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MTConnect-based decision support system for local machine tool monitoring

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Abstract

Cyber-Physical Machine Tools (CPMT) are becoming ubiquitous parts of manufacturing sectors. CPMT offer immense potentials in the current CNC machine tool through integrating the machine tool and the machining process using computation and networking to enhance interconnection and autonomy. This study contributes to literature by presenting a variety of MTConnect applications in facilitating the decision making process at different production levels. We do this through addressing the challenges of data communication and management with CNC machine tool. Using the MTConnect protocol, we gathered near real-time data from a CNC machine. Next, the collected data are utilized to develop a local monitoring system that facilitates the decision-making process with applications on: i) production planning, ii) preventive maintenance, and iii) energy consumption analysis. In each application, various analyses and visualization techniques are presented to show the capabilities of the decision support system (DSS) for the operator. Finally, the advantages of the local DSS to improve the interoperability of the CNC through MTConnect are discussed.

Keywords: Industry 4.0; Decision Support System; Machine tool 4.0; MTConnect

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1. Introduction

Machine tools are indispensable components in the realm of manufacturing sector as their performances considerably affect the production efficiency as well as its effectiveness. There is no doubt that machine tools play vital roles in the development of Cyber-Physical Production Systems (CPPS) [12] and Smart Factory [12]. The evolution of machine tool technologies from the 19th century to date has extensively emulated that of industrial revolution. Such mirrored development asserts the claim that the machine tools are the ubiquitous components in the modern manufacturing systems which is confirmed by their iconic position in the context of industrial modernization [10]. Subsequently, in the context of industrialization, given the significant role of machine tools in this path, we recognize the urgent need to develop machine tools that are in accordance with the concept of Industry 4.0. In this direction, similar to the industrial revolution [10], machine tools have passed through three stages of technological developments. Analogously, as we swing into the era of Industry 4.0, so do we to the epoch of Machine Tool 4.0 [11].

Cyber-Physical Machine Tools (CPMT), which are founded on the developments in Information and Communication Technology including Cyber-Physical Systems (CPS), Big Data, Data Analytics, and Internet of Things (IoT), offer promising solutions for Machine Tool 4.0. CPMT involve deeply integrated machining processes and machine tool through computation and networking in which the employed computations allow for monitoring and control of the machining processes [11]. Such integrated system results in a highly interconnected, self-governing, and hence more intelligent system. However, development of CPMT is accompanied by challenges in enabling data communication, integration, and management mainly due to the variety of manufacturing instruments and sensors in the system. Currently, a major proportion of machining production is performed using computer numerical control (CNC) machine tools that utilize servomotors and/or stepper motors to generate the tool motion. The CNC machine tools count on the sensor feedbacks in order to control the cutting process. Thus, the output data originating from these sensors can be manipulated to examine the machining process in general. For instance, the sensor data can be analyzed to evaluate the production rate of the machine. However, collecting data from the various sensors of the machine tool may involve problems especially if the attempts is to integrate data from many different types of devices.

Machine tool manufacturers have been embracing MTConnect as a viable choice for data transmission from various types of machine tools including CNC machines [17]. MTConnect is an open-source, royalty-free communication protocol that facilitates the data collection in a machine tool via a network connection [8]. While the benefits from the MTConnect implementation are numerous in many facilities, the literature lacks cost effective tools that could easily and rapidly be deployed to analyze the collected data for enhanced decision-making processes through MTConnect.

Effectively using the collected data requires the formation of a system that is capable of collecting, storing and utilizing data acquired from the manufacturing equipment. These three requirements (collect, store, utilize) although depend on one another, each necessitates its individual tools to implement and deliver the required tasks. To collect data, it is necessary to deploy acquisition systems with the aim to gather output data from the equipment. Nevertheless, implementing MTConnect waives the need for standalone data collection tool as this step can be operated by a computer being on the same network of the equipment for monitoring purposes. Accordingly, the storage requirement of the system can be achieved by using a database being networked with the same computer. This step is of great importance for the manufacturers as it allows for analyzing the historical data to perform prescriptive and predictive analysis. Lastly, the utilization of the collected (historical) data, including the current measurements, is a vital step of the acquisition system, which is usually communicated through data visualization with the manufacturers for facilitating the decision-making process.

