouf 2003; Chan & Prakash 2012) to examine and rank maintenance techniques. It is used in this study for its simplicity and suitability for the study's purpose.

To examine and rank the suitability of the most popular maintenance techniques, we will:1) Identify possible tasks that are needed to be handled by a maintenance technique in the factory of the future and when Industry 4.0 is implemented. 2) Identify the features that such a maintenance technique/system should acquire to be able to conduct the tasks in 1 above.3) Examine and rank the suitability of the most popular maintenance techniques to Industry 4.0.

## III. MAINTENANCE TECHNIQUES

In the recent decades the recognition of maintenance as an effective part of the company competitiveness and existence has grown(Waeyenbergh & Pintelon 2002; Al-Najjar & Alsyouf 2003; Maletic et al. 2014).The most relevant and widely implemented maintenance techniques that are considered in this paper are: Failure Based Maintenance/Breakdown maintenance (FBM), Preventive Maintenance (PM), Condition Based Maintenance (CBM), Total Productive Maintenance (TPM) and Total Quality Maintenance (TQMain).

Failure Based Maintenance (FBM)strategy (it is also called breakdown or corrective maintenance) is a reactive maintenance. It is doneat failure torestore a machine to a working condition as before. It is based on the concept: wait until the breakdown then fix it as soon as possible to as good as before(Al-Najjar 1997; Pintelon & Parodi-herz 2008). In FBM the failure may occur during inconvenient time, therefore long downtime and negative consequences should be expected. In order to reduce downtime and increase the availability, additional spare, redundancy equipment, labor and spare parts are often needed, which are very costly. However, even that the FBMis in some cases,consideredcost effective technique especially when no other maintenance technique is applicable(Waeyenbergh & Pintelon 2002; Chan & Prakash 2012).

The fundamental concept of Preventive Maintenance (PM) strategy is to reduce the probability of failures by replacing parts at intervals predefined by the manufacturer, end-user and/or experts for example at time T, regardless of the system condition(Waeyenbergh & Pintelon 2002; Pintelon & Parodi-herz 2008; Prajapati et al. 2012).T represents calendar time, age or real running time. So component will be replaced at failure or at fixed time T whichever comes first.PM is used in different industries when it is assumed to be cheaper than FBM and easier to plan as it is relied on scheduled time. However, there might be always a probability of over-maintenance and losing unnecessary production time, or early and unnecessary maintenance actions, e.g. replacements, with additional losses of resources.

StrategyofCondition Based Maintenance(CBM)concept advocates thatactionsare planned only if there are indications/symptoms assessed using relevant condition monitoring (CM) parameters. The CMparameters could be temperature, pressure, vibration, etc. CBM is a technique that utilizes the acquired information by CM parameters in order to act just before a failure when the deviations reach a predetermined level (Al-Najjar 1997; Chan & Prakash 2012; Rastegari 2015). CBM can be used as proactive when enough information of high quality is available and predictive otherwise.

Total Productive Maintenance (TPM) is a philosophy that involves all the employees in an organization, from the top management to the floor shop. It advocates operator maintenance that consists of well-defined activities, such as the daily maintenance work to reduce downtime, material waste, improve quality and overall equipment effectiveness. Simple problems are rectified by the operator whereas complicated ones are forwarded to the maintenance staff (Al-Najjar & Ingwald 2002; Chan & Prakash 2012). The assumed results are claimed to be earned in the long-term which make it difficult to be accepted by the higher management as they tend to focus on the early results (Al-Najjar 1997). The Overall Equipment Effectiveness OEE is advocated by TPM to measure the equipment effectiveness technically. However, there is no methodology presented in the framework for data gathering, management, processing and handling (analysis, diagnosis, prognosis and prediction) in order to be able developing as much as possible of a production holistic view. This increases the difficulties in the follow up of the technical and economical results of the improvement activities. TPM provides some tools and methods to investigate and analyze technical problems e.g. Phenomenon-Mechanism Analysis. However, originally in TPM there is no special technique for effective utilization of CM technologies and data. It is left to the operator's experience to decide what and how to measure (Al-Najjar & Ingwald 2002). The main goal of TPM is to maximize the equipment effectiveness through reducing the six big losses in order to meet the JIT (Just-In-Time) manufacturing tough needs, i.e. improve overall equipment effectiveness.

