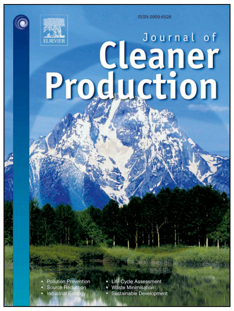

A Simple Energy Usage Toolkit from Manufacturing Simulation Data

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A Simple Energy Usage Toolkit from Manufacturing Simulation Data

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A fundamental problem in the management of energy usage is the inability to clearly predict any possible energy saving opportunities. The cost of both under or overestimating potential returns on investment can be prohibitive to a decision maker. In recent years the simulation of energy usage using existing manufacturing simulation tools has increased in popularity among researchers, but it is decision makers who need to see the benefits of this discipline. This paper proposes an interactive manufacturing energy management toolkit which makes use of existing productivity simulation models for the prediction of energy usage. An interactive Microsoft® Excel® based toolkit is developed to control Lanner's WITNESS® discrete-event simulation software using Microsoft® Visual Basic® for Applications. The toolkit has the ability to predict potential areas where energy saving opportunities can be made within a complex manufacturing line, and is accessible from management presentations and proposals. The interactivity of the toolkit provides an environment which facilitates efficient hypothesis testing. The paper includes an industrial case study where the approach was used to quantify theoretical savings from certain energy usage reduction scenarios within a complex automotive engine manufacturing line.

1. Introduction

The cost of industrial energy used to achieve the required product throughput is set to rise globally in the foreseeable future, as illustrated in Figure 1. This is mainly due to the ever increasing cost of fossil fuels and the need to reduce greenhouse gas (GHG) emissions (International Energy Council 2012). Despite global efforts to reduce energy usage, industrial energy consumption is forecast to increase over the next three decades, especially in non-OECD (Organisation for Economic Co-operation and Development) countries, as shown in Figure 2 (U.S. Energy Information Administration 2013).

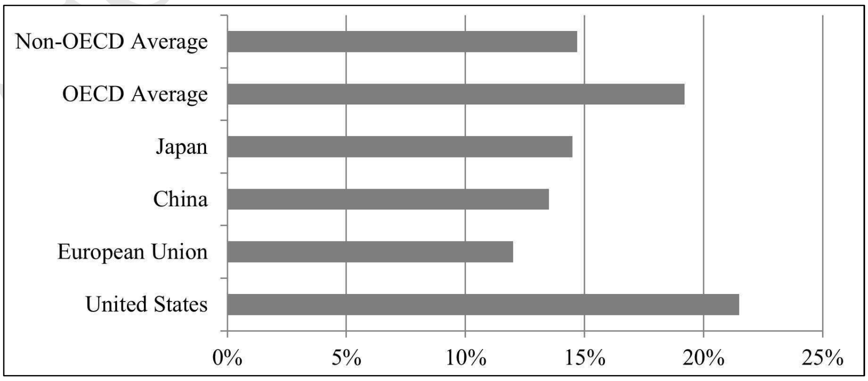


Figure 1: Predicted percentage change in end-user electricity prices from 2011 to 2035. (International Energy Council 2012)

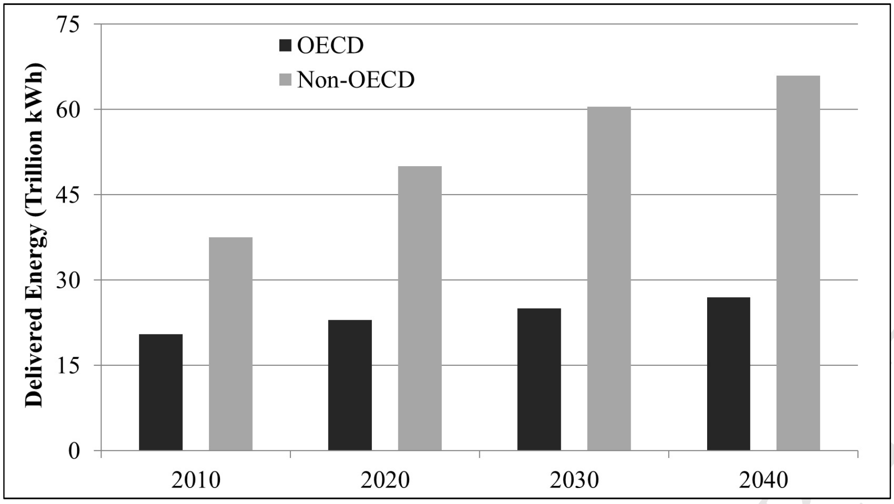


Figure 2: OECD and non-OECD industrial sector delivered energy consumption, 2010-2040. (U.S. Energy Information Administration 2013)

Energy efficiency measures can lead to reduced manufacturing costs as well as improved productivity and competitiveness but are not without their problems (Worrell et al. 2003; Ryan & Campbell 2012). The International Energy Council (2012) state that a major barrier to greater deployment of energy efficient technologies and practices is a lack of awareness, or “visibility”, by a decision maker such as a manager (Department of Energy & Climate Change 2012). How can decision makers be made aware of energy savings opportunities within their facilities? Manufacturing systems differ from company to company and from production line to production line making accurate information on which to base energy savings predictions difficult to find (Duflou et al. 2012).

There is a danger in assuming that all energy efficiency measures will reduce manufacturing costs, only “realisable” concepts will have this potential (Worrell et al. 2003). Therefore, a structured approach is required in order to benefit from any energy and cost saving opportunities. Several methods are detailed in the available literature (Abdelaziz et al. 2011), but certification to the International Standards Organisation (ISO) 50001 standard has recently shown promising results (ISO 2012; Backlund et al. 2012). Bentley Motors became the first UK automotive plant to achieve ISO 50001 certification. Using this framework a two thirds reduction in specific energy per vehicle produced and a 14% reduction for their site as a whole were achieved (Straughan 2012). This standard specifies the requirements for facility energy management system and follows the “Plan-Do-Check-Act” framework for continuous improvement similar to the well-known ISO 9001 standard (ISO 50001 2011).