A wide range of proprietary techniques have been employed by the large-scale machine tool builders for developing the acquisition system which are majorly customized for a specific operation besides being highly expensive [14]. However, many small- and medium-scale manufacturers do not possess a cost-effective system in order to make use of the piled-up data from their machine tools and hence the generated data are discarded over time [13]. Advances in developing free or open-source software have paved the way to access an acquisition system that does not count on exclusive and high cost commercial software. Furthermore, open-source software allows for free modification as well as customizability. Consequently, this paper contributes to literature by presenting the development and implementation of machine monitoring solutions, which allows for rapidly deployable decision support system. Our solution relies on the detailed applications of the open source and royalty-free MTConnect protocol in facilitating the decision making process at different production levels. We propose a Microsoft Excel-based dashboard tool, which organizes the data collected from the MTConnect-based CNC machine tool. The data are stored in a dashboard format that would allow both managers and machine operators to reliably check and save machine data. The organized data are analyzed, and visualization techniques are implemented which allow an operator to effectively make the necessary decisions. The rest of this paper is organized as follows: Section 2 provides the related work on applications implemented using MTConnect. Section 3 explains the basic architecture of MTConnect and describes the process of data flow from the data source to the decision support system. In section 4, the obtained results are presented and discussed. Finally, the conclusions and the directions for future work are provided in section 5.

2. Related work on MTConnect application

Modern manufacturing systems are augmenting connectivity in the factory through implementing various network strategies that can potentially lead to enhanced productivity [6]. In this direction, an effective networking within the factory cannot be achieved unless the manufacturing equipment can communicate via a common protocol. MTConnect is often the choice for the protocol of communication for machine tool applications [1]. MTConnect has attracted substantial attention due to its unique characteristics being open source, interoperable, extensible, and easy to be used and has been implemented in many applications. Franca et al. [4] used MTConnect data in order to collect machine tool probe results in a local implementation. Atluru and Deshpande [1] conducted an analysis on the smart machine platform initiative (SMPI) test-bed using a GE- Fanuc controller to enable data monitor of the machine tool. In contrary to these local implementations, Edrington et al. [3] developed a web-based machine monitoring system that collects the data, and performs analysis for any MTConnect compatible machines. Vijayaraghavan et al. [16] used MTConnect data from a machine tool in a case study for process planning verification. Shin et al. [15] established a virtual machining model using STEP-NC files as the process data to produce the MTConnect-based data for the machine monitoring system. Lei et al. [9] developed an MTConnect-based methodology for web-based monitoring system implementation. Literature includes alternatives to MTConnect such as FANUC MTLink [1] and OPC UA [12] in terms of application and the protocol of data exchange, respectively. Comparing to MTLink, MTConnect has the advantage of being an Open Source system while comparing to OPC UA, MTConnect has the limitation of serving as a unidirectional path. The current work presents a local implementation of MTConnect-based machine tool monitoring systems that is capable of collecting data output from a CNC machine. We use Microsoft Excel to enable efficient data collection, storage and visualization. The collected data are used for monitoring production status, energy consumption as well as developing preventive maintenance analysis of the CNC machine tool in a dashboard format.

3. Architecture of MTConnect-based DSS

The system architecture of the proposed MTConnect-based DSS is depicted in Fig. 1. It consists of three layers: Physical devices, Server PC, and Application-DSS. The details of each layer are described in the following sections.

