Estimation Of Energy Consumption By Theoretical Calculations And IOT Based Approach In Machining Process

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Abstract

A considerable amount of energy is consumed by the machine shops for material removal processes. Through a digital twin-based experimentation approach using Thing Worx, we have focused on determining a theoretical calculation to determine the exact amount of energy consumption during the material removal process. We have considered three models for machining operations i.e., Turning, Facing and grooving. We are calculating the power consumption by considering two variable parameters a) Cutting speed and b) Material Removal rate (MRR). Adding to that, we have also demonstrated a simulation using Autodesk Fusion 360 for the energy estimation for different cases. This IoT-based approach will convert conventional shop floors into smart shop floors as per Industry 4.0. This IoT-based prediction will help machine shops develop potential ways to save energy costs. We have considered different machining parameters (tools, material, geometry of the job, etc.) for better and more accurate results.

Keywords: Industrial Internet of Things, Digital twin, CNC machine, Energy consumption, Industry 4.0

1. Introduction

Industry 4.0 is revolutionising the manufacturing industry with the application of the IoT, AI, Machine Learning etc. IoT has a special place in this trending industrial era. The IoT is nowadays used on a large scale in industry and is termed the Industrial Internet of Things (IIOT). IIOT has made the work a lot easier and safer, as it helps the operator check the machine's workability, tool life, CNC code, etc. Additionally, traceability of the products since their initial stage is now achievable because of IIOT and its vast applications. IIOT is equipped with a variety of sensors and software that help in inspecting various machine parameters. Some of the advantages of IIOT are real-time data interfacing and generating and storing the data values of the machines used in an industry. IIOT has helped technicians fix all the machine errors and solve the customer's inconvenience.[1]

Since CNC machines play a vital role in machining processes for various applications, such as milling, turning, facing, undercutting, and so on, since the CNC machine is not a fully automated device, it needs some noticeable human assistance for loading and unloading purposes for the job parts. Also, for setting and running the CNC programme on the machine, an operator is needed for these tasks. With the help of IIOT, one can collect real-time data on the CNC machine in operation. Data acquisition and analysis of the data are now possible. We can gather the data, store, and analyse it, and send it to the server for further studies.

With the help of Thing Worx we can easily collect the real time data from the CNC machine. It is a set of IOT development tools which support production, connectivity, analysis, and many more aspects that make it possible to work with IOT. In this project, we connect Kepserver with Thing Worx in order to monitor the whole working process of the machine. For this, we use Thing Worx Cloud for the transmission of data. Thingworx was created with a specific goal in mind: to control and view live data through the use of a medium that acts as a data transfer source. This thingworx platform has coined a great place in the field of thingworx. Where we can virtually see the operations of industrial machines from anywhere with an internet connection are a complete end-to-end technology which has been designed for industrial working purposes. This helps in reviewing the working of the machine, its live running status, and also the control of the machine. as they created an augmented reality experience in the industry. A great place in the industrial internet of things, as thingworx created a coin. Because of their real-time viewing of the working machine, control of the machine, and many other specialties, most industries that have developed IOT, also known as industrial internet of things, have had a significant impact with thingworx. As they helped in creating their own customised platform, which will be suitable for the customers and according to their needs, as they are more user-friendly and more user-relative. So, customers can develop their own customised thingworx platform in which what types of machine work should be viewed and what types of machines running processes should be shown in the augmented reality screen in the thingworx platform.

Since energy is the main source of any machining process, in this paper we are focusing on calculating the energy consumption in a machining process. The main goals of this paper are to derive the theoretical calculations, simulation, and set up a machine learning algorithm experimentation for actual energy consumption data. As the machine will consume a considerable amount of energy for operations[2]. CNC machine can perform milling, turning, facing, undercutting etc. and each process consume a considerable amount of energy according to various parameters such as spindle load, feed rate, flow of the coolant, offset movement etc. Thus, we will be implementing the machine learning algorithm into the Thingworx, where the software gives command to CNC and collect the real-time data.