Computer simulation of manufacturing systems can be used as part of an energy management system to make the energy savings potential of a facility more visible. Nonetheless, energy simulation remains, for the most part, an academic research area despite computer simulation becoming more accessible in recent years (Duflou et al. 2012). Many manufacturing companies have production simulations which have already been built, run and validated against actual production data (Jahangirian et al. 2010). Typically the results of these simulations must pass rigorous scrutiny from operations managers and manufacturing engineers before being classed as ‘valid’ (Robinson 2004). Therefore, it seems a waste to have to reproduce these complex simulations from scratch for the analysis of manufacturing energy usage which is the current the state of the art (Duflou et al. 2012; Thiede 2012b). Where an existing simulation does not exist then the field of manufacturing computer simulation has developed refined methods to produce accurate simulations (Robinson 2004). To reduce cost and complexity the energy usage calculation can be carried out as a post process to these methods.

The aim of this paper is to propose a method of developing a post processing toolkit to reduce the time and cost of energy simulation by use of statistical data reported by the simulation software. The toolkit calculates the electrical energy use of a manufacturing line for the purpose of identifying potential energy saving opportunities. The paper briefly reviews current literature in the fields of manufacturing simulation and energy simulation. It continues with an industrial case study where the tool is used to approximately predict the electrical energy usage of a manufacturing line.

2. Energy Simulation

2.1 Computer Simulation

The simulation of manufacturing systems using computers has existed as a management decision support tool since the 1960’s thanks to the advent of high level computer programming languages (Goldsman et al. 2009; Nance & Sargent 2002). The discipline of simulation modelling has grown with the advance of modern computer systems and the development of Visual Interactive Simulation (VIS), such that its implementation can be found in numerous areas of operations management from manufacturing engineering to supply chain management (Bell & O’Keefe 1986; Jahangirian et al. 2010).

Law (2007) describes computer simulation as one of the three most important operations research techniques. It can be both static; imitating a system at a particular point in time or dynamic; imitating a system as it progresses though time (Robinson 2004). Modern dynamic computer simulation is achieved by one of, or a mixture of, three techniques: *Discrete Event Simulation*, *System Dynamics* and *Agent Based Simulation* (Jahangirian et al. 2010; AnyLogic 2014).

This paper is based on work for a large automotive manufacturer who use Lanner’s Commercial off the Shelf (COTS) discrete-event simulation (DES) software WITNESS® (Hereafter referred to as WITNESS) as well as other Microsoft® Excel® (Hereafter referred to as Excel) tools to build, run and validate detailed manufacturing line simulation models. These simulations facilitate manufacturing line design by allowing the experimental analysis of what-if scenarios. A set of key performance indicators (KPI’s) the same as those used to assess the performance of a real manufacturing system are output from the simulation. This allows the comparison of the simulation results to the real system output values. (Tjahjono & Ladbrook 2011; Benedettini & Tjahjono 2008)

2.1.1 Disadvantages of Computer Simulation

The principal disadvantage of simulation modelling is the time and cost required to create the models. Therefore, the cost effectiveness of the modelling process must be established prior to the commencement of the simulation project. Another potential problem is due to the "garbage in garbage out" (GIGO) analogy where simulation results may not compare with reality due to errors in the input data. (Banks et al. 2010)

2.2 Energy in Manufacturing

Energy usage within a single manufacturing facility can be divided into several levels as follows (Hesselbach et al. 2008):

- Unit Process level: The individual machine tools and their local ancillary devices such as hydraulic pumps, extraction systems and coolant systems. The energy use at this level is characterised by the electrical power consumption of the particular machine as well as other forms of energy usage at the machine level such as compressed air and liquid coolant.
- Process chain or Line level: An entire manufacturing line or group of machines operating in unison. The energy usage at this level is equal to the sum of all of the unit process level energies.
- Facility or Factory level: The energy usage at this level is equal to the sum of all of the manufacturing lines within a facility including the support machinery or Technical Building Services (TBS).

2.3 Energy Simulation

This paper will concentrate on calculating the simulated energy usage of value adding manufacturing machinery from the process chain perspective. At the unit process level there are a number of examples within the literature of energy efficiency measures using simulation (Duflou et al. 2012; Balogun & Mativenga 2013). These solutions are important to the overall field of energy efficiency research but typically require changes to machine tool design, are difficult to implement in existing systems, and lead to increased capital cost.

At the process chain level, a method of reducing energy usage within manufacturing is to change the "standard operating procedures" by which resources are used. This is also referred to as "energy aware process chain design and control" and there are several examples of this thinking in the literature (Rager 2008; Herrmann & Thiede 2009; Weinert et al. 2011; Pechmann & Schöler 2011). Although incurring less capital cost this approach carries its own potential costs, such as the 'hassle cost' of disruption to existing working production lines in order to run experiments or to implement changes (Department of Energy & Climate Change 2012).

Overcoming these problems is one of the fundamental advantages of computer simulation in complex manufacturing environments; the ability to see potential benefits *before* any expensive and potentially contentious changes are proposed. Unsurprisingly, research into unit-process and process chain level energy simulation has increased in the past decade

(Heilala et al. 2013; Thiede et al. 2013; Wright et al. 2013). Recent research by Thiede (2012a) aimed at a holistic energy simulation which considered all three levels of energy usage within a facility including all relevant energy flows (such as steam, compressed air and electricity). This work proposed a generic energy simulation methodology built around the multi-method capabilities of Anylogic®, but required the construction of a unique agent based simulation from scratch.

2.3.1 Disadvantages of Energy Simulation

Energy simulation adds further complexity, and therefore cost, to a standard manufacturing model which may not be recuperated by the potential savings. With energy simulation input errors could be in the production data or the energy data complicating the troubleshooting process (Solding 2008).

Obtaining accurate energy data from a manufacturing line can be complicated due to the tools and methods required, the amount of data required and the sensitivity of this data (O’Driscoll et al. 2012; O’Driscoll & O’Donnell 2013). Also the barriers to both simulation modelling and energy management must be overcome before any potential savings can be realised (Robinson 2004; Cagno et al. 2013).

3. Proposed Solution

Simulation software packages such as WITNESS store statistical machine utilisation information while the simulation is running and present it as a report at the end of a simulation run. In the case of WITNESS, this data can be accessed from within the software or by Microsoft® Windows® (Hereafter referred to as “Windows”) applications through Object Linking and Embedding (OLE) automation using Visual Basic® for Applications (VBA). This statistical data can be used to develop a static model of the system energy usage after a certain amount of time enabling the approximation of the energy usage of a production line by setting up a spreadsheet calculator.