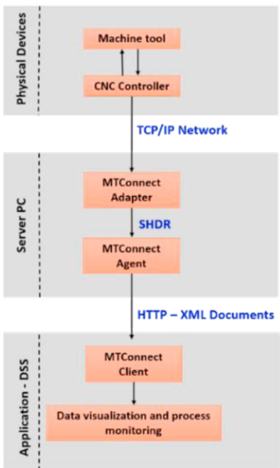


Fig. 1. Schematic illustration of MTConnect-based Local Monitoring System

3.1. Physical Devices

The first layer includes the physical devices where the real-time machining data of the machine tool are collected from the CNC controller. In this study, in collaborative work with IMOCOM Company [5], a Hartford Small Machining Center SMC-5 is used. This machine uses a Mitsubishi Electric M80 Series controller. Modern CNC controllers such as our case can provide real-time information including power status and axes positions of the machine tool. This machine allows linear movements in three axes and has a spindle driven by a silent motor. The machine is shown in Fig. 2.

Fig. 2. Hartford Small Machining Center SMC-5 at IMOCOM

3.2. Server PC – MTConnect Adapter and Agent

Through TCP/IP network, the physical machine tool is connected to one of the core elements of the MTConnect, called MTConnect Adapter. This connection enables transmitting all the real-time machining data from the CNC controllers to the MTConnect Adapter. When receiving the data, the adapter assigns a unique ID to each data item and converts them into SHDR (Simple Hierarchical Data Representation) format. Also, the adapter timestamps each data item. Next, these data will be associated with MTConnect data items and finally, MTConnect adapter filters the duplicated data and continuously sends the filtered data to the MTConnect Agent, another core element of MTConnect.

MTConnect agent includes an MTConnect-based machine tool information model. This model is an XML file representing the logical structure of the machine tool, such as the critical components and their data items. MTConnect Agent receives the SHDR data from the MTConnect Adapter and associates each data item with its corresponding component in the information model using their unique IDs. Doing this, data from different sources can be grouped to characterize the status of certain components. MTConnect Agent has the role of a web server that formats all the real-time data into XML files and sends these XML files to other applications according to specific HTTP requests using the TCP/IP protocol.

3.3. Application – DSS

This layer consists of the decision support system, which is developed using Microsoft Excel. The Excel-based dashboard is populated by the MTConnect data using which the operators can effectively monitor the CNC machine. The dashboard has a database, which locally stores the timestamped machining data. Excel is a powerful tool that enables both back-end VBA code development and front-end analytics using the stored data. Thus, Excel not only serves as the database of data but also the front panel, which interacts with the operators. The MTConnect Agent delivers easily- accessible data at specific time intervals using the VBA code and query tables from Excel. Excel is equipped with a built-in XML parser to process and map data to its cells. Analyzing the data, we propose a DSS that provides intuitive data visualization for facilitating the decision making on three applications: i) production control, ii) preventive maintenance, and iii) energy consumption analysis.

The dashboard organizes and analyzes the data for the above applications in three sections where each section presents statistics relevant to the machine performance that enable taking the necessary actions.

The first section contains information about the production cycle time per part produced by the machine. Additionally, the user can visualize the percentage of the time that the machine has been active, in addition to the percentage of idle time, setup time and downtime. It is also possible to access information about the number of parts produced during a specific period.

The second section contains information that concerns preventive maintenance decisions. The user is provided with a table of maintenance activities that should be considered to perform depending on the effective machining time. The DSS tool indicates the remaining number of hours left before a specific maintenance activity should be performed. Also, the severity of each maintenance activity is shown considering the number of hours left before the next maintenance activity is recommended to be performed.

The third section provides information for the energy consumption analysis. The tool presents a graphical analysis of the output power over time for each motor of the machine, i.e. the three axes and the spindle. The DSS also provides the total machine energy consumption, as well as the energy consumption for a particular part over a specific period of time.

4. Results and discussion

Here, we present the results obtained from the development of the MTConnect-based DSS tool according to the architecture described in section 3. We show the DSS results on the CNC machine for the three applications: production control, preventive maintenance, and energy consumption analysis.