2. Literature Review

2.1 IIOT, cloud computing & Industry 4.0:

S.V. Anil Kumar et al. has proposed a detailed study of internet 4.0, which occurs when a man, machine, and materials communicate with one another via the internet and explained the collaboration between the internet and industry and the good things that result from that [3]. In the context of Industry 4.0, the future generation of production is a result of big data and digitization[4].[5] As he explains, the "smart factory" is the next stage of the modern factory, which includes IoT based factories and monitoring technology which is used to enhance the data management service for collecting manufacturing information, result in very less rejections of the job parts and the collection of real-time monitoring data for production, planning and scheduling of the job parts. In smart shop floors, the Hidden Markov model was used for auto manufacturing job [6]. Throughout addition, in the manufacturing phase, end-to-end digital interrogation necessitates the interconnection of all physical resources on the shop floor to the industrial network for collaboration. The real-time data is collected via an RFID sensor, which serves to indicate the smart WIP's current location and ambient conditions. The internet, big data, digital twin and other information technology that will be employed in the manufacturing industries are all part of a digital twin-based industrial internet towards the smart manufacturing.[7] In comparison to the traditional perspective of dedicated manufacturing resources, these services require additional information. IoT based approaches and cloud computing are two recent advances in ICT (Information and Communication Technologies).

2.2 Modelling and monitoring:

In [8] they did research on digital twins (DT) for CNC Machine Tool in order to make CNCMT intelligent. Modelling technique for DT is developed, a relation between physical and digital entity is studied, and an independent Digital Twin model is provided. It involves the development of technologies ability to monitor and analyse data from an energy perspective, as well as typical industrial measures require a significant amount of energy. The purpose of the proposed prediction process was to generate a preliminary forecast; however, during the development and application phase, the process was designed to predict while evaluating. Manufacturers' energy costs are rising due to the impact of both rising energy prices and rising production needs; hence, decreasing the manufacturing processes that use less electricity assist manufacturers both economically and environmentally.[9] An empirical model is used to categorise the link between power consumption and machining parameters in material removal processes, and unit process energy usage concepts are developed through empirical modelling techniques, which entails monitoring energy consumption in relation to process parameters. The industrial internet platform's collaborative architecture connects the physical and cyber components, capacitating the resources, data, and knowledge available everywhere in the production system, which has become a hotspot in academic and industrial circles.[10]

2.3 Energy consumption and evaluation:

According to research published in [11], the new developed Internet of Things (IoT) technologies was used to create an energy management system. As a result, advantages of proposed system are demonstrated through an industrial application. In an IoT based energy monitoring system, the key methods for obtaining energy consumption of machining tool and machine workshop are fully shown [12]. Despite the fact that they have proposed that IoT methods can be used for real-time acquisition of power consumption in any machining operation, and various functions are improved and confined into cloud services. The data gathering layer, an ECEA Network, controlled services, client, IoT layer, and real manufacturing lifecycle layer are all part of the proposed IoT and cloud-based ECEA system's architecture. [13] It will be considerably easier to advance potential energy-saving measures throughout the product design and process planning stages if an accurate prediction of unit process power consumption can be made. They were successful in developing a modelling approach to compare process characteristics and energy consumption data from a large number of machines. [14] Separated the energy variables from the CNC machine used for cutting the additional removal of material w.r.t the actual parameters. Using the measured data, an empirical model was created in terms of the process parameters.

2.4 Working and calculations:

[15] The energy consumption of hard stainless-steel turning was determined. Calculating the power usage during the turning process of components, where the depth of cut is frequently less than the tool's nose radius, using the resultant cutting force and measured cutting forces. Rather than relying solely on the principal (tangential) cutting power, as is customary, the resultant cutting force was used to compute energy consumption, and the machining parameters were established on the machining responses stated, which included machining energy. According to the findings, spindle speed was inversely associated to cutting force, while feed was directly proportional to cutting force [7]. A work that builds a real-time data-driven joint mechanism in the fixed production framework for smart manufacturing and uses this mechanism to solve the problem. To boost the capacity of process monitoring, some production planning systems have been established.[16]

2.5 Gaps in literature:

From the above literature papers, it gives us clear indication that the correlation of IoT based approach using Digital Twin concept for energy calculations is being untouched. Also, the comparison of theoretical calculations, simulation-based models and experimentation data is not done for the energy consumption data in any of the literature. Thus, the accuracy comparison is needed to be done for better creation of an accurate energy consumption model. [17] Continuous iterations of all the calculations and changes in the parameters as per the experimentation results is not seen in the previous papers. A proper mapping of all the data whether the energy model can predict the energy consumption properly or not is not mentioned in the literature papers yet. The fixed position assembly method for smart manufacturing described in the previous research studies lacked a real-time data collaboration mechanism for remote access monitoring system.

