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DEVELOPING MAINTENANCE KEY PERFORMANCE INDICATORS FROM MAINTENANCE WORK ORDER DATA

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ABSTRACT

Maintenance management for manufacturing is a crucial activity for improving productivity within a facility. Within this process, maintenance work orders (MWOs) are used when tracking and solving any maintenance–related issue. The MWOs often capture the problem, the solution, at what machine the problem occurred, who solved the problem, when the problem occurred, and other information. These MWOs are manually written by maintenance technicians, entered into a database, or recorded directly into maintenance management software. Technicians often describe or record information informally — or do not record it at all — leading to inconsistencies and/or inaccuracies in the data. This paper outlines maintenance key performance indicators (KPIs), developed using MWOs, that show why consistent and accurate data collection is important for maintenance decision making. The maintenance data, or "elements," and their corresponding KPIs are derived from MWOs from real manufacturers (large manufacturers and small and medium enterprises). While all elements or KPIs are not recorded by every manufacturer, the guideline provided here outlines the elements necessary to calculate specific KPIs. These examples are developed to aid in common maintenance decisions.

INTRODUCTION

As manufacturers face increasing global competition, methods to increase productivity with less resource consumption are needed. Properly executed maintenance management procedures are one method to increase productivity through increased machine life and availability, and through reduced machine failures. These maintenance management procedures are often performed on an ad-hoc basis with little influence from previous historical data. This paper provides key performance indicators (KPIs) to guide maintenance management procedures using historical maintenance work order (MWO) data.

The standard IEC 62264-3 defines maintenance operations management as *"the collection of activities which coordinate, direct and track the functions that maintain the equipment, tools and related assets to ensure their availability for manufacturing and ensure scheduling for reactive, periodic, preventative, or proactive maintenance"* [1]. Maintenance operations management involves providing maintenance responses to equipment problems, scheduling and performing maintenance based on time or cycles of a machine or part, providing condition based maintenance, or optimizing resource operating performance and efficiency. Within IEC 62264-3, a number of steps are defined for performing maintenance operations management. One step is the development and management of key performance indicators related to maintenance. Key performance indicators are defined in ISO 22400-1 as a *"quantifiable level of achieving a critical objective"*, while the elements of a KPI are defined as *"relevant measurements for use in the formula of a* ***key performance indicator****"* [2]. Maintenance KPIs aid maintenance decisions, such as "what machine to send a technician?", "who to send to solve a problem?", "what is the most likely cause of the problem?",

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"what are common problems throughout the facility?", "how is a machine performing?".

Currently, no standardized set of maintenance KPIs exists, but existing research explores maintenance KPIs and how they relate to higher level organizational goals. Multiple maintenance KPI studies identify the relationship between maintenance performance measures and higher-level corporate and manufacturing objectives [3, 4]. Muchiri et al. claim that maintenance KPIs should be developed so they are aligned with higher-level functions in the organization ensuring that achieving maintenance performance objectives will support long-term strategic goals [3]. Wireman offers strategies for measuring maintenance performance and emphasizes the importance of keeping corporate objectives in mind [4]. Horenbeek et al. researched maintenance KPI selection determining which performance measures have the greatest impact on high-level objectives [5].

The use of computerized maintenance management systems (CMMS) has also been investigated thoroughly for the storage and retrieval of maintenance KPIs [6]. Although used in many applications, the effectiveness of a CMMS is often limited by its implementation. Many systems collect and analyze maintenance data, but further development of decision support capabilities of such systems is needed [7]. Another limitation of existing systems is the restriction of proprietary CMMS software packages. These systems do not use standard KPIs, making it difficult to compare performance across different CMMSs [8].

Often, the CMMS data has an unstructured, natural language component that can lead to inconsistencies in data analysis. No substantial work connecting raw data collection in the form of maintenance logs to the use of maintenance KPIs for decision making in manufacturing has been found. This paper bridges the gap between MWO data elements and maintenance KPIs.

The rest of the paper is structured as follows: Section 1 defines the data elements from MWOs used for maintenance KPIs defined in Section 2. Subsection 2.1 discusses common problem hot spot KPIs related to diagnostics and trend analysis, subsection 2.2 provides machine KPIs, and subsection 2.3 defines maintenance technician expertise KPIs. Each KPI subsection describes a KPI using elements defined in Section 1 and gives multiple examples of specific KPIs and how they relate to maintenance decisions. These KPIs are calculated from commonly measured elements in industry. Future work will expand these KPIs and link them to possible maintenance decisions as is discussed in Section 3.