4.1 Production control

Production control topics involve monitoring of the machine performance to obtain useful information for the relevant decision making. The information about the effective machining time, idle time, setup time and downtime are important to facilitate production planning decisions. MTConnect integration enables us to obtain such information using the collected data. Here, we used three types of data items to obtain information about machine performance. The item Controller Mode shows the current state of the controller, which can be AUTOMATIC or MANUAL. The item Execution Status indicates the status of the controller, which can take the states READY, STOPPED, ACTIVE, INTERRUPTED and WAIT. The item Emergency Stop represents the status of the emergency stop signal of an equipment, which can show ARMED or TRIGGERED. Fig. 3 shows an example of the data obtained using a specific HTTP request.

Timestamp	Type	Name	Id	Sequence	Value
2020-05-10T22:30:31.526550	Execution	execution	GFAgie01-path_basic_2	435178537	READY
2020-05-10T22:31:01.814554	ControllerMode	mode	GFAgie01-path_basic_3	435178865	MANUAL

Fig. 3. Snapshot of the Obtained Data from MTConnect Using HTTP Request

Using these three data items, the effective machining time is calculated by summing the time of the Controller Mode with status AUTOMATIC representing that the machine is busy working on a workpiece. To calculate the idle time, we considered the time the Controller Mode is in the MANUAL status and the Execution Status is in STOPPED. The setup time was calculated using the time the machine has been in the MANUAL state for the Controller Mode and READY for the Execution Status. Finally, downtime is the time the Emergency Stop is in the TRIGGERED mode.

It is essential for the user to analyze the above statistics for each part type in addition to the machine tool. MTConnect provides information about the part being manufactured through the data item Program which represents the name of the program that is used to manufacture a certain part. According to the required specifications for each part such as geometry and shape, a specific group of manufacturing process steps is considered to produce each part. These steps are grouped and uniquely assigned to the corresponding program which is distinguishable for each specific part. Thus, it is possible to differentiate the part information according to the program ran to manufacture each part. Accordingly, using MTConnect collected data, we have access to the information about machining time, idle time, setup time and downtime for each specific part being manufactured during the preferred period of time.

The decision support system incorporates the above information and provides data visualization and analysis functions to provide an intuitive perception of the process. To offer user-friendly and easily accessible interfaces, the DSS was designed as follows (see Fig. 4). The user can choose a desired part from a depository of the manufactured parts specifying the preferred start and end dates. Next, four different graphs will be generated presenting the percentage of machining time, idle time, setup time and downtime for the selected part as displayed in Fig. 4. Also, the information about the total time of data acquisition, and the total number of parts produced during the data acquisition period are provided.