3. Methodology

For an experimentation purpose, we designed a model. The general data like spindle speed, tool motion, offset position, Coolant on and Off status, total time for the machining process, total time for cutting process, how much energy has been used for the whole operation and energy consumption while turning or facing generated by the CNC machine. Then we performed theoretical energy calculations using some formulas. Then we did simulation in Autodesk fusion 360 to check what is the cutting time and other parameters and we got some data from that cad software.

Experimentation using CNC machine in which we will collect real time data through Thing Worx software and there will be some architecture connected between Thing Worx and CNC machine including various sensors and servers. The real time values will be shared in an application server where these servers will display the real time working of the CNC. Then with this data we will compare all the results and then change the values or parameters which we used in theoretical calculations, the type of equations we need to change, the values which we got from experimentation as discussed in Fig.1

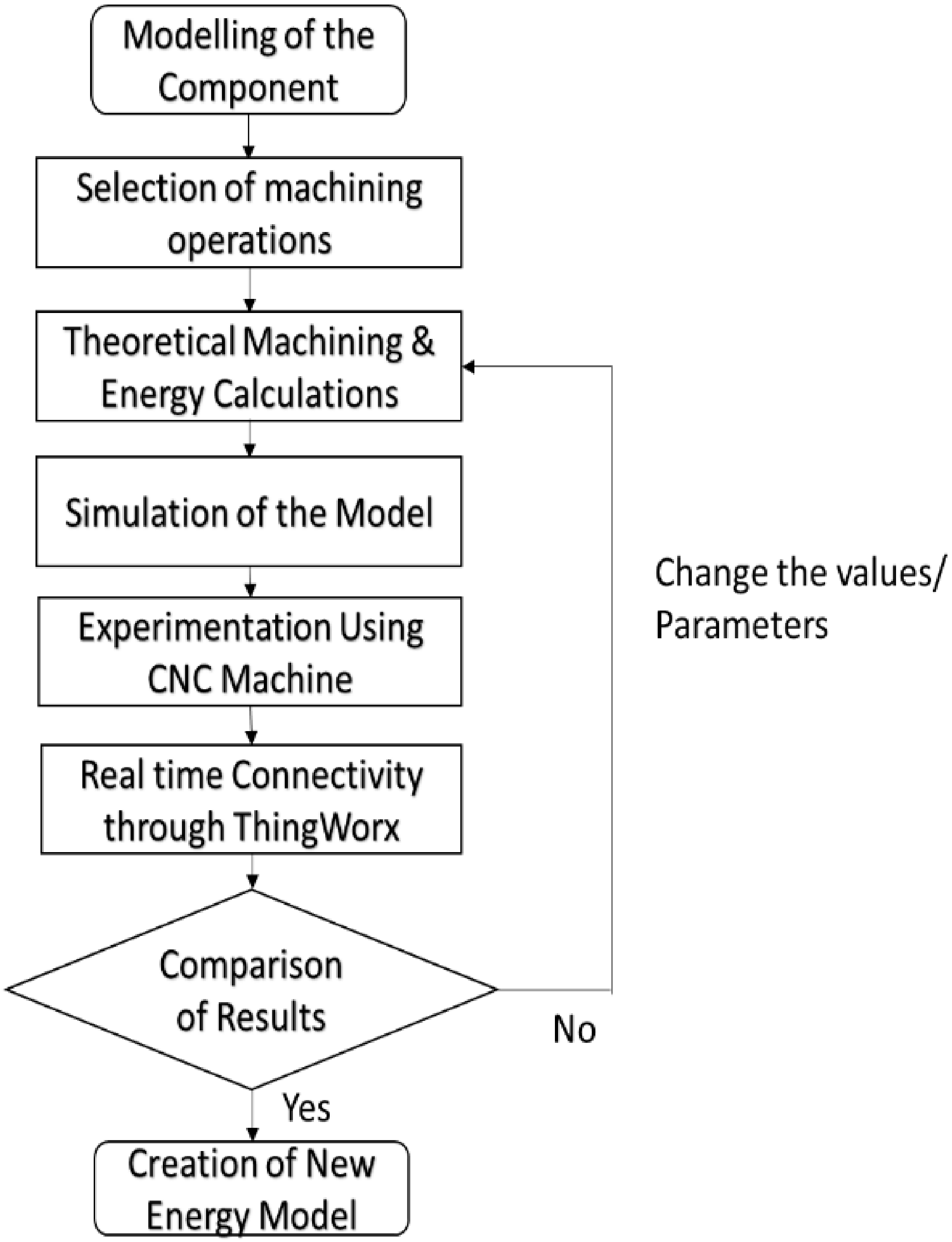

Fig. 1 Methodology

3.1 Theoretical Calculations:

Thus, the first step for estimating the energy we will calculate the power consumption through the assumptions for normal calculations. The power of a motor is the product of the torque and the shaft's velocity. In machining, this is equal to the torque acting on the spindle multiplied by the spindle speed:

In Non-Rotating applications (Turning and Grooving), it is the force acting on the workpiece multiplied by the workpiece's radius times the workpiece rotation speed (the spindle speed).[18]

The method to calculate the power consumption is to multiply the Metal Removal Rate (MRR) by the Specific Cutting Force (K)

DEPTH OF CUT: Dc

FEED RATE: Fr

CUTTING SPEED: Vc

EFFICIENCY: η

Specific Cutting Force (K): A material property that indicates the required force needed to extract a chip out of the workpiece.

$$K = Ka \times CT^{-\mu} \times (1 - 0.01 \times A) \qquad (1)$$

Ka= NORMALIZED SPECIFIC CUTTING FORCE (FROM VALUE CHART)

μ=SLOPE OF KC GRAPH

A= TOP RAKE RANGLE (+7°)

CT=CHIP THICKNESS

CT=Fr= FEED

Ka:

Each material has a specific Cutting Force coefficient that expresses the force in the cutting direction, required to cut a chip area of one square mm that has a thickness of 1mm with a top rake angle of 0°

A:

Each cutting tool has a radial rake angle. We considered the default value as +7°

CT:

It is calculated differently depending on the application.

When the approach angle is 90° (or more), the feed per revolution as the chip thickness, we use CT=μ

Metal Removal Rate (MRR):): MRR is the quantity of material machined per unit time in seconds during various machining operations.

$$MRR = Dc \times Fr \times Vc \qquad (2)$$

Assuming the input values are in mm and K in Mpa (N/mm^2) the result should be divided by 60,000 to get the power in kW.

$$Power = \frac{MRR \times K}{60 \times 10^3} \qquad (3)$$

3.2 Theoretical Calculations results:

The below table includes the theoretical calculation results we obtained from the equations (1), (2) and (3). From the assumptions that we made, we got power values slightly higher compared to simulation and experimentation results. This deviation is observed because of certain assumptions such as, feed rate, spindle speed, and the resulting cutting speed.

Table 1 Theoretical Calculations results

Model no.	**Spindle Speed (rpm)**	**Feed (mm/ rev)**	**Depth of cut/ Width (mm)**	**Cutting Speed (m/ min)**	**Power (kW)**
Model 1	1000	0.2	2.5	150	2.44
Model 2	1000	0.2	2	150	1.95
Model 3	1000	0.2	5	150	4.80

3.3 Simulation:

From the above results, we can study the three cases we have taken into consideration. With the following data, we can easily calculate the energy consumption for three different cases and compare them with the simulation results we will get from the Autodesk fusion 360 software. First step is to create the models for the three machining operations. The first case is the turning operation, the second is the facing operation, and lastly, it is the grooving operation. In all three cases, we have kept the dimensions of the part the same. We will be taking down the data from the setup sheet we will get from the CAD software (Autodesk Fusion 360) and calculating the power consumption for all three cases.