1 Maintenance Element Definitions

Common MWO elements (measurements) defined in this section have been generated using actual MWO data from multiple manufacturers, and are almost certainly not all-inclusive. The source MWO data ranged from hand-written text (and entered into spreadsheets) to fully automated CMMS system readouts. At least one unstructured, natural language text field was present in every work order studied. The elements in this paper were not measured by every manufacturer studied. Instead, the list was generated using commonalities among the datasets. This list provides a reference for calculating maintenance KPIs from MWOs.

1.1 Date and Time Elements

The date and time elements address the timing involved in a maintenance work order. These elements may include only dates or both dates and times. More accurate results require more precise measurements (for example calculating date and time to the second). The most commonly calculated time elements are Work Order Start Time and Work Order Completion Time. Section 1.2 describes the importance of measuring each of these time steps for more precise decision making. The following elements, represented by the variable on the right, are used in the remainder of the paper to formulate KPIs.

Machine Down Time-stamp $\mathrm{M_d}$
The date and time when the machine goes down.

Work Order Start Time-stamp $\mathrm{W_d}$
The date and time when the work order is started.

Maintenance Technician Arrives Time-stamp $\mathrm{T_d}$
The date and time when the maintenance technician arrives at the machine

Problem Found Time-stamp $\mathrm{S_d}$
The date and time when the problem is found at the machine.

Part(s) Ordered Time-stamp $\mathrm{P_d^{(i)}}$
The date and time when part *i* is ordered.

Part(s) Received Time-stamp $\mathrm{P_u^{(i)}}$
The date and time when part *i* is received. This can be from inventory or from an outside supplier.

Problem Solved Time-stamp $\mathrm{S_u}$
The date and time when the problem is solved at the machine.

Machine Up Time-stamp $\mathrm{M_u}$
The date and time when the machine returns to operation.

Work Order Completion Time-stamp $\mathrm{W_u}$
The date and time when the work order is completed.

1.2 Calculated Time Elements

Calculated Time Elements illustrate the amount of time spent during different time periods of the MWO described in Table 1. These elements are not always directly measured, but can be calculated using the *Date and Time Elements* in Section 1.1. The variable k represents the k^{th} issue for a MWO. The *Calculated Time Elements* provide a better understanding of the time spent on each portion of the maintenance work order, compared to the *Date and Time Elements*. For example, a maintenance manager can analyze the amount of time spent repairing an issue as compared to the amount of time only spent diagnosing the issue. A maintenance technician could then be trained on how to better diagnose certain types of issues, if diagnosing the issue takes disproportionately long for the MWO.

1.3 Human Elements

Human elements identify the humans and their traits as seen in Table 2. They include the operator, maintenance technician, and the skill level required for the MWO. A heuristic often determines what skill level is needed for a particular issue. Techniques using historical data to determine the required skill level to solve a problem will be explored in future work.

1.4 Machine Elements

Machine elements consist of machine related attributes as seen in Table 3. This data includes information about the machine, components of the machine, and the part in progress.

1.5 Raw Text Elements

The Raw Text elements consist of free text descriptions of the issue from a MWO as seen in Table 4. Often times, no standard format for this information exists. Examples provided in the table contain misspellings and different formats to illustrate the inconsistency and variation of the information captured.

One important step to defining maintenance KPIs is transforming the unstructured raw text data into a structured format for analytics. The next subsection describes the structured elements and the procedure for generating them.

1.6 Tag Elements

The *Tag Elements* represent the actions taken and items of interest within each part of the MWO. They are described in Table 5. These elements provide structure for the unstructured data found in the raw text elements. Previous work in [9, 10] researched automated natural language processing (NLP) methods to provide structured data from unstructured natural language input in MWOs using a procedure called "tagging." A tag element is a single unique token that represents a particular action or item.

Figure 1 shows the difference between *Raw Text Elements* and *Tag Elements*. The example shows a combination of multiple problems and solutions in the *Raw Text Elements*. The *Raw Text Elements* are first separated into **Problem Items** and **Solution Items** and **Problem Actions** and **Solution Actions** categories. To facilitate the calculation of several later-discussed KPIs, those elements are then combined into **Problem Item & Action** and **Solution Item & Action**.