A similar method was used by the SIMTER team who presented a toolkit which made use of simulation data to calculate energy usage. Their tool was also designed to communicate with the simulation software, but little details of the process used is given (Lind et al. 2008; Lind et al. 2009). The toolkit proposed in this paper builds on this previous work by adding further analytical functionality as well as looking at energy usage over time to aid trouble shooting and identification of further energy saving opportunities.

This paper considers the use of WITNESS for interest in other simulation software packages the Institute for Operations Research and Management Sciences conducts an extensive biennial survey (OR/MS 2013).

3.1 Advantages and Disadvantages of the Proposed Solution

The advantages of this approach are that:

- A valid existing manufacturing line simulation can be reused for energy simulation reducing the possibility of one source of error in the energy usage results.

- One computer runs the simulation software while the energy tool can be sent to all computers which have Excel.
- Once created the energy tool can quickly recalculate each time a change is made to the input data.
- The tool can be updated after each simulation run.

A disadvantage of this method is that the accuracy of the total energy calculation relies on averaging of the power consumption data for the process level elements. Also data can be collected that is not exactly representative of the particular machine power usage such as vendor information. In some cases establishing a tolerance for the final results may require completing the first set of simulations and calculations. A decision maker will then need to consider the accuracy of these results to establish whether more accuracy will be cost effective. Giving a number for the potential accuracy of this method is not possible as it will be different for each study undertaken.

Although simulation reuse is proposed in this paper it is not without its drawbacks as a model that is valid for one purpose may not be valid for another. For example, simulation models are often created to test specific scenarios and therefore cannot be reused to model the general operation of the target system. Therefore, it is important that the model is not reused blindly; the validity of the model must be established with regard to the objectives of the study. The decision maker may deem that a model which is similar to the real system is sufficient, despite being designed for a different purpose. (Robinson 2004)

3.2 The Manufacturing Line

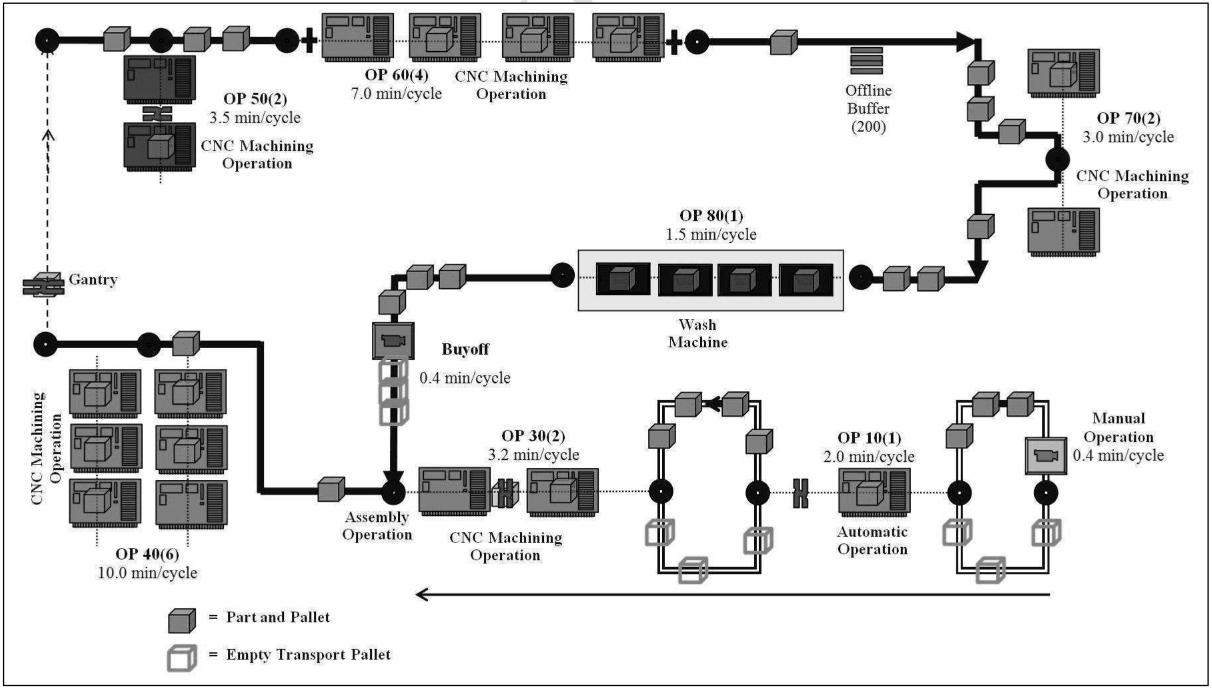


Figure 3: An example of a hypothetical manufacturing Line

Figure 3 shows a hypothetical manufacturing line for manufacturing a major engine part. This line consists of the following subsystems or “elements”:

- Conveyor systems to transport the parts around the line.
- Robotic gantry systems to move the parts to the respective machine tool
- Machine tool systems in the form of computer numerical control (CNC) machines to carry out the value adding operations
- Manual operation systems such as part assembly
- Buffer systems to store parts if need be
- And the parts themselves

3.3 Discrete-Event Simulation and WITNESS®

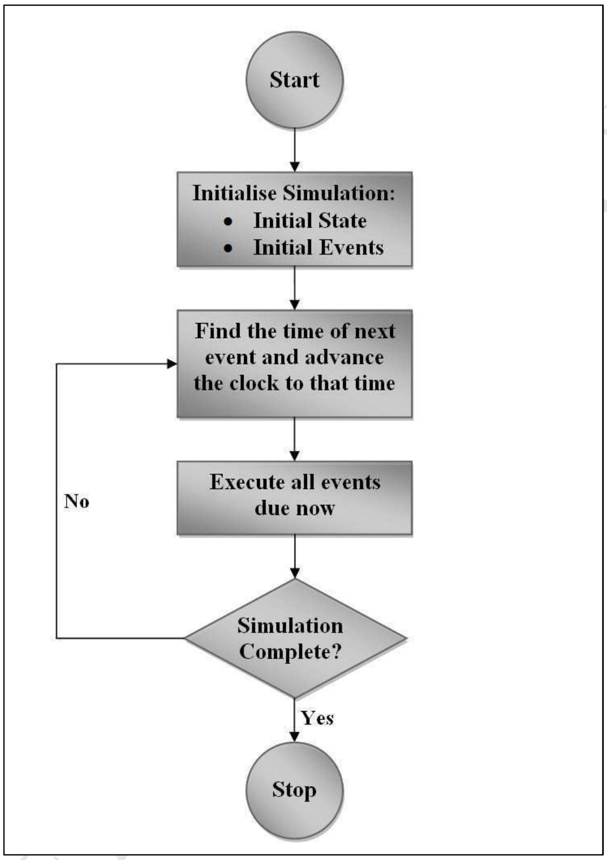


Figure 4: A simplified diagram of the principle of discrete-event simulation (Adapted from: Robinson 2004).

