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Identifying machine times with OPC UA for Equipment as a Service (EaaS) – possibilities and limitations

Dimitri Evcenko[a,*], Tonja Heinemann[c], Holger Kett[b], Armin Lechler[c], Oliver Riedel[b,c], Andreas Wortmann[c]

[a]*Institute of Human Factors and Technology Management (IAT), University of Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany*
[b]*Fraunhofer IAO, Fraunhofer Institute for Industrial Engineering (IAO), Nobelstraße 12, 70569 Stuttgart, Germany*
[c]*Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, Seidenstr. 36, 70174 Stuttgart, Germany*

* Corresponding author. Tel.: +49 711 970 5131. *E-mail address:* dimitri.evcenko@iat.uni-stuttgart.de

Abstract

With Equipment as a Service (EaaS), subscription-based business models are becoming increasingly popular in mechanical and plant engineering. The main argument in favor for EaaS is a better overall equipment effectiveness (OEE) when a factory supplier operates the equipment. Therefore, the constant determination of the OEE in EaaS operations becomes crucial. This value is usually determined combining data retrieved from the equipment itself in combination with data from higher level systems like the manufacturing execution system (MES) of the customers. The latter are not accessible by the factory supplier. To bridge this information gap, the OEE of a piece of equipment is determined based solely on the available equipment data retrieved through data exchange standards such as the Open Platform Communications Unified Architecture (OPC UA). To achieve this, the time information needed to determine the OEE as defined in the ISO 22400-2 standard is either directly determined from OPC UA data from the machines or approximated through assumptions and exclusions. As an example for the mapping of equipment data to different time information, machine tools are focused and, hence, OPC UA 40501 and OPC UA 40001. In addition, the findings are analyzed regarding limitations in using the available time data via OPC UA. The mapping's applicability is demonstrated with an exemplary use case and the OEE is compared when calculated only with equipment data retrieved via OPC UA with the OEE calculation having the additional information from a higher level system. This comparison allows to evaluate the uncertainty introduced by making assumptions and exclusions. The results are a valuable input to supplement the OPC UA Companion Specifications in order to cover the OEE determination in EaaS use cases.

Keywords: Equipment as a Service (EaaS), OPC UA, overall equipment effectiveness (OEE), machine monitoring

1. Introduction

A key driver of growth in the machinery and equipment engineering industry are service-centric business models [1]. Business models are categorized as cloud manufacturing, if they focus on offering production resources as a service via a platform. A distinction can be made between intangible and tangible production resources [2]. While intangible production resources can include software or the skills of an employee, tangible production resources comprise hardware, raw materials or machines and equipment. If machines and equipment are offered as a service, it is considered Equipment as a Service (EaaS) [3]. One main argument in favor for EaaS is a higher overall equipment effectiveness (OEE) when a factory supplier operates the equipment. Thus, the constant determination of the OEE is a key task of the service provider to be able to deliver a high-quality service.

OEE is a performance indicator widely used in the manufacturing industry [4]. It is based on the equipment's availability, efficiency and produced quality. It was introduced by Nakajima

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in the context of the Total Productive Maintenance Concept (TPM) whose goal it was to achieve and maintain a high equipment efficiency [5]. Today's standards for OEE calculation [6] are based on Nakajimas work.

In addition to current equipment data, data from production planning is required to determine the OEE. While the service provider has digital access to the equipment data via standards like OPC UA, this is not the case for production planning data, as they are usually part of the customer's manufacturing execution system (MES). In this paper, it is shown how this information gap can be closed from the service provider's perspective and how the OEE according to ISO 22400-2 [6] can be determined solely based on the available equipment data. The focus lies on machine tools and therefore on OPC UA 40001 [7] and OPC UA 40501 [8].

Section 2 presents the state of the art for OEE calculation according to ISO 22400-2 and provides a brief introduction to OPC UA. Section 3 describes the methodology used in this work. Section 4 presents the results and what information necessary for the OEE can be retrieved via OPC UA with which certainty. Section 5 describes an exemplary production day for a machine to show how the uncertainties stated in Section 4 affect the OEE calculation. Section 6 offers a discussion of the results. The work ends with a conclusion and outlook.