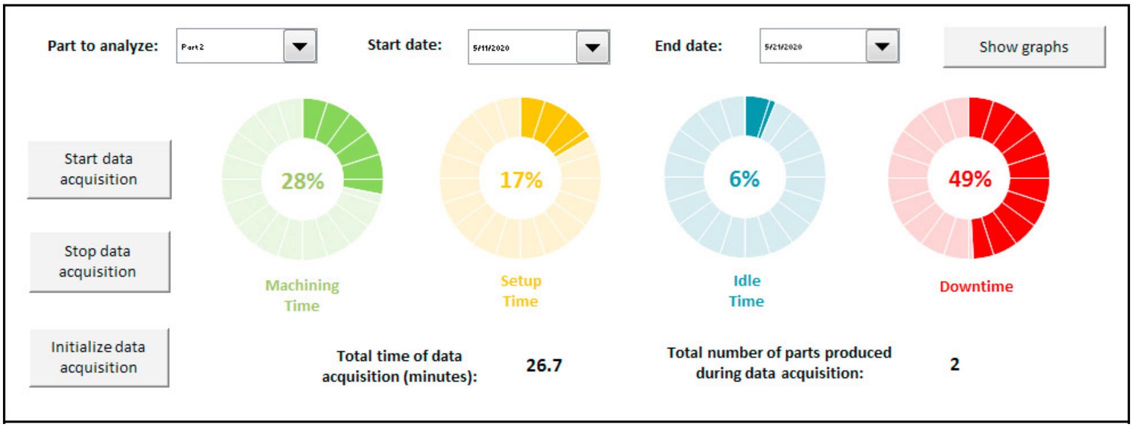


Fig. 4. DSS Interface Visualizing the Analysis on Production Control

The above information is valuable for production planning and control due to several reasons. The information on the production cycle time of each part can be used for comparison with the historic data to identify unusual situations that affect the machine productivity and thus the production planning. For instance, higher values of production cycle time may be due to high setup time that has resulted from process anomalies during the production process. This way, the DSS tool can support the operators/managers to detect potential problems and facilitate the decision-making process.

Furthermore, the information about the total number of produced parts provides the marketing people with the historical data about the machine production rate during the selected period of time. This information is beneficial since it can be incorporated for future sales planning.

4.2 Preventive maintenance

Maintenance is the process of defending machinery against deterioration, which, according to Bevilacqua and Braglia [2], can represent from 15% to 70% of the total production costs. Hence, its improvement can imply a great increase in profits [7]. Routine maintenance practices based on corrective and fixed-interval maintenance are still very common although they are substantially inefficient. Corrective maintenance leads to delays, overtime, and product rejects, while fixed-interval maintenance often implies excessive labor costs [7].

MTConnect collected data can be utilized to improve preventive maintenance protocols, especially in cases in which predictive maintenance, which relies on vibration, process parameters, temperature, tribology, or image monitoring is not convenient due to its complexity or relative costs. A combination of data of the actual operating time in conjunction with information extracted from manufacturers' catalog, national standards, industrial engineering time-and-motion studies, or historical experience [7] can lead to equipment-driven maintenance. Such analysis is valuable to determine the recommended operating time before maintenance practices. This way, the maintenance process is self-scheduled by the machinery and is more effective and efficient in comparison with common fixed-interval maintenance.

According to a document provided by IMOCOM [5], specialized maintenance (third level maintenance or above) should be performed every three months which is equivalent to 1000 working hours according to the same document for the Hartford Small Machining Center SMC-5. This is approximately equivalent to 16 operating hours per working day (HWD) assuming 30 days per month and 5 working days per week. The HWD value is calculated as HWD = rb×tc/T where rb is the ratio between the number of days and business days in the week (7/5), tc is the number of recommended operating hours before maintenance (1000) and T is the equivalent period in days (90).