Total Quality Maintenance (TQMain)is a philosophy that was developed to detect deviations in the condition and performance of the essential elementsinvolved in a production process(e.g. operation, quality control system, personal competence, methods, raw material quality and environment) and not only the machine, in order to make a cost-effective decision before the deviation/damage impacts the production performance. It advocates integration of relevant databases in order to detect damage causes, damage initiation and deviations and followupdamage/deviation development in, e.g. production cost, quality, production, machine condition at an early stage.

TQMain uses the PDCA (Plan-Do-Check-Act) cycle to continuously improve the process elements. But, its action is applied earlier than the failure occurrence because it is based on detecting changes in the machine/process condition and performance using data from relevant CM technologies(Al-Najjar 1997; Sherwin 2000; Chan & Prakash 2012). The performance indicators used in the TQMain is the Overall Process effectiveness (OPE). It is a modification of OEE covering whole process and not only the equipment (Sherwin 2000; Al-Najjar & Ingwald 2002). The measure of maintenance Cost Effectiveness (Ce) advocated by TQMain is the proportion of the difference between the cost of producing high quality item before and after maintenance improvement or policy changes (Bb) and (Ba) respectively, to (Bb), i.e.(Ce) = 1-Ba/ Bb.

TQMain aims to maintain the quality of the elements involved in a production processbasedon using a common database of real-time data. Information provided by TQMainis easily accessible by all stakeholders at different managerial and technical levels fulfilling the demand of vertical and horizontal integration of an organization. This helps to maintain the quality of the production process. It emphasizes the integration of the data from different disciplines such as production, maintenance, economy and quality.

## IV. MAINTENANCE TECHNIQUES CLASSIFICATIONS

In Industry 4.0, the entire value chain will be integrated and share digitalized information to cooperate and execute tasks. This will generate an enormous data mass from different elements over the network. An environment of gigantic data from different systems could provide tremendous value to achieve more accurate;detectionofproblemsand theirroot-causes as well asdiagnosis and prediction of damage development, assessment of effects, and reliableplanningof maintenance activities, which at the end avoids unplanned downtime (Lee et al. 2015). Hence, data coverage,quality and its utilization are important factors for maintenance in Industry 4.0.However, dealing with an environment of such huge data and developing tools to transform data into information could be challenging(Lee et al. 2014; Wabner 2018).

Based on data coverage, quality, and the level ofutilization thatdescribes the condition of a machine and component, maintenance techniques are classified as shown below:

Class 1; maintenance techniques able to utilize relevant real-time data from different relevant working areas, e.g. production, economic, quality, operation andeconomy toachieve more accurate:

- Diagnosis, prognosis, prediction and recommendations
- Assessment of the technical and economic impact of maintenance on company business.
- Identification of root causes and reliable opportunity for elimination.
- Cost effective maintenance decisions.
- Holistic view of a production station, line and consequently production process.
- Follow up of deteriorationdevelopment to select the most profitable maintenance time.

An example of Class 1is TQMain.

Class 2; maintenance techniques able to utilizeonlytechnical data and information related to the producing machine components in question. The data and information that are gathered using, for example FMEA, FMECA, FTA, CM techniques, statistical tools for describing and modeling time to failure behavior. The accuracy of the maintenance developed based on only this type of data varies depending on the availability of thetechnicaldata, e.g. CM-data, failure data, andthe methods/modelsused(Al-Najjar 2012). However, as all of the data gathered in this class are technical, therefore the outcomes that are not technical-related are not expected. Examples of the maintenance techniques under this category are TPM, CBM and PM

Class 3; maintenance techniques that are not using any data, for example FBM, i.e. nothing is done before a failure is occurred.