Without this tagged data, data analysis and KPI measurement is difficult. If a maintenance manager analyzed the commonality of the "Description of Problem" fields, the results would only include specific descriptions. For example if "Brush unit forward" was part of the MWO 3 times and "Brush unit stuck forward - motor not spinning" was part of the MWO 2 times, both descriptions contain the problem "Brush unit forward." Only analyzing the "Description of Problem" field leads to two separate issues, instead of the common issue "Brush unit forward" due to the inconsistency in the data input. This use of natural language including pervasive jargon and abbreviations is the norm in the MWOs studied and one of the primary impediments to reusing this data.

2 Maintenance Key Performance Indicators

Maintenance KPIs are calculated from these MWO data elements to aid in maintenance operations management decisions. This paper describes a selection of KPIs that can be calculated using these MWO data elements. A guideline on creating and selecting maintenance KPIs while accounting for different stakeholders using ASTM E3096-17 [11,12] will be explored in future work.

2.1 Common Problem Hot Spot Indicators

Common problem hot spot KPIs for diagnostics and problem tracking throughout the facility are described in this section. *Tag Elements* are required data for common problem hot spot KPIs. To perform trend analysis, comparing the facility performance to either a baseline historical level or to other facilities, is necessary. Including *Machine Elements* or *Calculated Time Elements* allows for more in depth analysis of common problem hot spots. These elements are summarized below:

COMMON PROBLEM HOT SPOTS: ELEMENTS
Required:
Tag Elements
Optional:
Machine Elements; *Calculated Time Elements*

Common problem hot spot KPIs with *Machine Elements* identifies trouble spots, provides comparisons of problems at different machines, and analyzes machine performance for specific problems. Calculating common problem hot spot KPIs with *Calculated Time Elements* tracks time spent on specific problems. Examples of common problem hot spot KPIs are discussed in the following subsections.

2.1.1 Common Problem Items

The "Common Problem Items" KPI investigates the number of issues at a facility for specific items. For example:

*MWO issued **40 times** for a **Bearing**.*

*MWO issued **20 times** for **Gears**.*

This KPI is used to compare problem items for outliers in the number of MWOs issued for a specific item or to compare problems among different facilities or years. For example:

***2012** MWO issued **30 times** for **bearings**.*

TABLE 1: CALCULATED TIME ELEMENTS

Name	Description	Formula	Notes on Data
Time Between Failure	The time between machine failures (from machine up $M_u(k-1)$ to machine down $M_d(k)$.	$M_d(k) - M_u(k-1)$	*This is the time between the last failure (k-1) and the current failure (k)).*
Time to Repair	The time from when the machine is down $M_d(k)$ until the machine is up $M_u(k)$.	$M_u(k) - M_d(k)$	*This can be misleading as the entire duration of this time period might not be spent repairing a machine.*
Work Order Completion Time	The time the maintenance work order is issued $W_d(k)$ until when it is closed $W_u(k)$.	$W_u(k) - W_d(k)$	*This is often used to approximate Time to Repair for a work order.*
Time to Dispatch	The time from when the machine is down $M_d(k)$ until the maintenance technician arrives $T_d(k)$.	$T_d(k) - M_d(k)$	
Time to Return to Operation	The time from when the maintenance technician arrives $T_d(k)$ until the machine is up $M_u(k)$.	$M_u(k) - T_d(k)$	
Time to Issue Work Order	The time from when the machine is down $M_d(k)$ until the work order is issued $W_d(k)$.	$W_d(k) - M_d(k)$	
Time to Travel	The time from when the work order is issued $W_d(k)$ until the maintenance technician arrives $T_d(k)$.	$T_d(k) - W_d(k)$	
Time to Solve Problem	The time from when the maintenance technician arrives $T_d(k)$ until the time when the problem is solved $S_u(k)$.	$S_u(k) - T_d(k)$	
Time to Diagnose	The time from when the maintenance technician arrives $T_d(k)$ until the time when a problem cause is found $S_d(k)$.	$S_d(k) - T_d(k)$	*This can be difficult to calculate since it is hard to calculate when diagnosing stops and fixing a problem begins.*
Time to Order	The time from when the problem cause is found $S_d(k)$ until the time when a part is ordered $P_d^{(i)}(k)$.	$P_d^{(i)}(k) - S_d(k)$	*This is only necessary if a part i needs to be replaced to solve the problem.*
Lead Time for Part	If a part *i* is ordered, the time from when the part is ordered $P_d^{(i)}(k)$ until the technician begins work on repairing the problem $P_u^{(i)}(k)$.	$P_u^{(i)}(k) - P_d^{(i)}(k)$	*This can be applied if a part is in inventory.*
Time to Fix	The time the maintenance technician begins work on repairing the problem $P_u^{(i)}(k)$ until the problem is solved $S_u(k)$.	$S_u(k) - P_u^{(i)}(k)$	*This can be difficult to calculate since it is hard to calculate when diagnosing stops and fixing a problem begins.*
Time to Turn On	The time from when the problem is solved $S_u(k)$ until the machine is up $M_u(k)$.	$M_u(k) - S_u(k)$	