2. State of the Art

2.1. OEE calculation based on ISO 22400-2

Table 1: Relevant times and information for determining the OEE

Time/information	Description
Reference time (RT)	Available time for production and maintenance tasks
Planned operation time (POT)	Time in which a work unit can be used
No production time (NPT)	Time in which no production is scheduled (e.g., sundays)
Planned down time (PDT)	Time for e.g., planned maintenance
Planned busy time (PBT)	POT-PDT
Actual unit busy time (AUBT)	Execution of a production order
Actual unit down time (ADOT)	Work unit is not executing although production order is available
Actual unit processing time (AUPT)	Setup and production
Actual unit delay time (ADET)	Unwanted extension of processing time (e.g., malfunction-caused interruptions)
Actual production time (APT)	Producing (only value-adding functions)
Actual unit setup time (AUST)	Preparation of an order
Good Quantity (GQ)	Produced quantity which meets the quality requirements
Produced Quantity (PQ)	Produced quantity in relation to a production order
Planned run time per item (PRI)	Planned time for producing one quantity unit

The determination of the OEE according to ISO 22400-2 requires the times and information shown in Table 1. These times and information are used to calculate the availability (1), effectiveness (2) and quality ratio (3), which are multiplied to determine the OEE (4).

$$Availability\ (A) = APT/PBT \tag{1}$$

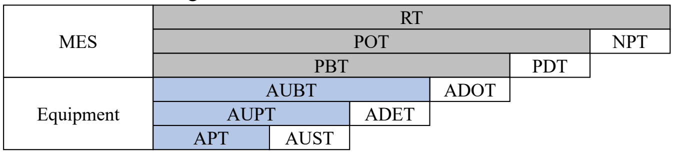
$$Effectiveness\ (E) = PRI * PQ/APT \tag{2}$$

$$Quality\ ratio\ (Q) = GQ/PQ \tag{3}$$

$$OEE = A * E * Q \tag{4}$$

The various times and their relationships to each other are shown in Fig. 1. The production planning data POT, PDT and PBT are not stored on the equipment but are available through a higher level system like an MES.

Fig. 1 Different times and data sources



2.2. OPC UA 40001 and 45001

Open Platform Communications Unified Architecture (OPC UA) [9] is a standard in communication. It defines all technical aspects, e.g., what protocols and encodings to use, what encryption is possible and how communication partners interact with each other. On top of these aspects, OPC UA defines a means to describe the data and metadata in information models. These information models can be used to state what data to transmit in a given scenario, e.g., for a specific domain. If such an information model is defined with the OPC Foundation's knowledge and published by the OPC Foundation, it is called a Companion Specification. [9]

There are multiple Companion Specifications available, with more being designed every year [10]. The OPC 40001 series *OPC UA for Machinery* is of special importance in manufacturing. The specifications in this series define common information for devices in the machinery domain, including identification information, metadata for complex measuring results, device status information and job information [7].

In OPC 40001-1, part 1 of the machinery series, the status information is presented as two OPC UA state machines. An OPC UA Server providing this information has two variables that show a state. The first variable is called *MachineryItemState*, it describes the current task of the equipment as one of *NotAvailable*, *OutOfService*, *NotExecuting* or *Executing*. The second one is called *MachineryOperationMode*. It describes the current state of action as one of *None*, *Maintenance*, *Setup* or *Processing*. In Annex C to OPC 40001-1, an interpretation of the combination of these values towards KPI calculation is given. Each combination of *MachineryItemState* and *MachineryOperationMode* is combined with a higher level system condition state and interpreted as a time element of ISO 22400-2. The higher level system information can, for example, be the information whether a production order exists, saved in a MES.

This information is often not available on the machine, because it is not needed by it during operation. [7]

In OPC 40001-3, an information model for handling jobs is presented. This model includes means to transfer jobs to the machinery item, receive their results and monitor their status. OPC 40001-3 also indicates how to transmit AUBT, AUST, ADET and APT directly along with the results of job orders. However, the data is not mandatory. [11]

There are multiple specifications that extend the concepts of OPC UA 40001 for a more specific domain. One of them is OPC 40501 OPC UA for Machine Tools. The OPC 40501 model defines data intended for monitoring purposes, information about the job predating the introduction of OPC 40001-3, information about the tools on the machine and an aggregated point for all messages and notifications of the machine. Some of these data are intended for KPI calculation and are described as such in the document. Some of the data are defined as mandatory and must be provided by interfaces implementing the specification. [8]

Harmonized OPC UA Companion Specifications simplify gathering and evaluating device data. To companies, the calculation of KPI, especially the OEE, are important in this context [12]. As specifications like OPC 40001-1 and OPC 40501-1, both released in 2022, are being implemented into products more and more, mapping their data to OEE calculation becomes worthwhile. OPC 40001-3 has been released in February 2024, it is not yet implemented in products. At the same time, it is promising to look at it, as it is likely to be included into domain specific OPC UA standards.