## V. MAINTENANCE 4.0

### 5.1 Industry 4.0 and its demands on advanced maintenance

Several advantages are expected from Industry 4.0. For example, the technologies of CPS, IoT,IoS and the networking allow the integration of data/information from different working areas/disciplines (e.g., sales, quality, production, production cost and price, risk management, environment, etc.) which facilitates the coordination among them and draw synergies. In addition, the utilization of the available data by intelligent systems provides theability to utilize the resources efficiently as well as the ability tocustomize evenin small production quantities, and yet remains profitable. The different data sources in Industry 4.0 will make factories able to predict and respond rapidly to changes, e.g. in production, delivery, failures, etc. and able to compensate temporary shortages. Theflexibility in Industry 4.0 will result in a better working condition for the workers and better life-work balance.InIndustry 4.0, new ways of services will be created and therefore, a new business models and opportunities will appear(Kagermann et al. 2013). In a conclusion, Industry 4.0 will result in:

- High customization ability to meet individual customer requirements
- Continuous improvement and optimized decision making
- Productivity and resources efficiency
- Work-Life Balance
- New business opportunities

The objectives of Industry 4.0 are driven by the need of shorter time to market, customized mass production and increased efficiency(Helmrich 2015).In order to sustain the successfulness of Industry 4.0; Maintenance 4.0, i.e. maintenance meeting Industry 4.0 demands, should have the following objectives(Al-Najjar 2015):

- Rapid responsiveness to meet the dynamic and rapid changes in the operating conditions and surroundings
- Maintain quality of machines at low cost, which makes maintenance and production processes more profitable, and
- Achieve high quality performance of producing machines

### 5.2 Maintenance 4.0; Tasks and Features

In general, maintenance activities are responsible of reducing the probability of failure and unplanned stoppages. This minimizes the impact of failure consequences on company performance through maintaining the continuity of a production process and product quality at a predetermined rate, andreducingproduction cost. In addition, maintenance activities have a very high influence on company's internal effectiveness, due to its internal interaction and impact on different important working areas, such as production cost, energy consumption, safety, delivery on time and working environment(Al-Najjar 2007; Maletic et al. 2014). Therefore, a reliable and efficient maintenance not only increases the profitability, but it also improves the overall performance of the company (Waeyenbergh & Pintelon 2002). Therefore, reliable and effective maintenance methods are an important factor for Industry 4.0 to succeed.

Several researchers discussed maintenance tasks for different intelligent maintenance systems(Labib 2006; Lee et al. 2011).However, in the context of thispaper, the below are themaintenance tasksnecessary to meet the needs stated by Industry 4.0:

- Abnormalities detection:It should be able to detect abnormalities in the condition of assets and production process performance in addition to abnormalities in energy consumption, working environment and operating conditions (e.g. speed, load and temperature).
- Diagnosis, prognosis and prediction: to identify and localize the causes and damages,estimate damage severity and follow up its development, predict its future development and alsoassess the assetremaininglife.
- Maintenance scheduling: tosuggest the most profitable time for maintenance associated with the resources and competence required. Also, it shouldautomatically generate the maintenance action schedule to synchronize maintenance actions with production planning.
- Maintenance execution: to conduct specific actions automatically to achieve self-healing assets. For those problems where automatic actions are still impossible from technological point of view, the maintenance system should automatically provide report surveying the condition of the machines and work orders/recommendations to conduct actions for the components suffering of severe damage development.
- Short time to repair: It should able to communicate with Augmented Reality (AR) system to provide maintenance engineers the assistant required for conducting actions properly, reliably and in a short time.
- Self-learning: to learn from past data (failures and condition-based actions)to continuously improve and optimize maintenance decisions and actions.
- Data presentation: to present relevant and real-time information, and results from analysis, diagnosis,predictions,maintenance work progress, completed tasks and pending tasks.

In order for Maintenance 4.0to be able to perform the above mentioned tasks in a factory of future implementing concepts of Industry 4.0, it should possess the following features:

1. Real-time communication: Ability to easily communicate with data gathering platform, import and export data with relevant working areas and be user friendly for different stakeholders and at different levels.
2. Decentralization: Capable to be suited for decentralized production as it is advocated strongly by Industry 4.0.
3. Damage detection: Able to detect damage initiation at an early stage and follow up its development in order to avoid failures and unplanned stoppages.
4. Automation: Able to be automated, i.e. to automate all maintenance steps/activities, to easily fit with digitalized and automated production process
5. Real time presentation: Provide accessibility of real-time and relevant data in an easy way to enable production process an easy re-configuration and re-planning of production with respect to the condition of the manufacturing machines.
6. Intelligence: Intelligentand be improved continuously toenhance the decisions' accuracy basing on its ability in extractinginformation from data andbe self-learned.
7. Cost effective:To be sustainable maintenance technique, cost effectiveness should be considered.
8. Scalable:To meet the dynamic operation and technology growing demands, it should be able to be integrated with different new modules, adds-on and software. For example, a fleet could require a new machine technology and the machine ~~also~~ could require a new CM technique, a new sensors type,and new analysis software. Maintenance 4.0 should be flexible to include and exclude modules and activities.
9. Monitoring production process: Able to monitor additional element in addition to the machine, such as working environment, energy consumption and operating condition.
10. Accurate decisions: Able to provide more accurate recommendations and decisions. It is economically necessary to utilize as long as possible a component/equipment life length without increasing the risk of failure~~s~~.
11. Digitalized: Able to be digitalized in order to ease maintenance automation and integration with digitalized and automated production.
12. Production KPIs consideration: Ability of considering real-time performance measurements (production and maintenance process KPIs). The maintenance technique/system should be able tomap production performance indicators in order to identify and assess the maintenance impact and improve it.

## VI. TOOLS TO DISTINGUISH MAINTENANCE TECHNIQUE SUITABILITY FOR DEVELOPMENT OF MAINTENANCE 4.0

In this paper, thesuitability of the discussed maintenance techniques in section3 is examined and ranked with respect to their suitability to be developed for Maintenance 4.0. The features introduced in section 5.2 are used as examination criteria. Multi Attribute Decision Making (MADM) issuedas it is suitable for this case (since the purpose is to evaluate alternatives over criteria), as well asit is a well-known tool in the decision making (Triantaphyllou & Shu 1998).There are several techniques for the MADM such as Simple Additive Weighting (SAW), Weighted Product Method (WPM), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), etc. In this study, SAW is selected due to its simplicity as well as it is often used as benchmarking method to compare results from other MADM methods(Janic & Reggiani 2002).

Next sections will explain the used tools to distinguish maintenance technique suitability for development of Maintenance 4.0.

### 6.1 Multi Attribute Decision Making (MADM)

Multi Attribute Decision Making (MADM) is considered to be one of the most known branch of decision making (Triantaphyllou & Shu 1998). In general, the steps of the MADM are: forming the criteriaC and assessing their weight Wby experts/decision-makers, thenthe possible alternativesA are determined.

In the decision matrix, the experts/decision-makers score the value $V_{mn}$thatdescribes the alternative$A_m$(m = 1,2,3 ..i)with respect to the criterion$C_n$ (n = 1,2,3 .. j )and its weight $W_n$. Then applying a MADM method, in order to get collective evaluation and ordering of each alternative(Al-Najjar & Alsyouf 2004; Chan & Prakash 2012). Table 1 shows the decision matrix.

**Table 1. Decision matrix**

| | Criteria | $C_1$ | ... $C_n$ ... | | $C_j$ |
|---|---|---|---|---|---|
| | Weights | $W_1$ | ...$W_n$ | | $W_j$ |
| Alternatives | $A_1$ | $V_{11}$ | $V_{1n}$ | .... | $V_{1j}$ |
| | . | . | . | | . |
| | . | . | . | | . |
| | $A_m$ | $V_{m1}$ | $V_{mn}$ | .... | $V_{mj}$ |
| | . | . | . | | . |
| | . | . | . | | . |
| | | . | . | | . |
| | $A_i$ | $V_{i1}$ | $V_{in}$ | .... | $V_{ij}$ |

### 6.2 Simple Additive Weighting (SAW)

In a decision matrix where A is the alternatives and Cis the criteria withW assigned weights, the best alternatives is the one with the highest score(Triantaphyllou & Shu 1998). This can be modeled as follow:

$S_b = \max S_m = \sum_{n=1}^{c} WnVmn for m = 1,2,3, \ldots j$ (1)

$S_b$ is the best alternative

$S_m$ is the overall score of the m-alternative

C is the number of the decision criteria

V is the value of the m-th alternative with the respect to n-th criterion

$W_n$ is the weight of the n-th criterion

## VII. RANKING MAINTENANCE TECHNIQUE WITH RESPECT TO THE FEATURES OF MAINTENANCE 4.0

Fivepopularmaintenancetechniques (alternatives)and 12features (criteria)are used. Thefive maintenancetechniques and the 12 features that are described in Section 1.1 and 2.2 respectively. For simplicity, all of the features/criteria areassumed to be equally valuable and therefore no weights have been assigned. The MADM matrix then was constructed as shown in Table 2.