WITNESS is classed as visual interactive discrete-event simulation software. Models in this simulation software are made up of "elements" which are imitations of real manufacturing sub-systems. These are principally: machines, parts, conveyors, buffers, vehicles and labourers (Waller 2012). The mechanisms of modern DES software are complex and in depth explanations can be found in the available literature (Robinson 2004; Law 2007; Banks et al. 2010); however, the fundamental mechanism by which DES works can be explained in short as follows (as illustrated in Figure 4) (Law 2007; Robinson 2004):

1. The elements make up the simulation model.
2. These elements will assume certain "states" during a simulation run.
3. An "event" is an instantaneous occurrence resulting in a change in the element's state. In manufacturing simulation the state changes are triggered by the arrival of a part. Parts are fed into the model at discrete arrival times forming a queuing system.

4. In a discrete system the state changes occur at discrete points in time, hence “discrete-event” simulation.
5. When the simulation is started these events are placed in an “event list” and the simulation clock advances from the time at the first event to the next event time and so on.
6. The simulation software then executes the required tasks at each individual event.

The proposed solution will concentrate on the “Machine” element which in this case simulates a manufacturing line operation. Table 1 lists the WITNESS Machine element states, which are similar to the operational states of a real machine in a manufacturing line. Each of these states can be assigned a duration giving the DES software a start and finish time. This allows the future start and finish events to be placed in the event list. (Law 2007; Robinson 2004; Waller 2012)

State	Description
1. Idle	The machine is on-shift but it has not yet received a part
2. Busy	The element is processing a part for the duration of the “cycle time”
3. Blocked	The part cannot leave the element and continue along the process chain as there is a blockage
4. Cycle Wait Labour	The cycle cannot complete as there is no labour available (for manual operations)
5. Setup	The machine is warming up or ramping up or a tool change process is simulated etc
6. Setup Wait Labour	The setup cannot complete as there is no labour available
7. Broken Down	The machine is broken down. The breakdown frequency is due to the “Mean Time Between Failures” (MTBF) and the duration due to the “Mean Time to Repair” (MTTR)
8. Repair Wait Labour	The repair cannot complete as there is no labour available
9. Off-Shift	The machine is shutdown

Table 1: The WITNESS® machine element states (Lanner Group 2013)

3.4 Calculating Energy Usage

3.4.1 Power Data Collection

The proposed solution has been developed using measured electrical “real power” consumption data. However, the method is applicable to other energy flows measured as a rate with respect to time.

Power consumption data can be obtained by use of energy data logging equipment, collecting data from machine vendors as well as collecting life cycle assessment (LCA) data (Lind et al. 2009). The methods of collection and the tools required are detailed in (Kara 2011; O’Driscoll et al. 2012). Power consumption data is typically represented on a time series graph as shown in Figure 5.

In the example in Figure 5 the power consumption of a manufacturing CNC machine was sampled at one-second intervals. Energy data logging equipment will sample power consumption at varying frequencies. Increasing the sampling frequency of the data logger will improve the resolution of the time series graph, but will incur added costs. A balance must be agreed based on the specific requirements of the study to avoid investment in unnecessarily costly equipment (O'Driscoll et al. 2012).

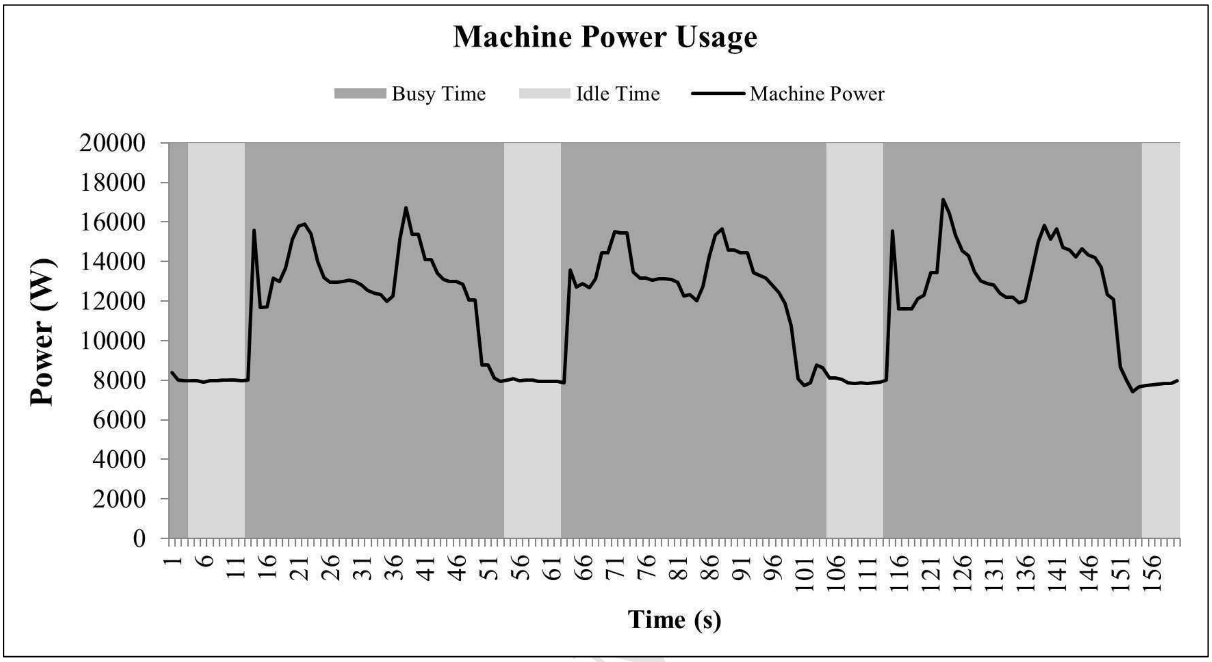


Figure 5: Time series of the power consumption of a manufacturing CNC machine

3.4.2 Calculating Energy

Essentially, electrical power consumption is the rate of electrical energy usage of a machine tool, conveyor or entire manufacturing line with respect to time. Therefore, Electrical energy usage is equal to the product of the Power Consumption or load (*P*) and the time period or duration (*T*), provided the load is constant (El-Sharkawi 2013). More in-depth explanations of power calculation in Alternating Current (AC) electrical supply systems can be found in the available literature (Herrmann et al. 2010; Kara 2011).