3. Methodology

Section Annex C to OPC UA 40001-1 shows how various combinations of *MachineryItemState* (*MIS*), *MachineryOperationMode* (*MOM*) and Higher Level System Condition State (*HLSCS*) are assigned to the time elements defined in ISO 22400-2. For the OEE calculation the determination of ADET, ADOT, APT and AUST is essential. Table 2 shows how the *HLSCS* is broken down into single information.

Table 2: Break down of *HLSCS* into single information

ID	*HLSCS*
H1	System state is order registered
H2	No maintenance activities
H3	Time is just out of cycle time
H4	System state is planned busy time based on operation calendar
H5	No order registered
H6	System state is planned operation time based on operation calendar
H7	System state is shut down time based on operation calendar (NPT)
H8	Maintenance activities
H9	SPLIT in setup time (AUST) and value added production time (APT) as retrograde confirmation (backflush)

Due to the focus on machine tools, the specifications OPC UA 40001-3 and OPC UA 40501-1 are analyzed to check whether, how and with what certainty the *HLSCS* information can be substituted to determine the different times. All further reasoning is based on the assumption: Orders that are processed on the equipment and are not registered in the system, are not part of a standard production situation and not considered here.

4. Results

Table 3 lists the combinations of *MIS*, *MOM* and *HLSCS* defined in Annex C to OPC 40001-1 assigned to the APT, AUST, ADET and ADOT times. It can also be seen whether and with what certainty – possible, possible under assumptions and not possible – the corresponding *HLSCS* information can be substituted with the available equipment data retrieved via OPC UA. Each cell in column *MOM* which includes *last sent* in it refers to the most recent valid value received, as the connection between OPC UA Server and Client or between OPC UA Server and the equipment may be down due to the machine being *NotAvailable* [7].

Table 3: Substitution of *HLSCS* information using OPC UA; ✓= possible, (✓) = possible under assumptions, ✕ = not possible

Time	ID	*MIS*	*MOM*	*HLSCS*	OPC UA
APT	1.1	*Executing*	*None*	H1	✓
	1.2	*Executing*	*Processing*	H1	✓
	1.3	*NotExecuting*	*Processing*	H1	(✓)
	1.4	*Executing*	*Setup*	H9	✕
AUST	2.1	*OutOfService*	*Setup*	H1	✓
	2.2	*NotAvailable*	*Setup (last sent)*	H1	✓
	2.3	*NotExecuting*	*Setup*	H1	✓
	2.4	*Executing*	*Setup*	H9	✕
ADET	3.1	*OutOfService*	*Processing*	H1, H2	(✓)
	3.2	*NotAvailable*	*Processing (last sent)*	H1, H2	(✓)
	3.3	*NotExecuting*	*None*	H1	✓
	3.4	*NotExecuting*	*Processing*	H1, H2, H3	(✓)
ADOT	4.1	*OutOfService*	*None*	H4	(✓)
	4.2	*NotAvailable*	*None (last sent)*	H4, H5	(✓)
	4.3	*NotExecuting*	*None*	H4, H5	(✓)

4.1. Possible information substitution

Table 3 shows that the information substitution via OPC UA is possible for information component H1, the information whether a job order is registered in the system or not. This allows determining the value combinations with the ID 1.1, 1.2, 2.1, 2.2, 2.3 and 3.3. The assumption for H1 and its negation H5 is, that each execution of a job order is intended by the higher level system. If the OPC UA interface presents data about job orders, and if a job order is available and active (neither in preparation nor finished), H1 is true. In OPC UA 40001-3 this information can be retrieved via a list of available jobs that each indicate a state. In this case, *AllowedToStart*, *Running* or *Interrupted* can be counted as active states. In OPC UA

40501-1, there is always information about a program, which is defined as a production program like a Numerical Control (NC). Here the OPC UA element *ProductionProgramStateMachineType* shows the state of a program. If the *CurrentState* is *Running* or *Interrupted*, the program is active. Among the optional elements in OPC 40501-1, there is information about the state of a job order with the same options for states.