Each alternative $A_m$ assigned a value $V_{mn}$against criterion $C_n$.It was not possible to obtain precise quantified values for $V_{mn}$. In this case, the MADM matrixrequires information that experts/decision-makers assign. As the human judgments often are ambiguous, it will be very difficult to assess the value $V_{mn}$ in a precise quantitative form. Thus using the linguistic approach is more realistic(Herrera & Herrera-Viedma 2000; Chan & Prakash 2012). Therefore, linguistic variables are used to assign the value $V_{mn}$. The linguistic values are: “high”, “middle”, “low” and “none”, the corresponding numerical values are: 9, 6, 3 and 0 respectively. The assessment of the values $V_{mn}$ was done basing on the author Al-Najjar’s long experience in the industry and maintenancetechnology, table 2, shows the linguistic value of the matrix. These valuesare related to the working domain of rotating machines, and different applications may possess different values.

As this is a human judgment, there could be some degree of uncertainty and subjectivity in the assigned values. Therefore, in the discussions section below, the authors chose to provide arguments to reveal and motivate the reasons behind assigning a particular valuein Table 2 to each alternative against each criterion.

**Table 2: Linguistic estimation of the suitability of the most popular maintenance techniques with respect to the features of Maintenance 4.0**

| | | Maintenance techniques (alternatives) | | | | |
|---|---|---|---|---|---|---|
| No. | Features (criteria; abilities of Maintenance 4.0) | FBM | PM | CBM | TQMain | TPM |
| 1 | Real-time communication | none | Low | middle | high | middle |
| 2 | Decentralization | high | high | high | high | high |
| 3 | Damage detection | none | none | middle | high | none |
| 4 | Automation | none | Low | middle | middle | low |
| 5 | Real-time data presentation | none | none | low | high | none |
| 6 | Intelligence | none | none | middle | high | none |
| 7 | Cost effective | low | middle | high | high | middle |
| 8 | Scalable | high | Low | middle | high | low |
| 9 | Monitoring production process | none | none | low | high | none |
| 10 | Accurate decisions | none | Low | high | high | middle |
| 11 | Digitalized | low | middle | high | high | middle |
| 12 | Production KPIs consideration | none | Low | low | high | low |

### 7.1 Discussion of the linguistic values and numerical analysis

The suitabilityof every examined maintenancetechnique in Table 2, is assessed based on its actual definition and successful applications. The suitability of combined techniques, e.g. CM associated with TPM, is out of the scope of this study and is a subject for a future study.

In Table 2, the criterion "Real time communication", FBMcannotcommunicatewith other systems because it is only relying on action after failure. PM have low level of communication with other working areas/systems/activities, because they have usually a static planning of regular maintenance actions while production and operation are in dynamic changes. This makes active interactions between these maintenance techniques and other systems low. Using TPM-circles for never ending improvement provides a special space for communication with, e.g. production and quality working areas. This is why it acquires middle level. In many cases, CBM can utilize real time operational data, such as production speed and loading, thus it has higher level of dynamic interactivity and integration with the operational process, so the value "middle" is given. TQMain has high level of communication, as it emphasizes using real-time relevant information from other working areas utilizing common database to achieve cost-effective decisions and planning of maintenance activities, so it possessed the value "high".

The values given to the criterion "Decentralization" highlight the ability of the maintenance technique to execute maintenance tasks in a decentralized production. In many cases, the decentralized production is associated with an inconsistent production process(Garrehy 2015), as the management is left to each unit manager. This will vary the production process and hence will vary the deterioration process, failures types and their quantity among the machines. However, this will not prevent the maintenance techniques from performing their tasks specially if they are applied decentrally as well. Therefore, all of the maintenance techniques are set to be "high".