$$E= P(W)\times T(h)=PT(Wh) \tag{1}$$

In the case of a varying load the electrical energy (*E*) is the integral of the power consumption profile (*P*) over the time period (*T*). (El-Sharkawi 2013)

$$E= \int_0^T dt \tag{2}$$

A simplified method of approximating the energy used during a value adding cycle with a varying load is to average the numerical values of the discrete samples over the time period agreed as the 'cycle' (Solding 2008).

3.4.3 Calculating the Time Period

In order to calculate the simulated energy use of a machine element the percentage of total simulated time period that the element was in a certain state is required. The total simulated time period can be the total simulation run time or discrete time segments within a simulation run.

First the individual state time period sum (t_{sum}) is calculated for the particular machine:

$$t_{sum} = \sum_{r=1}^{n} t_r \tag{3}$$

Where 't' is the individual state time period and 'n' is the total number of state occurrences within the study time period.

t_{sum} is then divided by the total simulation time period (T) to give the individual state utilisation percentage (SUP) for a particular machine. All of the utilisation percentages for a particular machine must add up to 100%

$$SUP = \left(\frac{t_{sum}}{T}\right) \times 100\% \tag{4}$$

At the end of any simulation run WITNESS solves Equations 3 and 4 automatically and stores the results for each machine element as a report.

3.4.4 Calculating Machine Energy Usage

These 'SUP' values can now be substituted into Equation 1 to give the approximate energy usage for the particular state and can be repeated for the remaining states. The energy usage of an individual machine E_m over the study period is the sum of all of the state energies:

$$E_m = \sum_{r=1}^{n} (\bar{P}_r \times \left(\frac{SUP_r}{100}\right) \times T) \tag{5}$$

Where $\bar{P}$ is the average power consumption for the particular state and n is the total number of states for the particular machine. The total energy usage for the manufacturing line is then the sum of all individual machine energies

3.5 Developing the Excel Tool

The simulation report can be imported by manually copying the data from the WITNESS statistical report window and pasting it into an Excel spreadsheet. The data can then be easily manipulated manually to make the requisite calculations using Equation 5. However, the process can be automated to improve repeatability. This way a spreadsheet pro-forma can be maintained, while the simulation data is imported by click of a button. The utilisation percentages stored at the end of a simulation run can then be used to approximate the energy usage by use of Equation 5; however this will yield a single energy value and the energy usage 'behaviour' of the system under study is overlooked.

To find the energy behaviour of the system the report must be accessed at discrete points during the simulation run such as every simulated hour. This allows the analysis of ‘how’ the energy was used by the system over time. The Manhattan chart in Figure 6 shows an example of this analysis. In this example the simulated manufacturing line total energy usage is calculated after each hour. The result is then separated into busy, idle and broken down states and compared with the number of parts produced by the line. It would be impractical to attempt to perform this task manually; hence it is necessary to automate the process.