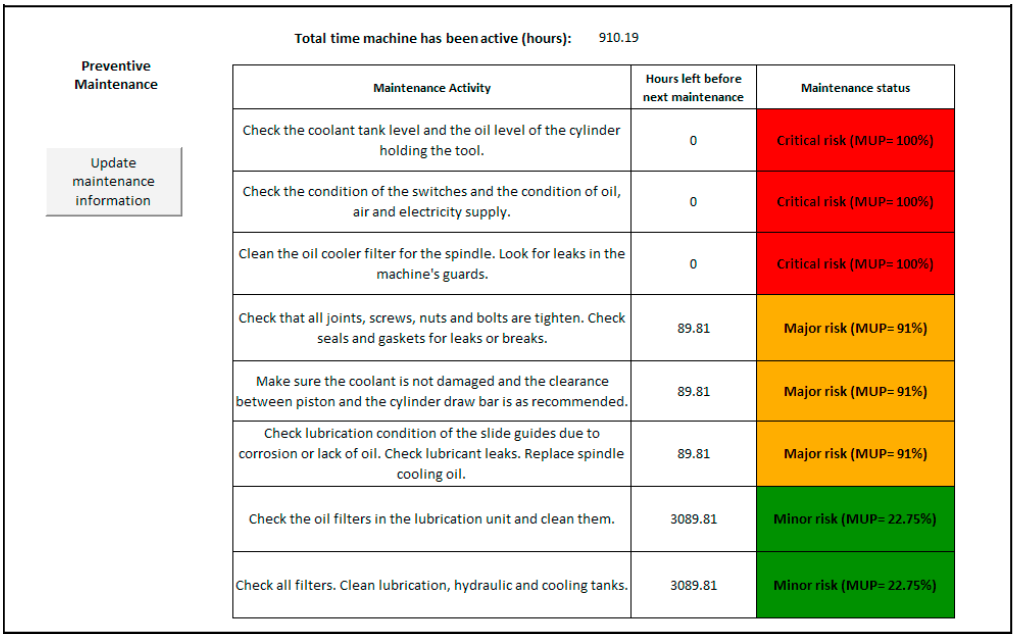
If we consider the case in which the machine is underused, for example, being used on average for 4 hours per working day (such as the CNC machine in a university laboratory), it would imply that specialized maintenance should be done once a year approximately. It is important to notice that this is a simplified scheme, factors such as operating conditions can greatly affect maintenance needs and further analysis is required. In our case, by using the recommended operating time before maintenance from the catalog and calculating the real machine usage time embedded within the MTConnect, it would be possible to determine the recommended maintenance schedule.

To facilitate efficient maintenance planning, the DSS in this work is designed to provide the user with alerts on the recommended maintenance activities using the actual operating time of the machine. The alerts are shown for different scenarios and not only when the maximum operating time has been reached, hence the preventive maintenance. To accomplish this, we determined an indicator using which a mapping was developed to warn about the necessary maintenance activity. We defined the indicator as Machine Usage Percentage (MUP) which is calculated as the proportion of the time that the machine has been active to the maximum operating time as:

$$MUP = \frac{Time\ machine\ has\ been\ active}{Maximum\ operating\ time} \tag{1}$$

This indicator is used along with percentage ranges defined by the user in the DSS to provide the operator with the information about the recommended maintenance activities. For this, the user is required to decide about percentage ranges that will differentiate among the maintenance activities according to the MUP value. Four percentage ranges are considered and labeled as minor, moderate, major, and critical risks. For instance, the user may decide that having a machine usage under 85% signifies a minor risk, between 85% and 90% a moderate risk, between 90% and 95% a major risk and over 95% a critical risk.

Once the desired ranges have been selected by the user, the total time during which the machine has been active (in hours) is shown (see Fig. 5). Furthermore, here, the remaining hours before the next maintenance activity is recommended to be performed are presented in a list as displayed in Fig. 5. The recommended activities are specific to the machine tool used in this study which were obtained from a document provided by the manufacturer. As shown in Fig. 5, for each maintenance activity, the severity is expressed by different colors depending on the involved risk level defined by the user. For instance, if MUP is in the minor range defined by the user, the corresponding maintenance status is shown by a green message. However, if the MUP value is in the critical range defined by the user, the maintenance status will be shown by a red message recommending that the machine should not be used before maintenance is performed.



Maintenance Activity	Hours left before next maintenance	Maintenance status
Check the coolant tank level and the oil level of the cylinder holding the tool.	0	Critical risk (MUP= 100%)
Check the condition of the switches and the condition of oil, air and electricity supply.	0	Critical risk (MUP= 100%)
Clean the oil cooler filter for the spindle. Look for leaks in the machine's guards.	0	Critical risk (MUP= 100%)
Check that all joints, screws, nuts and bolts are tighten. Check seals and gaskets for leaks or breaks.	89.81	Major risk (MUP= 91%)
Make sure the coolant is not damaged and the clearance between piston and the cylinder draw bar is as recommended.	89.81	Major risk (MUP= 91%)
Check lubrication condition of the slide guides due to corrosion or lack of oil. Check lubricant leaks. Replace spindle cooling oil.	89.81	Major risk (MUP= 91%)
Check the oil filters in the lubrication unit and clean them.	3089.81	Minor risk (MUP= 22.75%)
Check all filters. Clean lubrication, hydraulic and cooling tanks.	3089.81	Minor risk (MUP= 22.75%)