Data from CM technologies are effectively utilized by CBM and TQMain, but at different level of accuracy. TQMain is considered superior compared with CBM, thanks to the additional data supporting the description of the machines condition. TQMain acquires data from other relevant working areas, for example production, quality, economy, working environment, and also it has its own tools for reducing uncertainty in the measured data. For example, Common database is advocated by TQMainto, compare information, and Cumulative Sum Chart (CUSUM) chart for reducing randomness in the picked up vibration measurements. This suggests that the ability of TQMain in detecting initiation of damage is "high", while it is "middle" in CBM due to the randomness in the measurements. Other maintenance techniques, such as PM and TPM may use data from CM technologies. However, in many cases, CM data is used just for statistical modelling of the condition data to estimate the time to failure without giving a reliable attention to the dynamic changes of the damage development rate during operation. The latter is important to follow-up deterioration process and choose the most suitable time for maintenance action in order to enhance maintenance decision accuracy.Observe thatFBM acquires no data and consequentlyno ability for detecting damage initiation.

Generally, the practice of FBM in the industry does not involve automation, while in many cases, TPM and PM has some level of it. Applying, PM, maintenance planning system triggers work orders automatically at the time of the planned preventive maintenance actions. TQMain and CBM are much more prepared for digitalized data management and communication with other systems; therefore, they are highly prepared for automation. For example, CBM can be used to trigger different physical actions, such as stopping producing machine when the CM-level, e.g. vibration level, exceeds a predetermined level. While in TQMain, the same machine can also be triggered off basing on additional parameters than vibration, for example if the number of defective items or a production cost exceeds a predetermined level and a work order is automatically sent to the maintenance engineer.

For the criterion “Real-time data presentation”, as discussed previously, only TQMain has this feature. In CBM only some operational data e.g. Loadand speed of machine, could be associated in the monitoring dashboards. This motivates to set all of the techniques to be “none” except TQMain and CBM to be “high” and “low” respectively.

In order for Maintenance 4.0 to be intelligent in supporting decisions, real time,relevant,wide coverage and high quality data is essential in addition topossessing cognitive algorithms. There are several studies forthe application of this criterion in CBM and TQMain(Durbhaka & Selvaraj 2016; Maliha Salem et al. 2010; Gerdes 2013; Cheng et al. 2008).TQMain has the accessibility to these required data as well as it uses Smart eMDSS with built-in intelligence and self-learning feature. CBM provide less data as described previously and there is algorithms and techniques to utilize these data e.g. Machine Learning(Coraddu et al. 2016). For these reasons, TQMain is given the value “high”, CBM is “middle”. FBM, PM, and TPM do not provide sufficient data nor there are intelligent algorithms with self-learning feature.

In general, CBM and TQMain often are more cost effective when they are applied properly, as they detect damages initiation before they impact the production(Maletic et al. 2014; Baoqiang et al. 2014).Therefore, they both are given the value “high”. PM, and TPM have tools and methods to reduce the probability of production stoppages. However, they are not always early enough. While FBM, has no meansto reduce probability of failure and reduce stoppages and consequently becomes cost-effective. This motivates to set PM and TPM to be “middle” and FBM to be “low”.

For the scalability, in general, most of the maintenance techniques have high ability to be applied on additional similar machines and components. But, for dissimilar machines and components, i.e.of different design, functions, operating conditions or technology, scalability willnot be equally easy. In the contrary, it may demand special efforts, configuration and planning as they may have different problems, deterioration processes and behavioral model. In the discussion of this ability/criterion, we still consider the degree of maintenance technique scalability and accuracy simultaneously. Observe that the repair actions belonging to any of these maintenance techniques are equivalent to those demanded by FBM. In general, scalability of PM and TPM demands reliable analysis and understanding the machine structure, functions and behavior of the time to failure in order to design a suitable maintenance plan and actions. In the CBM and TQMain the biggest efforts will be mainly when selecting and implementing the suitable CM first time. Basing on the fact that, this does not require technical analyses only, -which could be complex in many cases- but also requires economic analyses to select the suitable and profitable CM technique. Therefore, it is assumed that the effort in this case is the highest in the first implementation time. But, if applying CM, e.g. using vibration, temperature, CBM or TQMain for monitoring and maintaining rotating machines/components, its scalability will be increased much higher (than the first implementation). It does not demand more than reconfiguration of the CM-system i.e. identify machine and components IDs and define warning levels for the components in the new machines. In many cases, it is also possible to do this configuration automatically as the case, for example in Smart eMDSS. This is why it has high scalability when it concerns components of the same category, for example rolling elements bearings, pulleys, gears, shafts, does not matter the machine type. In TQMain, as long as many relevant information parameters are already considered, therefore its scalability can be higher than CBM, because it is designed to easily include and exclude different CM parameters. What is really needed in this case is the reconfiguration of the system as described above in CM. For these reasons, the highest value for scalability is given to FBM and TQMain. The value “middle” is given for CBM, while “low” is given to PM and TPM.