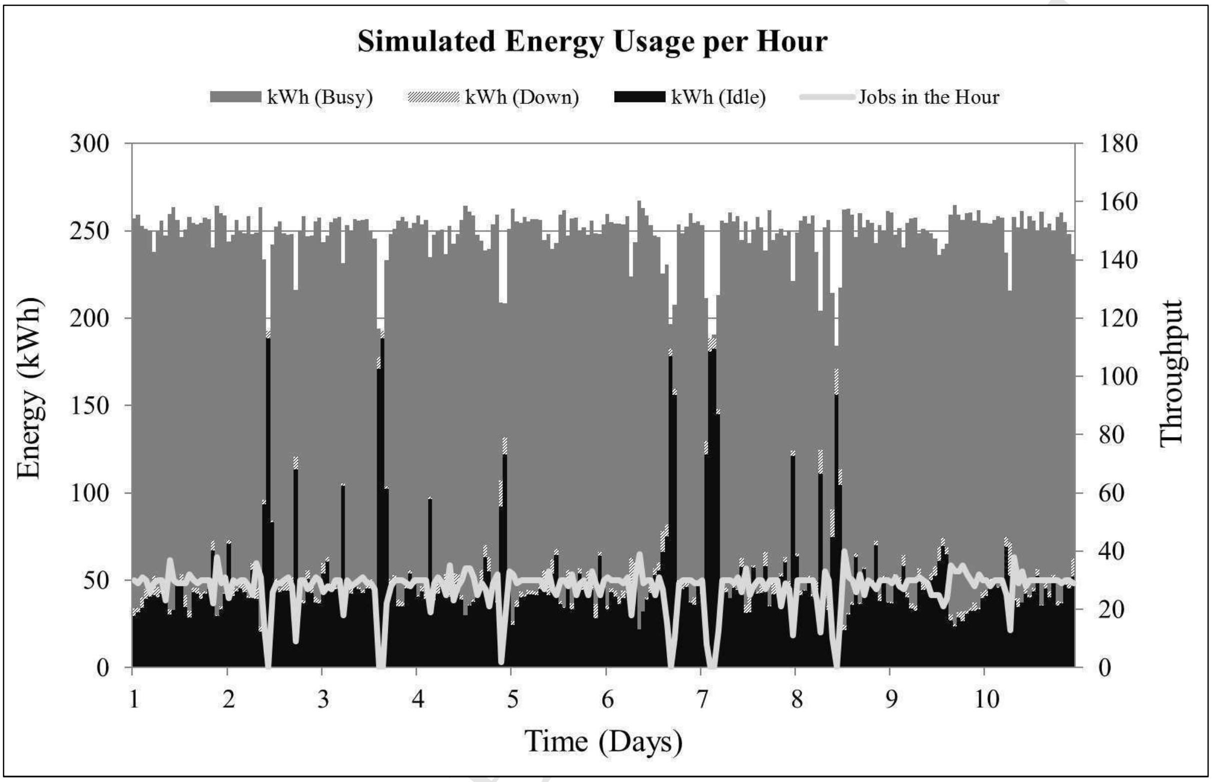


Figure 6: Simulated energy usage over time

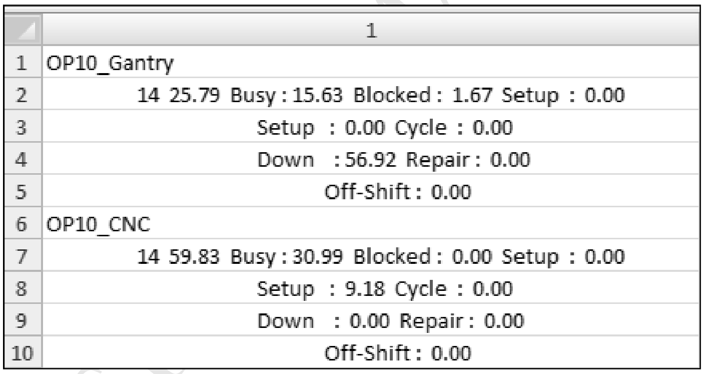
3.5.1 Visual Basic for Applications

VBA is an application automation language which has evolved from Microsoft® BASIC® (Beginner’s All-Purpose Symbolic Instruction Code). Automation is achieved by VBA’s ability to interact with the “object model” of the host application such as Excel, as well as other Windows applications which host VBA. VBA enables intercommunication between applications within Windows, such as between Excel and WITNESS, by access to the Object Linking and Embedding (OLE) automation infrastructure. As VBA is an “OLE automation controller” it can control other Windows applications, whereas WITNESS is an “OLE automation server” as it can be controlled, but cannot itself control other applications. OLE automation is nowadays simply referred to as “automation”. (Lomax 1998; Mansfield 2008)

WITNESS has a suite of OLE commands or methods which can be executed in VBA. Table 2 lists a selection of WITNESS OLE commands. Using the WITNESS OLE command ‘Report’ the WITNESS utilisation reports can be added to the active computer operating system clipboard as text and then pasted into Excel using a VBA procedure. Once pasted in Excel the report appears as shown in Figure 7. The utilisation data is contained within the cell text string and can be accessed using VBA’s string manipulation functions and then placed into the requisite cell in the spreadsheet. The total energy can be calculated by use of Equation 5 as formulae in the spreadsheet

OLE Command	Description
Batch	Runs the model without display to a specified time
Function	Executes a function in WITNESS
Pause	Pauses the simulation run
Report	Outputs a report as text
Resume	Resumes the simulation after being paused
Run	Runs the simulation with display
Stop	Completely stops the simulation run
Variable	Accesses and sets data in a WITNESS variable
WCL	Allows changes to be made to the model such as adding and editing elements

Table 2: WITNESS OLE commands (Lanner Group 2013)



	1
1	OP10_Gantry
2	14 25.79 Busy : 15.63 Blocked : 1.67 Setup : 0.00
3	Setup : 0.00 Cycle : 0.00
4	Down : 56.92 Repair : 0.00
5	Off-Shift : 0.00
6	OP10_CNC
7	14 59.83 Busy : 30.99 Blocked : 0.00 Setup : 0.00
8	Setup : 9.18 Cycle : 0.00
9	Down : 0.00 Repair : 0.00
10	Off-Shift : 0.00

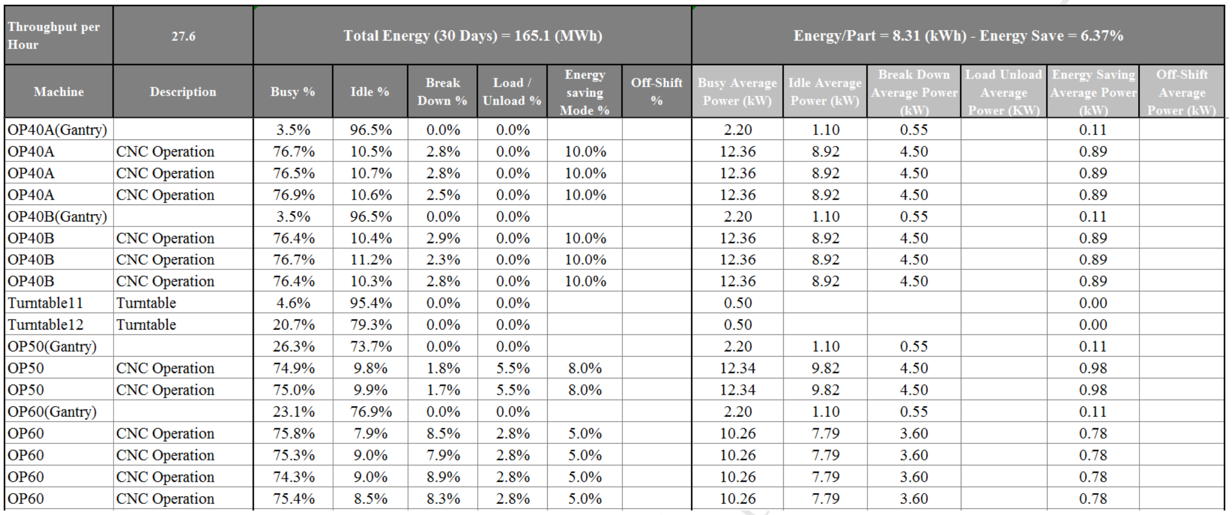
Figure 7: The WITNESS utilisation report once pasted as text in Excel

Figure 8 shows an example of an energy use calculator for the machines in a hypothetical manufacturing line. The calculator makes use of the simulation utilisation percentage and the average power consumption for each machine to calculate total energy and energy per part produced (or specific energy). The calculator includes inputs for the cycle, idle and down energy levels and also includes inputs for three other states namely:

- The load and unload percentage: This is the duration of time that a machine is waiting to be loaded or unloaded by a robotic system or an operator. This is essentially machine idle time, but it is idle time that cannot easily be converted into energy saving time.
- The energy saving percentage: This allows testing of a what-if scenario where a machine switches to an energy saving mode. Here the user can theoretically convert idle time into energy saving time to see the potential benefits of this type of energy optimisation technique.