TABLE 2: HUMAN ELEMENTS

Name	Description	Examples	Notes on Data
Maintenance Technician	The person responsible for fixing the machine.	"John Smith" "J.S."	*The format might not be consistent as illustrated by the examples. Multiple technicians or a third party might solve the problem. This type of information should be captured here.*
Operator	The person operating the machine when a MWO was issued.	"Warren, Bill" "B.W."	*The format might not be consistent as illustrated by the examples. It is possible to have one operator for multiple machines. This can be null if the machine is automated.*
Skill or Craft	The required skill level or craft needed to respond to the MWO.	"Mechanical" "Electrical"	*The format for this field will depend on the company. Smaller companies might not have this field.*

*2013 MWO issued **600 times** for **bearings**.*

This information enables managers to investigate the increase in issues in a given year for a given part.

2.1.2 Common Problem Items per Time Between Failure

The "Common Problem Items per Time Between Failure" KPI investigates the time between issues at a facility for

TABLE 3: MACHINE ELEMENTS

Name	Description	Examples	Notes on Data
Machine Name	The machine where the problem occurred.	"Milling Machine 1" "HURCO 1" "Machine H1" "HURCO VMX24i"	*The format depends on the company.*
Machine Manufacturer	The manufacturer who made the machine where the problem occurred.	"HURCO" "Hydromat"	*The manufacturer might not be known for older machines.*
Machine Type	The type of process the machine was performing when the MWO was issued.	"Milling" "Drilling"	*The machine might be capable of multiple processes.*
Machine Location	The area where the machine was located.	"Machining Line 1" "Line A" "Mechanical Cell"	*This cannot be calculated if the production line is not broken into distinct areas.*
Part in Process	The part being processed by the machine when the MWO was issued.	"Part A" "CA10110"	*The format depends on the company.*
Necessary Part	If a part is necessary for repair, this is the part that was ordered or taken from inventory.	"Gear 1012" "Bearing A2"	*The format will be dependent on the company and machine.*

TABLE 4: RAW TEXT ELEMENTS

Name	Description	Examples	Notes on Data
Description of Problem	A free text description of a maintenance problem.	"Hydraulic leak/leaking valve" "Noise at spindle because of lose bearing"	*This element can include both "cause" and 'effect" information.*
Description of Observed Symptoms (Effects)	A free text description of the observed effects.	"Hydraulic leak at accumulator" "Noise at spindle"	*A "cause" versus an "effect" is often difficult to decipher.*
Description of Cause	A free text description of the cause of a problem.	"Leakin valve caused hydraulic leak" "loose bearing"	*It can often be difficult to capture what is truly the root cause of a problem.*
Description of Solution	A free text description of the solution taken to solve the problem.	"Repiar valve and remove gear" "replace bearing at machine h1"	*A MWO might involve multiple solutions.*

TABLE 5: TAG ELEMENTS

Name	Description	Examples	Notes on Data
Item	The item(s) described in the description of problem, effects, cause, or solution.	"Hydraulic System" "Bearing"	*The item described can be different for problem, effect, cause, and solution.*
Action	The action(s) described in the description of problem, effects, cause, or solution.	"Broken" "Noise" "Repair"	*The action described can be different for problem, effect, cause, and solution.*
Item & Action	The item and action pair(s) described in the description of problem, effects, cause, or solution.	"Broken Gear" "Replace Hose"	*These item & action pairs can be different for problem, effect, cause, and solution.*

specific items. For example:

MWO issued ***every 10 days*** *on average for* ***bearings***

MWO issued ***every 20 days*** *on average for* ***gears***.