4.2. Possible information substitution under assumptions

For some of the values in Table 3, the missing *HLSCS* information can be substituted under assumptions.
One such case is the distinction between the value combinations with the ID 1.3 and 3.4. These must also be differentiated from an interpretation as time to repair (TTR) which is applicable if maintenance activities are carried out (H8), as stated in Annex C to OPC UA 40001-1. The TTR describes the actual time in which the equipment is unavailable due to a failure [6]. The suggested assumption for H2 and H8 is that maintenance is only considered if there is a clear indication in the data, e.g., a boolean value indicating whether maintenance activities are ongoing. This assumption is based on the optimistic view that machines need maintenance for a small amount of the overall time. However, in both OPC 40001-3 and OPC 40501-1 an indication of maintenance does not exist. To distinguish the value combinations with the ID 1.3 from 3.4, it must be known whether the time is just out of cycle time (H3). Assuming that the cycle time or PRI can be estimated by observing the production process over a longer period and calculating the mean value of actual production cycles, this is possible for both OPC 40001-3 and 40501-1. Both offer a job order state, indicating the beginning and end of the production, in conjunction with information about the number of parts produced. Alternatively, a service provider may know the PRI of the equipment, if it is defined as part of the negotiation of an EaaS contract with the service user.
To differentiate the value combinations with the ID 3.1, 3.2 and TTR from each other, the assumption for H2 and H8 is used.
The value combinations with the ID 4.1 and 4.2 must be differentiated from an interpretation as Actual Shut Down Time (ASDT) which is part of PDT. Annex C to OPC UA 40001-1 states that the combinations are interpreted as ASDT if the operation calendar schedules NPT (H7). A practical assumption for H7 and thus its opposite H6 is to gain insight about typical production times and to assume that the typical times are POT and all other times are NPT. Typical production times show patterns that repeat across the days and represent shifts, with possible differences on weekends and holidays, which are known from the calendar. With OPC UA, the information needed can be concluded by the interface being shut down, returning no connection to the data source or showing no value changes.

The same assumption can be used for the value combination with the ID 4.3. This combination must be differentiated from ADET and PDT. To be differentiated from ADET, there must be no order registered (H5). This information is interpreted from the state of a production order and is just the inverse of H1, e.g., for OPC UA 40501-1 the *ProductionProgramStateMachineType* shows *Initializing*, *Ended* or *Aborted* as the *CurrentState* or provides no value at all. To be differentiated from ASDT, like for the value combinations with the ID 4.1 and 4.2, the operation calendar assumption for H7 and its opposite H6 is used.

4.3. Impossible information substitution

There are cases, where the *HLSCS* information cannot be substituted reliably. This applies to the differentiation between the value combinations with the ID 1.4 and 2.4. The values for these combinations can be split retrospectively into AUST and APT as retrograde confirmation (H9). The split is carried out in higher level system like a MES. Neither OPC 40001-3 nor OPC 40501-1 give any indication about this.

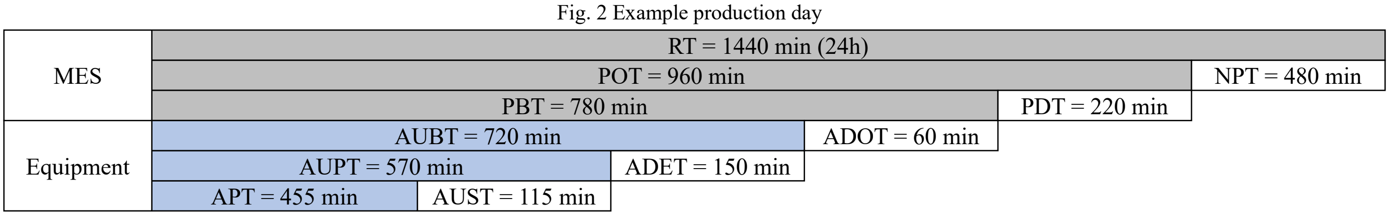
4.4. GQ, PQ and PRI

In addition to the various time elements, information regarding GQ, PQ and the PRI are also required for the OEE calculation. In OPC UA 40001-3 the values representing GQ and PQ are called *GoodQuantity* and *ProducedQuantity.* For the PRI the value *PlannedProductionTime* can be divided by the value *PlannedOrderQuantity*. In OPC UA 40501-1 the information on PQ is stored in *ProductionJobType/PartsCompleted* and the information on GQ in *ProductionJobType/PartsGood*. Information on the PRI itself cannot be determined with OPC UA 40501-1, only estimated with the assumption for H3.
For both specifications, the GQ value represents parts as good if there is no contradicting evidence. It is possible that e.g., a manual quality check identifies the parts as rework or scrap. At the same time, from the perspective of a service provider, the PRI is known as it is part of the EaaS contract.