- Off-Shift Percentage: Not all manufacturing machines are shut down during off-shift; therefore, a value can be input to calculate the energy usage during this time.

Using VBA and automation any changes to the simulation can be added to the calculator automatically. Also as all of the calculation is done automatically in Excel the tool is interactive allowing a decision maker to see immediate results on changing the value of the inputs.



Throughput per Hour	27.6	Total Energy (30 Days) = 165.1 (MWh)						Energy/Part = 8.31 (kWh) - Energy Save = 6.37%					
Machine	Description	Busy %	Idle %	Break Down %	Load / Unload %	Energy saving Mode %	Off-Shift %	Busy Average Power (kW)	Idle Average Power (kW)	Break Down Average Power (kW)	Load Unload Average Power (KW)	Energy Saving Average Power (kW)	Off-Shift Average Power (kW)
OP40A(Gantry)		3.5%	96.5%	0.0%	0.0%			2.20	1.10	0.55		0.11	
OP40A	CNC Operation	76.7%	10.5%	2.8%	0.0%	10.0%		12.36	8.92	4.50		0.89	
OP40A	CNC Operation	76.5%	10.7%	2.8%	0.0%	10.0%		12.36	8.92	4.50		0.89	
OP40A	CNC Operation	76.9%	10.6%	2.5%	0.0%	10.0%		12.36	8.92	4.50		0.89	
OP40B(Gantry)		3.5%	96.5%	0.0%	0.0%			2.20	1.10	0.55		0.11	
OP40B	CNC Operation	76.4%	10.4%	2.9%	0.0%	10.0%		12.36	8.92	4.50		0.89	
OP40B	CNC Operation	76.7%	11.2%	2.3%	0.0%	10.0%		12.36	8.92	4.50		0.89	
OP40B	CNC Operation	76.4%	10.3%	2.8%	0.0%	10.0%		12.36	8.92	4.50		0.89	
Turntable11	Turntable	4.6%	95.4%	0.0%	0.0%			0.50				0.00	
Turntable12	Turntable	20.7%	79.3%	0.0%	0.0%			0.50				0.00	
OP50(Gantry)		26.3%	73.7%	0.0%	0.0%			2.20	1.10	0.55		0.11	
OP50	CNC Operation	74.9%	9.8%	1.8%	5.5%	8.0%		12.34	9.82	4.50		0.98	
OP50	CNC Operation	75.0%	9.9%	1.7%	5.5%	8.0%		12.34	9.82	4.50		0.98	
OP60(Gantry)		23.1%	76.9%	0.0%	0.0%			2.20	1.10	0.55		0.11	
OP60	CNC Operation	75.8%	7.9%	8.5%	2.8%	5.0%		10.26	7.79	3.60		0.78	
OP60	CNC Operation	75.3%	9.0%	7.9%	2.8%	5.0%		10.26	7.79	3.60		0.78	
OP60	CNC Operation	74.3%	9.0%	8.9%	2.8%	5.0%		10.26	7.79	3.60		0.78	
OP60	CNC Operation	75.4%	8.5%	8.3%	2.8%	5.0%		10.26	7.79	3.60		0.78	

Figure 8: The energy usage calculator in Excel for a hypothetical manufacturing line. Showing average power consumption data and the utilisation percentages for each machine.

3.6 Validation

Simulation involves imitating a real system; therefore, the results of the simulation study must be validated. Validation aims to ensure that the model is sufficiently accurate with reference to the purpose for which the model is to be used. Thus, the purpose of the model must be known before it can be validated. If the model is given the objective of achieving an output KPI within 5% of the real system and it achieves this then the model is valid for its specific task. (Robinson 2004)

3.7 Testing Hypotheses

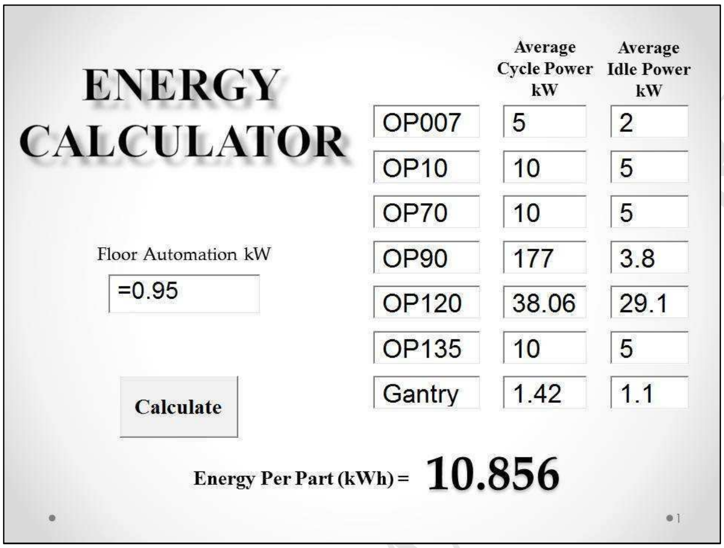
It is possible to test three different energy saving methods with the Excel energy tool without having to rerun the simulation and these are:

1. Adjusting the average machine power consumption: In this case the six average power values for the machines in the line can be changed to see the effects on the total energy usage. The accuracy of these inputs will affect the accuracy of the total energy calculation, but these values can be updated as more accurate data becomes available.
2. Convert idle time into energy saving time: The top right cell in Figure 8 shows the percentage "energy saving" that was achieved in the hypothetical line example by replacing approximately half the machine idle time with energy saving time at a lower average power level (approximately 6%).

3. Changing the utilisation percentages to hypothetical values: This step would not be advised as it would corrupt the simulation report data but may be useful as a quick test.

Numerous other scenarios can be tested by making changes to the model and rerunning the simulation.

3.8 An Interactive Energy Usage Presentation



ENERGY CALCULATOR

Floor Automation kW: =0.95

	Average Cycle Power kW	Average Idle Power kW
OP007	5	2
OP10	10	5
OP70	10	5
OP90	177	3.8
OP120	38.06	29.1
OP135	10	5
Gantry	1.42	1.1

Energy Per Part (kWh) = **10.856**

Figure 9: An example of an interactive Microsoft® PowerPoint® presentation slide.