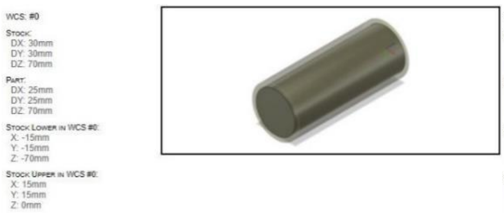

Fig.2 Turning Operation

Fig. 3 Facing Operation

Fig. 4 Grooving Operation

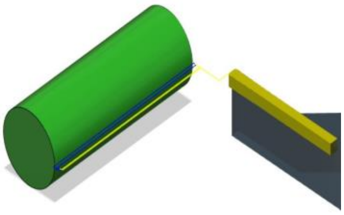

Fig. 5 Model 1

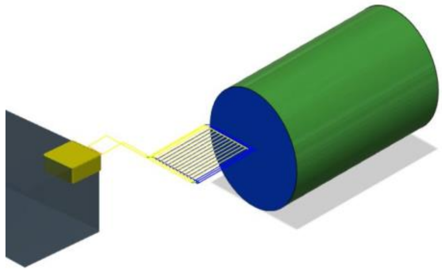

Fig. 6 Model 2

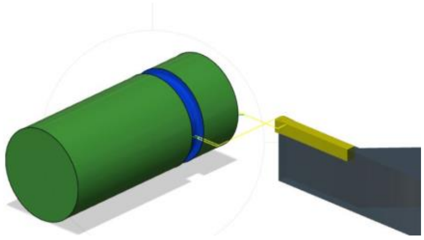

Fig. 7 Model 3

3.4 Simulation Results:

From the calculations using the (1), (2) and (3) equations we have calculated the power consumption for the simulation case. We kept feedrate and spindle speed constant as 0.127mm/rev and 1000rpm respectively. The above table includes the calculations of power consumption which we got with the help of Fusion 360 software and then calculated using the same formulas which we used in theoretical calculations. Also, we assumed the material to be mild steel. There is slight difference in power values of turning and facing operations. The simulation models are previously mentioned.

Table 2 Simulation results

Model no.	**Spindle Speed (rpm)**	**Feed (mm/ rev)**	**Depth of cut/ Width (mm)**	**Cutting Speed (m/ min)**	**Power (kW)**
Model 1	1000	0.127	2.5	94.24	1.07
Model 2	1000	0.127	2	94.24	0.855
Model 3	1000	0.127	5	94.24	2.14

3.5 Experiment Working:

After the calculations we will compare the results with the actual CNC machining process using digital twin concept. Here we have discussed the working of the experiment which we carried out.

The general data like spindle speed, tool motion, offset position, Coolant on and Off status, the total time for the machining process, the total time for the cutting process, how much energy has been used for the whole operation, and energy consumption while turning or facing which will be generally generated by the CNC machine in which it will be connected to the Programmable Logic Controller (PLC). For the IoT device, we use KepServerEx as a medium. This KepserverEx medium is installed with the PLC so that the data which are acquired from the CNC will be collected and analyzed and sorted by PLC which will transfer to the server with the help of KepserverEx. This KepserverEx will be connected to the internet in which the data will be transferred to the cloud medium.

Here Thingworx cloud is the cloud medium for this project as we use Thingworx application for viewing the real-time running data to capture the real-time data and to give a command by assuming the time and energy to be consumed by the machine to do an operation by altering the working motion and speed accordingly. As we use a CNC machine that is embedded with sensors to detect the spindle speed, offset position, tool movement, product count, and more which will be connected to a PLC for collecting the data from the CNC. The PLC is connected with the CNC for collecting the real-time data of the working machine. Now the KepServerEX is connected to the PLC to sort out the data which will be collected by the PLC. The Kepserver will be installed in the PLC by using an installation medium. The sensor data acquired from CNC will be collected by the plc and then the kepware will help to sort out the data i.e., which data has occurred from which sensor this the work of plc which each sensor value and will transfer to the application medium where we can see the real-time working data which are occurred from the sensors connected in plc to detect and collect information of each part in the machine.

The real-time values will be shared in an application server where these servers will display the real-time working of the CNC. The Kepware will send the data to the cloud server where we can open the Thingworx with the same IP address which will be given to the Kepserver to view the real-time operating data. Multiple machines can be connected to the Kepserver to view the Realtime operation of all the machines connected to the single server.

When we give a time and energy level to do a work in CNC it will automatically do the calculation within that time period and by consuming the particular amount of energy it varies the working procedure by changing the speed of the spindle by changing the offset motion and by changing the movement of the tool the CNC will complete the operation within the given time period and amount of power consumed.

4. Experiment:

First, we keep a workpiece in CNC for doing a simple turning operation. Now we do a normal simple turning operation so that we can get the data.

So, we use a workpiece to get details for a simple turning operation. When the machine starts working the CNC while doing every operation like the movement of the tool spindle speed and so on will be acquired and collected and analyzed and sorted by the plc like these data is for the particular operation in real-time those data with the help of ethernet cable is transferred to the KepserverEx which is an IoT medium will transfer data with the help of Local area network to the Thingworx cloud which acts as a cloud platform. Then the Thingworx server from the system download the data from their cloud server and will display it on the screen virtually as it shows the running operation of the whole CNC virtually on the screen and the data like spindle speed, offset position, feed rate, and the energy consumption values are generated.

This Thingworx server will also generate an excel sheet of whole data from the initial working process till the finishing of the process all the data will be collected and separately sorted out.