5. Evaluation

To show the effects of the uncertainties in determining the times via OPC UA on the OEE, an example production day of an equipment with the times shown in Fig. 2 is used. In the example, the TTR is 60 minutes. On this day, the machine produces a total of 5350 parts (PQ), of which 4815 are of good quality (GQ). The performance of the machine is specified by the service provider with the equipment needing 0.06 minutes to produce one piece (PRI).
The PBT required to calculate the OEE cannot be read from the equipment data, as it is an information usually stored in a higher

Fig. 2 Example production day



level system with the production plan. For this reason, the PBT is estimated by adding up the following times:

$$PBT = APT + AUST + ADET + ADOT \quad (5)$$

For this sum, the differentiation between the value combinations with ID 1.4 and 2.4 (H9) is unnecessary, as the result is added in any case. So, the combination can always be interpreted as either of the two values. Following (1), (2), (3) and (4) the OEE for this example is 37.04 %.
Since the determination of the times is associated with the uncertainties listed above, the deviation range is shown by defining a worst-case, a best-case and an average scenario.

5.1. Worst-case scenario

In the worst-case scenario, there are many maintenance activities without a clear indication for them. Therefore, the value combinations with the ID 1.3, 3.1, 3.2 and 3.4 include the time in which the equipment is unavailable due to failure. This time is part of TTR which in this example is 60 minutes. The 60 minutes are equally split up and added to both APT and ADET which results in 485 respectively 180 minutes.
The value combinations from the ADOT times with the ID 4.1 and 4.2 are considered as ASDT when H7 applies. In the worst-case scenario, the POT can't be determined from the equipment data by i.e. identifying typical shutdown times and therefore the production shifts. As the ASDT is part of the PDT the inability to distinguish between ADOT and ASDT must be considered. For the worst case scenario, the total PDT value is added to ADOT, which results in 280 minutes . The times can be seen in Table 4.
Following (1), (2), (3) and (4) the OEE results in the OEE of 27.25 % for the worst-case scenario. The OEE including the factors for the calculation can be seen in Table 4. All values in Table 4 are rounded to the fourth decimal place.

5.2. Best-case scenario

In the best-case scenario, there is a clear indication for all maintenance activities. Therefore, the value combinations with the ID 1.3, 3.1, 3.2 and 3.4 are correctly distinguished from TTR. So APT and ADET times are determined according to the reality with the length of 455 respectively 150 minutes.

Moreover, the POT can be determined from the equipment data and the ADOT times with the ID 4.1 and 4.2 can be distinguished from ASDT. Therefore, the PDT is not added to the 60 minutes of the ADOT. Following (1), (2), (3) and (4) the best-case scenario OEE results in 37.04 %. The times can be seen in Table 4 while the OEE and the factors are shown in Table 5.

5.3. Average scenario

The average scenario in the example is determined as the mean value between the times determined in the worst-case and the best-case scenario. This results in an OEE of 31.41 %. The corresponding times and OEE values can be seen in Table 4 and Table 5 which also shows the deviation from the correct OEE value for this example. While the OEE can be correctly determined in the best-case scenario with 0 % deviation, it is 26.43% resp. 15.20% worse than actual in the worst-case scenario and the average scenario.

Table 4: Worst-case, best-case and average scenario for calculating the OOE

Time/information	Worst-case	Best-case	Average
APT	485 min	455 min	470 min
AUST	115 min	115 min	115 min
ADET	180 min	150 min	165 min
ADOT	280 min	60 min	170 min
PBT	1060 min	780 min	920 min
PRI	0.06 min		
PQ	5350 pcs		
GQ	4815 pcs		

Table 5: OEE values for the worst-case, best-case and the average scenario

OEE factors	Worst-case	Best-case	Average
A	0.4575	0.5833	0.5109
E	0.6619	0.7055	0.6830
Q	0.9000	0.9000	0.9000
OEE	0.2725	0.3704	0.3141
Deviation	-26.43 %	0 %	-15.20 %

6. Discussion and practical implications

To calculate KPI, the most accurate value available should be chosen. So if the PRI is known, it shall be used over a mean value of measured runtimes. If any of AUBT, AUST, ADET or APT are transmitted with the OPC 40001-3 model, that value is to be preferred of the variants discussed in this work.