Similarly to "Common Problem Items", comparing issues against other facilities or previous year's data is possible with this KPI. Estimating failure rates of specific parts is possible, but this is not accurate as a MWO does not always indicate a failure of a part.

2.1.3 Common Problem Items by Machine Type

The "Common Problem Items by Machine Type" KPI investigates the number of issues at a certain machine type for specific items. For example:

MWO issued ***40 times*** *for* ***Milling Machine*** *Bearings*

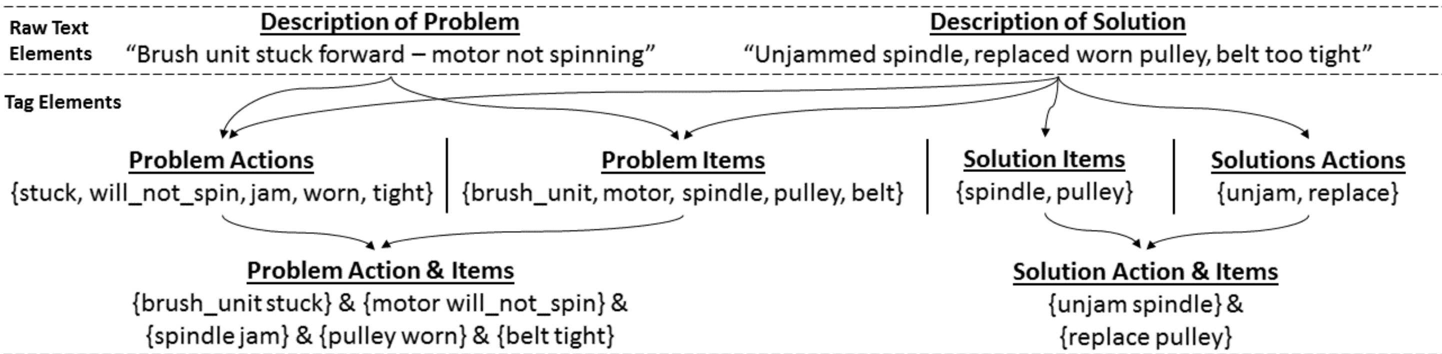

FIGURE 1: Illustrating the procedure to develop structured data (*Tag Elements*: Table 5) from unstructured, natural language text (*Raw Text Elements*: Table 4). This example shows how the data is transformed from **Description of Problem** and **Description of Solution** to **Items** and **Actions** and finally to **Item & Action** pairs. The problem and solution actions and items can come from both the **Description of Problem** and **Description of Solution** elements. Adapted from [10].

MWO issued ***30 times*** *for* ***Milling Machine*** *Gears*

compared to

MWO issued ***60 times*** *for* ***Drilling Machine*** *Bearing*

MWO issued ***80 times*** *for* ***Drilling Machine*** *Gears*

This KPI compares performance of specific machine types. It can also serve as a baseline to compare different machines of the same machine type. For example:

MWO issued ***200 times*** *for* ***Milling Machine #1*** *Gears*

MWO issued ***20 times*** *for* ***Milling Machine #2*** *Gears*

when the average for all Milling Machines is known to be 30 Gear MWOs — Milling Machine #1 is likely an outlier.

2.1.4 Common Problem Item & Action per Time to Repair

The "Common Problem Item & Action per Time to Repair" KPI investigates the amount of time to solve an issue for a specific Item & Action. For example:

Broken Gears*: **20 hours** total repair.*

Worn Bearings*: **10 hours** total repair.*

Comparing types of issues for specific Item & Action elements allows for identification of outliers of types of failures that need to be addressed.

2.2 Machine Performance Indicators

Tracking performance of a machine and simulation of machine failures are possible with this set of Machine Performance KPIs. The required elements are *Machine Elements* and *Calculated Time Elements*. To analyze machine performance as related to specific issues requires *Tag Elements*.

MACHINE PERFORMANCE ELEMENTS

Required:

Machine Elements; *Calculated Time Elements*

Optional:

Tag Elements

Some possible examples of machine KPIs are detailed in the following subsections.