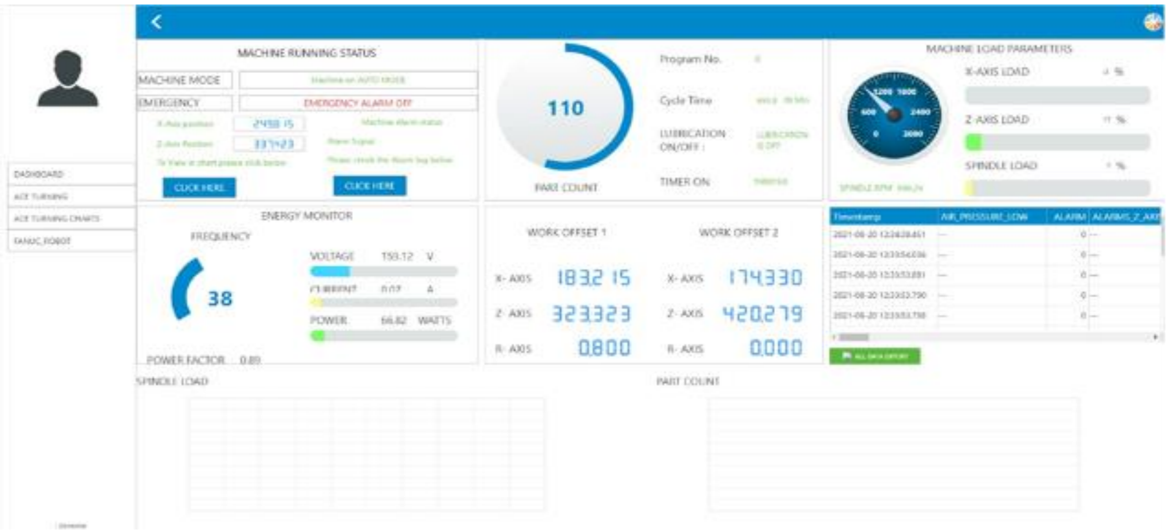

Fig. 8 Thingworx Interface

All the equipment which are required to get the real-time data. There are 2 PLCs in which one PLC is connected with the machine i.e., the CNC machine in which it gathers all the real-time data of the spindle speed, offset position, tool movement, workpiece motion, and so on. Those data will be acquired by the sensors and will be sent to the MCU then will be transferred to the PLC which is connected to acquire the data from the sensors in the CNC.

Now those data will be transferred to the PLC which is connected to the KEPSERVEREX with the help of an ethernet cable. Now those transferred data will be sent to the KEPserver where it will sort the data i.e., which sensor acquired which data and will send the data to the Thingworx cloud in which the people can see the real-time data of the running CNC machine. Now in the Thingworx server, we upload an updated program for the requirement of our project so that when we provide a specific time and specific energy to do the turning operation. So, after we upload the program, we will get an option for providing the required running time and consumable energy to run the application.

Now we set the machine to the initial state for a turning operation. As the first procedure, we keep a new workpiece and the same operation which is a Simple turn. And keep the tool fixed in the position for turning and the process is going to be started. Before starting the process, we will give the energy limit in the Thingworx platform. We start the process to work and the whole working process gets started and the turning process gets started and the whole process will be virtually viewed in the Thingworx platform. As the whole running process like spindle speed, offset position, feed rate, cutting time, and so on.