TQMain emphasizes using common database and monitoring the essential elements involved in a production process. Thus, it is given the value “high” for the criterion “Able to monitor additional element”. CBM possessed lesser value “low”, as in practice, it can be used to identify whether external disturbing factors, such as load, ambient/operating temperature, imported shock and vibration, are influencing, e.g. vibration signals The rest of the techniques, in general, have no possibility to monitor the condition/quality of otherproduction elements, so the value “none” isgiven to them.

The previous discussions suggest FBM to be "none" in the criteria "Accurate decisions" when other maintenance techniques can be implemented for the same machines to avoid failures. PM is based on historical failure data to make the decision, which is not always easy to find due to lack of such data because of the condition-based replacements are done to avoid failures. Thus, it is given the value "low". TPM have besides the past data acquired by PM, knowledge and experience accumulated when conducting analysis for improving machine performance and availability (in the case of TPM working groups) using, for example Failure Mode Analysis (FMEA), Failure Mode and Criticality Analysis (FMEACA) and Fault Tree Analysis (FTA), therefore, TPMis given the value "middle".CBM can even gather real-time CM data but due to the uncertainty in measured data, for example randomness in the vibration signal, make the accuracy moderate, therefor it is also given value"middle".A more accuracy could be obtained by using real-time CM data and techniques for reducing the impact of the randomness in the CM signals associated with data gathered from other relevant working areas and thus "high" is given to TQMain.

The value "high" is given to the TQMain and CBM in the criterion "Digitalized"; as in general, most of steps of these maintenance techniques are digitalized. PM, and TPM have lower level of digitalized,e.g. the maintenance plan, triggering work orders, and thus they are given the value "middle". While the maintenance process of FBM is the lowest in the digitalization.

Maintenance activities aim to improve the production performance. Hence utilizing production KPIs -e.g. production quality, productivity and production time- and mapping them to the maintenance activities will help to identify and asses the maintenance impact. The ability of considering the production KPIs in the maintenance activities, -i.e., the criterion "To consider real-time performance measurements"- has no mean in FBM. As it has no tools and process of collecting, storing and analyzing production data. While in TPM it is possible to utilize the production KPIs to improve the maintenance performance through TPM circles. But, it is not easy to handle when it concerns PM as long as maintenance planning is static as we discussed above. However, some KPI's, for example the costs and losses related to production and maintenance are usually considered when developing and optimizing statistical models for PM. But, these models are, in general, not able to follow the costs'/losses 'dynamic changes during operation. In general, CBM does not consider real-time performance measurements. But, it gives better ability for that, as it relies on digitalized techniques and data which can easily be combined with real-time process data. TQMain gives the best possibility among the discussed maintenance techniques, since real-time, relevantand wide covered data from the production process could be used to assess the maintenance impact, performance and improvements. Therefore, FBMis given the value "none".PM,and TPM are given the value "low", CBM is "low" and TQMain is "high".

## VIII. RESULTS AND DISCUSSIONS

After the conversion from the linguistic into numerical values, SAW is then performed to obtain the global value for the performance of each alternative, see table 3, and the maintenance techniques are ranked.

Table 3 shows that the lowest scores are acquired by FBM and then PM (24) and (36) respectively, followed by TPM which scored (equally 42). CBM acquired double the score that acquired by TPM, while TQMain's score is almost three times that acquired by TPM and more than one and a halve times the score acquired by CBM. The ranking of the selected maintenance techniques can be re-considered based on the modifications done in the contents and structure of any of these maintenance technique.

We will discuss the possibility of dramatic variation inthevalues given to the featuresPM, and TPMwith more focus for the values 0 or 3. This discussion is considered instead of sensitivity analysis, because the linguistic assessmentdone is knowledge and experience based.