2.2.1 Machine per Time Between Failure

The "Machine per Time Between Failure" KPI investigates the amount of time between failures for a given machine. For example:

Machine #1*: MWO Issued **every 10 days** on average.*

Machine #2*: MWO Issued **every 20 days** on average.*

Comparing how often a maintenance work order is issued for a specific machine is provided by this KPI. *Tag Elements* are needed to determine the specific issues for each work order. This KPI can also be used for simulation of a facility by inserting random downtime events for specific machines.

2.2.2 Machine by Problem Action per Time Between Failure

The "Machine by Problem Action per Time Between Failure" KPI investigates the amount of time between failures for a given machine for a given issue. For example:

Machine #1	***Broken*** *every* ***10 days*** *on average*
	Cleaned *every* ***30 days*** *on average*
Machine #2:	***Broken*** *every* ***100 days*** *on average*
	Cleaned *every* ***50 days*** *on average*

Simulation of a facility by inserting random downtime distributions for machines with multiple failure types is possible with this KPI. More specific information is provided with this KPI as compared to the "Machine per Time Between Failure" KPI for how often and why the MWO was issued for a machine.

2.2.3 Machine Type per Time to Repair

The "Machine Type per Time to Repair" KPI investigates the time to repair for a given machine type. For example:

***Milling Machines**: **20 hours** spent solving issues*

***Drilling Machines**: **50 hours** spent solving issues.*

Analysis of the length of repairs for different machine types is provided with this KPI. This KPI provides comparison between specific machines within the same machine type. For example:

*Milling Machine #1: **50 hours** spent solving issues*

*Milling Machine #2: **40 hours** spent solving issues*

where the average time spent solving Milling Machines issues is 20 hours. A maintenance manager can investigate why time spent on issues for Milling Machine 1 and 2 is much higher than the average Milling Machine.

2.2.4 Machine Type per Problem Item per Time to Repair

The "Machine Type per Problem Item per Time to Repair" KPI investigates the time to repair specific items for a given machine type. For example:

Milling Machines:	***20 hours** spent solving issues for **gears***
	10 hours** spent solving issues for **bearings
Drilling Machines:	***80 hours** spent solving issues for **gears***
	100 hours** spent solving issues for **bearings

This KPI provides comparison between types of items that have issues on different types of machines. A maintenance manager can analyze the usage of a machine to investigate why a part might fail more often in one type of machine compared to another type of machine.

2.3 Maintenance Technician Expertise Indicators

Indicators related to maintenance technician expertise are used for tracking the number of times a maintenance technician addresses an issue. Training procedures to help maintenance technicians acquire more expertise in an area can be developed with the information provided by these KPIs. Lastly, dispatching procedures can be developed for sending the most experienced maintenance technician to solve a type of problem at a specific machine. For this set of KPIs, the required elements are *Human Elements* as well as either *Tag Elements* and/or *Machine Elements*. If *Tag Elements* are utilized, analysis of a maintenance technician's expertise with certain problems or solutions is provided. If *Machine Elements* are used in the KPI calculation, maintenance technician experience for specific machines or machine types/manufacturers is calculated. Adding in *Calculated Time Elements* to these KPIs allows analysis on the time spent on maintenance issues by a specific technician. These elements are summarized below:

MAINTENANCE TECHNICIAN EXPERTISE ELEMENTS

Required:
Human Elements; *Tag Elements* or *Machine Elements*
Optional:
Calculated Time Elements

Some examples of maintenance technician expertise KPIs are detailed in the following subsections.

2.3.1 Maintenance Technician Expertise per Problem Item

The "Maintenance Technician Expertise per Problem Item" KPI investigates the number of times a maintenance technician works on a specific item. For example:

Maint. Tech. A:	***40 times** working on **gears***
	20 times** working on **bearings
Maint. Tech. B:	***30 times** working on **gears***
	100 times** working on **bearings

Comparing different maintenance technician's expertise on specific items within a machine, determining where a maintenance technician needs training on specific items, or dispatching a maintenance technician based on expertise are all possible with this KPI.