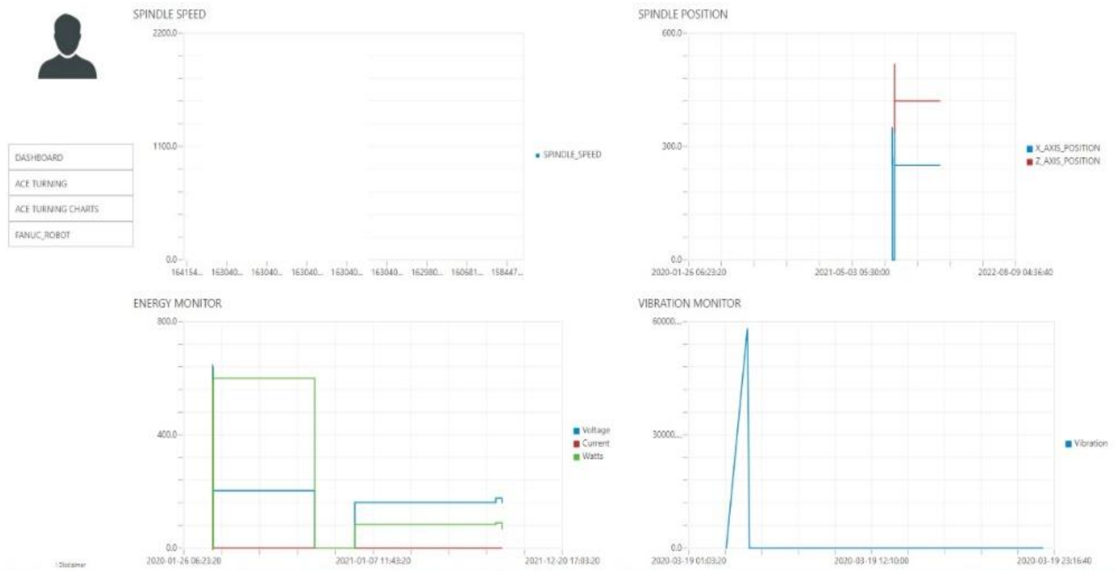

Fig. 9 Graphs generated in Thingworx Platform

These data will be virtually seen in the Thingworx platform and we can see all the running data virtually in the Thingworx platform. This Thingworx platform will generate the Excel sheet of all data from initial to final and successfully the CNC machine has done the process that the whole process has been done within the energy given.

5. Results and Conclusions:

This excel sheet sample below is taken from the thing Worx software. All data is separately collected and sorted out. From these values, we plotted the graphs shown below in below table 3.

Table 3 Real time data gathered with help of Thing Worx

Diameter (mm)	Spindle Speed (rpm)	Cutting speed (m/min)	Depth of cut (mm)	MRR (cm^3/min)	Power (kw)
30	2114	199.4559	2.5	63.32724825	2.267432124
30	2114	199.4559	2.5	63.32724825	2.267432124
30	2114	199.4559	2.5	63.32724825	2.267432124
.	.	.	.	.	.
.	.	.	.	.	.
30	0.127	132.9391	2.5	42.20818013	1.511263889
30	0.127	066.5160	2.5	21.11906813	0.756168234
30	0.127	066.5160	2.5	21.11906813	0.756168234
30	1409	132.9391	2.5	42.20818013	1.511263889
30	1230	116.0505	2.5	36.84603375	1.319272238

For all the three models in the table 4 we observe slight deviation in the power calculation values for all the three cases. As the assumptions and the tool details match in the simulation and the experimentation results the power consumption values are slightly similar.

Table 4 Power consumption calculations results comparison

POWER CALCULATIONS	Theoretical Calculations (kW)	Simulation (kW)	Experimentation (kW)
Model 1	2.44	1.07	1.04
Model 2	1.95	0.85	0.79
Model 3	4.8	2.14	1.81

5.1 Comparison of MRR and Power consumption

We plotted the two graphs through the excel data we got through Thingworx. In this graph, we can clearly see the difference in both, Metal removal rate (MRR) and Power. In this graph we can clearly spot the difference in values of MRR and power.