Fig. 5. DSS User Interface for Preventive Maintenance Application

4.3 Energy consumption analysis

The information concerning the energy consumption of the components of a CNC machine is important since it can be used to evaluate the performance of the machine and identify possible unusual situations. This analysis can also be used for estimating the energy cost associated with each specific manufactured part.

MTConnect data can be used to obtain information about the consumed energy of the four components of the CNC machine, i.e., X-axis, Y-axis, Z-axis, and the spindle. To perform the analysis on energy consumption, we used the data item Load from the MTConnect collected data. This data represents the measurement of the actual versus the standard rating of a device. In other words, this value is a percentage of the maximum power rating of each component of the CNC machine. The servo power rating of each component is obtained from the Hartford Small Machining Center SMC-5 manual and listed in Table 1. For instance, a value of 80% for spindle load, signifies an output power of 4.4 kW for that component.

Table 1. Power Ratings for each Component.

Component	Power Rating (kW)
X-axis	1.5
Y-axis	1.5
Z-axis	1.5
Spindle	5.5

Given this, the output power for a component of the machine at any time can be calculated using the following expression:

$$P_m = P_r \times LOAD \tag{2}$$

where P_m is the output power of a component (kW), P_r is the power rating of a component (kW), and $LOAD$ is the percentage of the maximum power rating of a component. Since our interest relies on obtaining information on energy consumption, the following expression is used:

$$E = \eta \times \int_{t_1}^{t_2} P_m(t) \cdot dt \tag{3}$$

where E is the energy consumption of a component (kWh), $P_m(t)$ is the output power of a component (kW) which is a function of time, $t_1$and t_2 are the initial and end time, respectively (hours) during which the energy is calculated and η is the energy efficiency rating of the motors of the components. In this study, we conservatively assumed a 90% energy efficiency rating for all servo motors recommended by IMOCOM. We collected the data in interval time equal to one second.

The DSS interface is designed as shown in Fig. 6. In this application, the user will be provided with a graph showing the power output for each component over time for a comparative analysis. Moreover, the user has the option to visualize the graph only for a specific component.

The user can view the total energy consumption of the four components for all the parts manufactured by the machine. Furthermore, the user has the possibility to analyze energy consumption for one specific part during a specific period of time. For this purpose, the DSS allows to choose the part, the start and end dates for the analysis (Fig. 6).