2.3.2 Maintenance Technician Expertise per Problem Action

The "Maintenance Technician Expertise per Problem Action" KPI investigates the number of times a maintenance technician spends on a specific action. For example:

Maint. Tech. A:	***40 times** working on **leaks***
	20 times** working on **low pressure
Maint. Tech. B:	***30 times** working on **leaks***
	100 times** working on **low pressure

This KPI compares maintenance technician's expertise for specific actions and illuminates possible training for technicians on how to respond to various problems.

2.3.3 Maintenance Technician Expertise per Problem Item & Action per Time to Repair

The "Maintenance Technician Expertise per Problem Item & Action per Time to Repair" KPI investigates the amount of time a maintenance technician spends repairing an issue. For example:

Maint. Tech. A:	***40 hours** working on **hydraulic leaks***
	20 hours** working on **bearing failure
Maint. Tech. B:	***30 hours** working on **hydraulic leaks***
	100 hours** working on **bearing failure

Dispatching a maintenance technician for repair based on the current observed issues at a machine is possible with this KPI.

2.3.4 Maintenance Technician Expertise per Problem Item & Action per Time to Diagnose

The

"Maintenance Technician Expertise per Problem Item & Action per Time to Diagnose" KPI investigates the amount of time a maintenance technician spends diagnosing an issue. For example:

Maint. Tech. A: ***40 hours diagnosing*** *hydraulic leaks*
20 hours diagnosing *bearing failure*
Maint. Tech. B: ***30 hours diagnosing*** *hydraulic leaks*
100 hours diagnosing *bearing failure*

Dispatching a maintenance technician to diagnose an issue based on the current observed issues at a machine is possible with this KPI. This would involve sending one technician to diagnose the problem and then dispatching the technician with the most expertise to fix the given issue.

2.3.5 Maintenance Technician Expertise per Solution Item & Action per Time to Fix

The "Maintenance Technician Expertise per Problem Item & Action per Time to Fix" KPI investigates the amount of time a maintenance technician spends solving an issue. For example:

Maint. Tech. A: ***40 hours repairing*** *leaks*
20 hours replacing *accumulators*
Maint. Tech. B: ***30 hours repairing*** *leaks*
100 hours replacing *accumulators*

Dispatching a maintenance technician to solve the problem more efficiently, once the problem is diagnosed, is possible with this KPI.

2.3.6 Maintenance Technician Expertise per Machine Type per Time to Repair

The "Maintenance Technician Expertise per Machine" KPI investigates the number of times a maintenance technician spends on a particular machine type. For example:

Maint. Tech. A: ***40 hours*** *working on* ***milling*** *machines*
20 hours *working on* ***drilling*** *machines*
Maint. Tech. B: ***70 hours*** *working on* ***milling*** *machines*
100 hours *working on* ***drilling*** *machines*

This KPI illuminates comparison of a maintenance technician's expertise for different machine types and can identify which technicians need training for a type of machine.

3 Conclusions & Future Work

The different possible elements of a MWO and associated KPIs for common problem hot spots, machine performance, and maintenance technician expertise are discussed in this paper. These examples do not provide every possible KPI, but they illustrate how the MWO elements can be assembled into indicators used for decision making. Each KPI type is presented at a high level to illustrate which elements are necessary for calculation and what decisions can be made with that type of KPI. More detailed examples are provided to illustrate how a specific KPI can be calculated with maintenance work order elements depending on the needs of the factory. Equations and analysis techniques will be explored in future work to demonstrate how to calculate the KPIs discussed in this paper.

Formal guidelines on how to properly use MWO data for maintenance decisions will enable widespread adoption of this work. Many of the KPIs required structured data for accurate results. The guidelines will include instructions on structuring data, data storage, cleaning data (using the method developed in [10]), calculating KPIs, and making the correct decisions based on KPI results.

Several areas for exploration follow from this work:

1. Incorporation of sensor data into the information framework: Merging MWO data with sensor data to aid in maintenance decision making is an important research topic as sensor technologies become cheaper and easier to implement.
2. Implications for system level decision making: KPIs that are useful for machine level decisions are presented in this paper. More data needs to be collected to properly make decisions at the system level. This system level information allows maintenance decisions to be linked to operations to perform maintenance procedures without affecting productivity of the facility.
3. Roles of different decision makers and divergent interfaces to the data: Roles, such as the operator, maintenance technician, and maintenance manager are not discussed in this paper. Future work will investigate which KPIs are important to each decision maker and how to properly visualize this data.

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