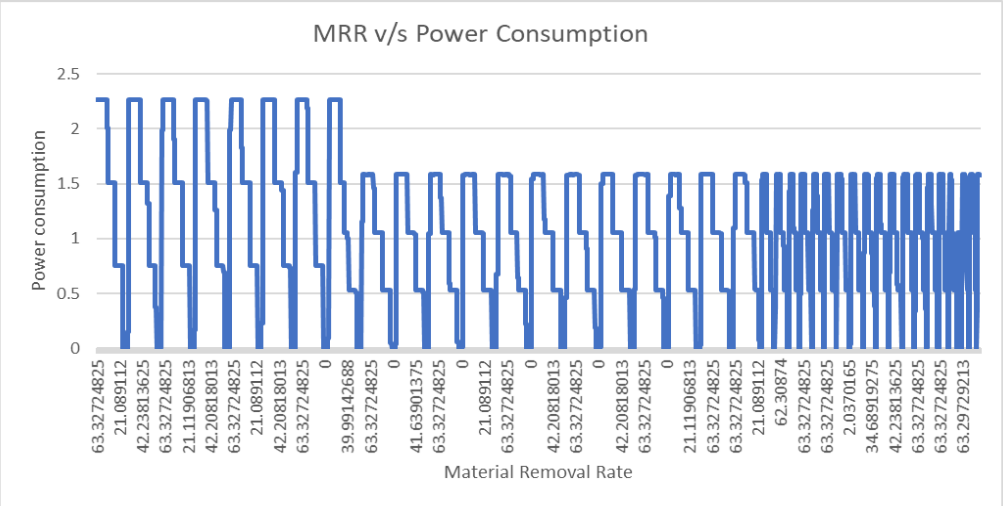

Fig. 10 MRR Vs Power

5.2 Comparsion of Cutting speed and Power:

Here, we are comparing both, the power and cutting speed. In the Thingworx software, we can see how much the amount of energy they can be consumed in each process by the previous operation and by reducing the speed of paarticular operation and increasing the speed of another operation where the consumption of energy amount is reduced and by calculating some amount of energy in the movement of toolbed and increasing the spindle speed.

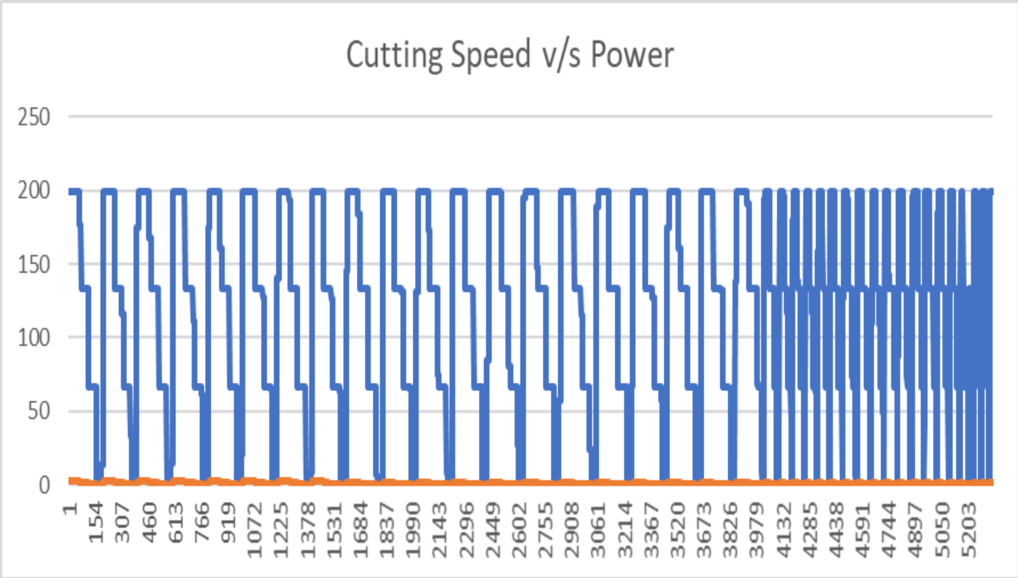

Fig. 11 Cutting Speed Vs. Power

6. Conclusions:

Our aim was to calculate the energy and controlling the power consumption in an CNC machining operation. We compared the power consumption for 3 different cases and iterated the calculations based on the digital twin Thing Worx data. There was difference in the calculations because of the various assumptions considered during theoretical calculations and the simulation results. After that we carried out the actual experimentation and acquired some data from the digital Thing Worx software. After then via continuous iterative energy model process, we got similar results for all the three cases as per our assumptions. From the iteration process we can see the power consumption values are close. By this the IOT has coined a greater position in the industrial field before which has been said as the IIOT which is Industrial Internet of Things and this work has coined a place in IIOT where the consumption of energy has not only been monitored but also have been made the first step in consuming the amount of energy that means we have made the initial step by sending the command to the machine to consume the amount of energy should be used within the limit we have assigned them.

7. Future Scope

We calculated the power consumption values using theoretical calculations, modelling, and experimentation. We revised our earlier assumptions and obtained the final power consumption estimates based on the equations we explored using continuous iterations. We were able to derive a correlation of the power values from the three methods.

With the help of Thing Worx, a IOT platform one can duplicate the process or an object in the digital world. One can perform a lot of experiments and acquire much knowledge using this digital twin technology. Ordinary shop floors can be transformed into SMART Shop floors using this technology. We can also connect more than one CNC machines and work simultaneously in the factory. This will surely save costs and modernize the industries. Also, we can connect the robot arm with the CNC’s and monitor the energy consumption of both robot and CNC machine simultaneously. The real time data obtained from the Thing Worx software will help factories to upgrade themselves to the Industry 4.0.

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