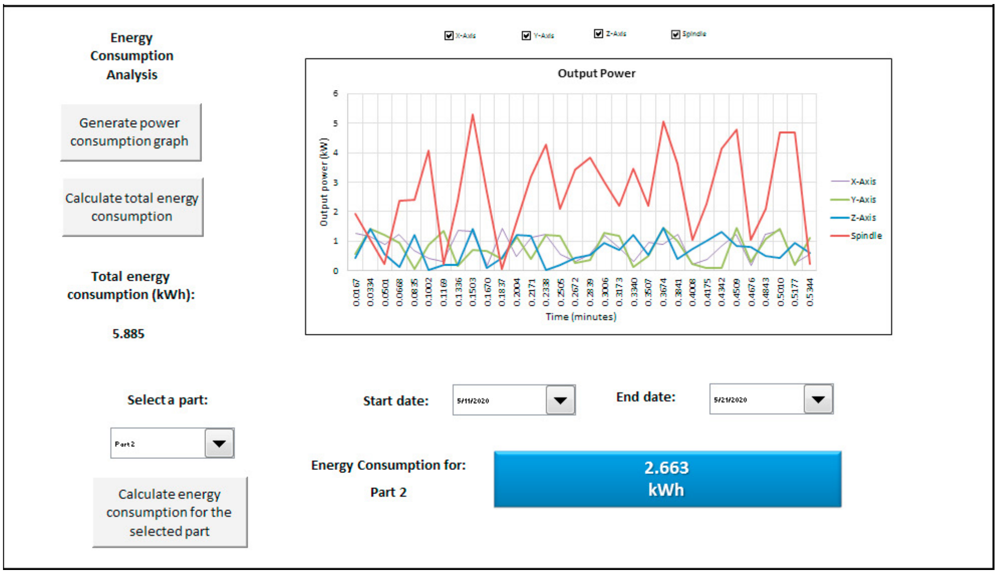


Fig. 6. DSS Interface for Energy Consumption Analysis

The information on energy consumption is useful for the managers and operators. The output power graph can be used to identify unusual situations or potential problems in the performance of the machine relevant to its four components. For example, high values of output power for a specific component can be a signal of a potentially unsafe operation of the machine. Hence, the operators or managers can take concrete decisions to detect the cause of this situation and contemplate possible solutions.

Furthermore, one of the important considerations nowadays is energy and resource consumption in production and manufacturing. The information on the efficient use of machine tools in the production process is valuable for the engineers and designers of the tools. Processes and systems towards developing green manufacturing facilities can be analyzed using the DSS. The provided information can allow for mechanisms with the aim of process monitoring and optimization with respect to energy and resource minimization, the means to lean and sustainable manufacturing.

Lastly, information on energy consumption can be used partially for the estimation of the total cost of energy as well as the production cost per part.

5. Conclusions and future work

Machine tools play vital roles in manufacturing companies. The efficiency of a manufacturing process relies mainly on the performance of the machine tools used in the process. In this context, decisions taken by managers and operators to improve the performance of the devices are significantly important. Thus, the decision-making process has become a fundamental activity in which accessibility to precise information is essential to enhance the process. A shop-floor manufacturing system would substantially benefit from effective decision support systems (DSS) which convert the raw data to information that can be easily used and analyzed by the user in the decision-making process.

It is important that the DSS be fed with real-time data collected from the machine tool. In this study, MTConnect protocol was used to communicate with the CNC machine for data collection. This protocol was easily implemented and used for the purpose of real-time monitoring of the machine tool. Using the data collected through the MTConnect system, a DSS was developed in Excel to organize, present, and visualize the information in a user-friendly format.

The DSS facilitates the analysis of three applications: production control, preventive maintenance, and energy consumption analysis. The design of the DSS and descriptions of the three applications were explained. We presented the various analyses that can be performed in the three applications including the production planning decisions that can be efficiently enhanced by the manager or the operator of the machine tool using the DSS visualized information.

We should note that the developed DSS presents a local solution for machine tool monitoring. While cloud solution has its own pros and cons, either one could be the proper choice depending on the application. For example, the proposed local solution has the advantage of cybersecurity since the local storage of the data is less vulnerable to security problems that are involved in Internet connection. Furthermore, a local database allows for faster insertion and retrieval of data comparing to the cloud solution.

It is noteworthy that MTConnect is a protocol that allows to collect various types of data besides the ones presented in this study. Future work can include data on velocity, temperature, pressure, and acceleration which are of potential value for further analysis to increase performance of the machine tool. Furthermore, sensors can be installed on the machine tool to collect additional useful information which can lead to develop a more robust DSS tool by involving other machining parameters. Obtaining more data will allow for additional future work to focus on the implementation of artificial intelligence and advanced data visualization and analytics algorithms.

Finally, MTConnect can serve as a standard interface across a variety of machine tool platforms. Hence, it would be possible to capture the information from various machine tools utilizing a similar set of software tools. This ease of implementation further reduces the deployment and development time and cost in factory environments. Accordingly, future work can consider implementing MTConnect in multiple machine tools.

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