H1 and H5 are deducted from a job order being in an active state on the machine. This discards waiting times, e.g., towards the beginning of the job. The assumption has been chosen to account for jobs that are transmitted to the machine long before their starting time – such jobs would be in a state like *Initializing* of OPC UA 40501-1. Both the OPC 40001-3 and the OPC 40501-1 allow the representation of this information. The information in the job order of OPC 40001-3 and the job of OPC 40501-1 are similar in quality. Even though the mandatory information about the program state is always available if OPC UA 40501-1 is implemented, the job information is to be preferred: it contains the relation of programs to jobs and programs to parts.

The assumption for H2 and H8 – maintenance is only considered if there is a clear indication – will lead to values that are correct or too large for ADET for the value combinations with the ID 1.3, 3.1, 3.2 and 3.4, as all times where the assumption is false would be TTR. In the OEE this results in a lower than actual availability factor. For the information components H2 and H8, there is no clear indication in OPC 40001-3 or 40501-1. But such a value or hints towards it can be transmitted with OPC UA if available, e.g., if maintenance personnel identify themselves at the machine's interface.

The assumption for H3, using mean values of measured data for the PRI, tends to use too large values for the PRI, as the actual runtime per item is usually longer. This leads to a larger than actual APT at the cost of a smaller ADET. In the overall OEE calculation, this leads to a larger than actual effectiveness. It has no effect on PBT calculation as APT and ADET are added together for it. If the PRI is known, this is of no concern. Both OPC UA 40001-3 and OPC UA 40501-1 contain the produced number of parts. For OEE calculation, the number of produced parts and good parts are needed, so even though the information is optional, OEE calculation requires it. For OPC UA 40501-1 the job information needs to be available, as the produced parts are structured as sub-elements of a job. With both models, it is possible to distinguish similar and different kinds of parts. This information is optional in both models.

There is no implication or suggestion for information component H4, as the production plan and therefore the PBT is saved in the MES. For identifying the relevant time elements for the OEE calculation, H6 and H7 have been used.

For the assumption for H6 and H7, estimating POT and NPT, the uncertainty is highly dependent on the actual production situation. This assumption discards both planned machine shutdown due to operating procedures and overtime hours for example. Estimating the POT and thus also the NPT with aggregated information about the machine's typical shut down times can be realized in several ways. If the OPC UA Server is shut down along with the machine, it is unavailable to the Client and this information can be used to identify time patterns. If the OPC UA Server keeps running if the machine is shut off, e.g., due to a different power supply, the appropriate way to indicate this to a client is to use the proper *StatusCode* defined by the OPC Foundation, e.g., *BadNoCommunication* or *UncertainNoCommunicationLastUsableValue* [13]. As a last resort, the information about no production can be used, so no running programs or jobs, or no value changes at all. These approaches are independent of the information model used.

H9, the information about a retrograde split of time elements between APT and AUST, is out of scope for an OPC UA Server that displays the information a machine has in the field. This retrograde split is not needed by the machine to pursue operation, so there is no need to transmit the data to it. For an OEE estimate, the respective times can be distributed between APT and AUST. For any KPI calculation that is following Annex C to OPC UA 40001-1, the implementation must follow its assignments of value combinations to times. This means, i.e., that if the machine gains knowledge about a breakdown, it must change the *MachineryItemState* to *NotAvailable*.

7. Conclusion

If actual planning data is unavailable, the information needed to determine the OEE can be estimated based on OPC UA data defined in information models like OPC UA 40001-3 or OPC UA 40501-1. As the assumptions for unidentifiable values don't change, OEE-like values calculated on this basis will show changes that correspond to the measured actual times. Especially for the OEE factors *Effectiveness* and *Quality Ratio*, there are no downsides to the approach under the assumption that more accurate measurements of APT, GQ and PQ are not available. The APT measurement gains accuracy, if information about maintenance is available. If not it cannot be clearly distinguished from TTR. At a minimum for this apporach to work, the OPC UA data must include the *MachineryItemState* and *MachineryOperationMode* from OPC 40001-1 as well as information about GQ, PQ and job orders.
From the perspective of an EaaS service provider, this approach can be used to monitor the equipment, even though information from higher level systems is unavailable to them. In the worst-case, the deviation is 26.43 % from the best-case, which matches the actual OEE of the example. As the calculation gets more accurate with information to the production plan and maintenance activities, the service provider could consider the transfer of these information as part of the EaaS contract. With that, the OEE calculation solely based on available equipment data is possible without limitations.

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