The possibility that any of the maintenances techniques will be able to detect damage initiation (feature number 3) except CBM and TQMain is relatively very low. If any of the other techniques applies CM technologies, then it should be re-ranked to be equivalent to it utilization of the data provided by CM.

Ability of PM and TPM in providing real-time communicating with other systems for; datagathering/data accessibility and monitoring production process condition, (features 1, 5, 9 and 12) is either 3 such as in features 1 and 12, or 0 in features 5 and 9. These values will not be easy to be improved due to the concept and structure of PM and TPM.

When using statistical models, the possibility that PM and TPM becomes more intelligent and effectively competing with CBM and TQMain is rather low.To enhance the estimation of the failure rate and expected time to failure, it is important to change or modify the probability distribution function. The latter demands very big amount of failure data of identical/similar components, which is not easy and maybe impossible to find due to condition-based replacements

Ability of PM and TPM to be more scalable is also low because the latter demandshigh level of digitization, ability to provide wide real-time data coverage of high quality and communication with other systems, which are, in general, low in these maintenance techniques. In other hand, PM, TPM and even FBM,can be more cost-effective (feature 7) than CBM and TQMain in special applications. But, it will not be probable that these maintenance techniques will be more accurate in diagnosis, prediction and decisions, i.e. feature 10. Also, additional improvement in the ability in automation (feature 4) of these techniques will not influence appreciably the final result.

Therefore, the uncertainty in the results achieved in Table 3 due to possible dramatic changes in features' values due to the methodology being used is low.

**Table 3: Numerical values of MADM**

| | | Maintenance techniques (alternatives) | | | | |
|---|---|---|---|---|---|---|
| No. | Features (criteria; abilities of maintenance techniques) | FBM | PM | CBM | TQMain | TPM |
| 1 | Real-time communication | 0 | 3 | 6 | 9 | 6 |
| 2 | Decentralization | 9 | 9 | 9 | 9 | 9 |
| 3 | Damage detection | 0 | 0 | 6 | 9 | 0 |
| 4 | Automation | 0 | 3 | 6 | 6 | 3 |
| 5 | Real-time data presentation | 0 | 0 | 3 | 9 | 0 |
| 6 | Intelligence | 0 | 0 | 6 | 9 | 0 |
| 7 | Cost effective | 3 | 6 | 9 | 9 | 6 |
| 8 | Scalable | 9 | 3 | 6 | 9 | 3 |
| 9 | Monitoringproduction process | 0 | 0 | 3 | 9 | 0 |
| 10 | Accurate decisions | 0 | 3 | 9 | 9 | 6 |
| 11 | Digitalized | 3 | 6 | 9 | 9 | 6 |
| 12 | ProductionKPIs consideration | 0 | 3 | 3 | 9 | 3 |
| | $S_m$ | 24 | 36 | 75 | 105 | 42 |

## IX. CONCLUSION

In order to develop a proper maintenance approach for Industry 4.0, it is important to describe the abilities of the selected maintenance techniques for conducting the tasks demanded by Maintenance 4.0 and their suitability for further improvement towards Maintenance 4.0. Therefore, in this paper we discussed and analyzed thesuitabilityof most popular maintenance techniques, such as FBM, PM, CBM, TPMand TQMain with respect to the features demanded by Maintenance 4.0.

This paper characterizes Maintenance 4.0 by its tasks and features, which is necessary for researchers and practitioners in maintenance to design such a technique. The major conclusionis;the most important featuresthat should be possessed by Maintenance 4.0are;Real-time communication, Decentralization, Damage detection, Automation, Real-time data presentation, Intelligence, Cost effective, Scalable, Monitoring production process, Accurate decisions, Digitalized, Production KPIs consideration. In addition, applying the results achieved will ease the task of developing a suitable Maintenance 4.0 needed to maintain the profitability expected by adopting manufacturing to Industry 4.0. Applying such sophisticated and advanced maintenance technique, i.e. Maintenance 4.0, may mean increased maintenance cost. However, does not matter how much maintenance budget will increase as long as maintenance cost per high quality product is decreasing. Future work could include developing weights for the features (criteria) and applying the results in three real industrial cases which are now included as a demonstration companies in H2020-FoF09, PreCoM (Predictive Cognitive Maintenance Decision Support System).

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