In the same way that Excel can control WITNESS, Microsoft® PowerPoint® can control Excel by OLE automation (Lomax 1998; Mansfield 2008). Figure 9 shows an example of a simple presentation slide which was used in an energy management meeting. The user was able to make changes to the machine data within the manufacturing line by indicating the name of the operation and the average cycle and idle power usages. On clicking “Calculate” a VBA procedure transferred the data from the text boxes to an Excel calculator such as the example in Figure 8 and a new result was returned.

4. Manufacturing line Case Study

An energy tool similar to the example in Figure 8 was created for the purpose of predicting the energy usage of proposed future manufacturing lines. The energy management team wanted to establish the accuracy of the tool given certain limitations and assumptions (discussed below). To this end, the energy tool was used to model the energy usage of an existing manufacturing line.

There was no access to power consumption data from the line at the machine level but power usage data was available from the main supply busbars. This created an opportunity to compare the energy usage calculated by the energy tool with real manufacturing line data as a method of validation. The busbars principally supplied manufacturing machines; therefore the sum of the busbar supply data was approximately equal to the line energy use. However, some assumptions had to be made as the data from the busbars was collected remotely from an on-line database. Information on the how the machines were connected to the busbars was based on original design data.

At the machine level power consumption data was collected by the energy management team from various sources such as measurements from machines running similar operations to the machines in the study and machine vendor information. The WITNESS simulation model for the line was already complete as it was created as part of a previous manufacturing productivity project. Using a VBA procedure containing WITNESS's OLE automation commands the simulated utilisation percentage for each machine was collected for each simulated hour.

4.1 Validation

Initially a single value for the simulated specific energy was calculated using the toolkit and compared with a real manufacturing line sample with the difference being 13%. In order to understand why there was such a large difference it was necessary to know 'how' the energy was being used over time by the two systems.

Figure 10 shows the total energy usage calculated for each hour of a two-week simulation run, which includes off-shift time (in this case weekends). The total energy usage per hour for the value adding manufacturing machines and processes was separated into the busy, idle and broken down energy usages. The following assumptions were necessary in producing this profile:

- The balance of the simulated manufacturing line was adjusted to achieve an average monthly output similar to the recorded output of a real manufacturing line.
- The power consumption data for the machines were approximations based on data from similar operations being carried out at other plants and vendor information on the machine power usage.
- The average power usages of the conveyor systems and known manufacturing support systems connected to the busbars were included subsequently. The energy usages of these machines were considered constant to simplify the calculations during the simulation run.
- Off shift average power was also input as a constant usage and was approximated to the average of the real line weekend data.

After analysing the real data it was found that a large TBS machine was connected to the 'machine' busbars. The usage of this machine was then removed from the real data as the machine was not being used during winter months. Also the list of support machinery attached to the real line busbars was not complete as this would have required a full line energy audit. This was deemed unnecessary given the 10% tolerance as sending environmental engineers to site would be costly. A Manhattan plot of the total energy consumption per hour of the real manufacturing line over a two-week period is shown in Figure 11.

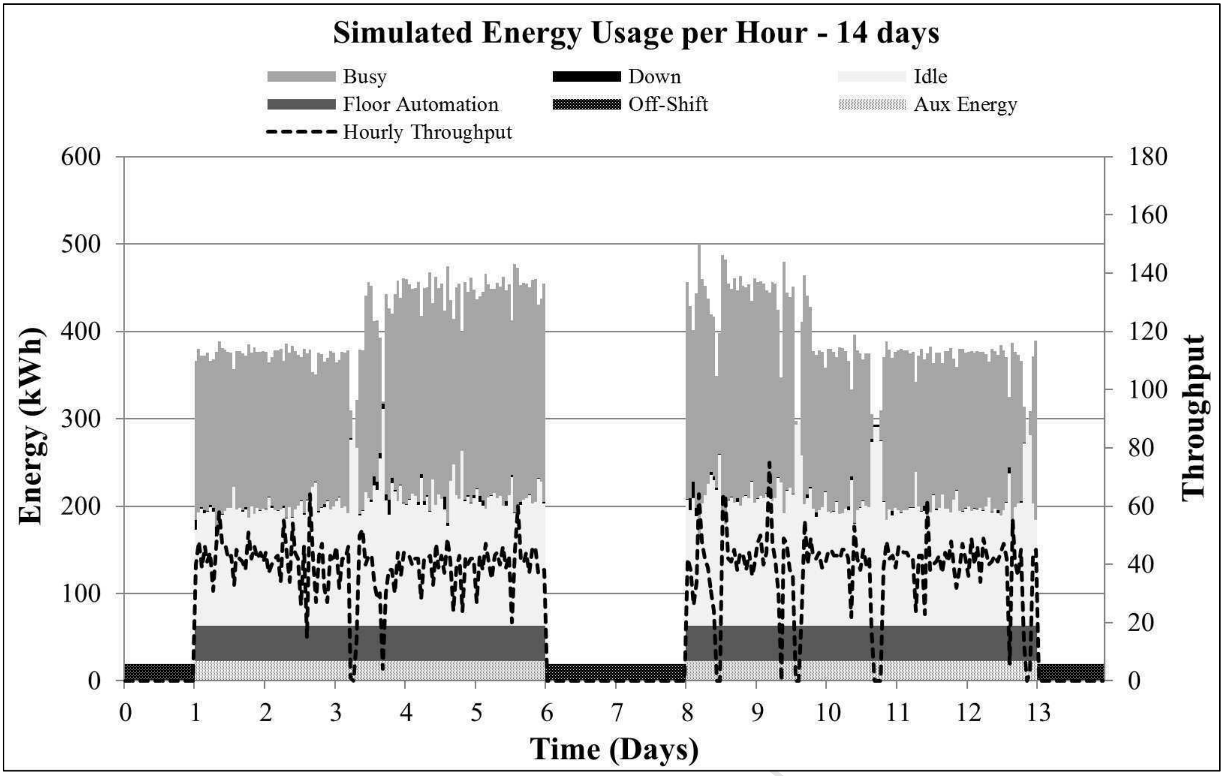


Figure 10: Total energy per hour for the simulated manufacturing line.

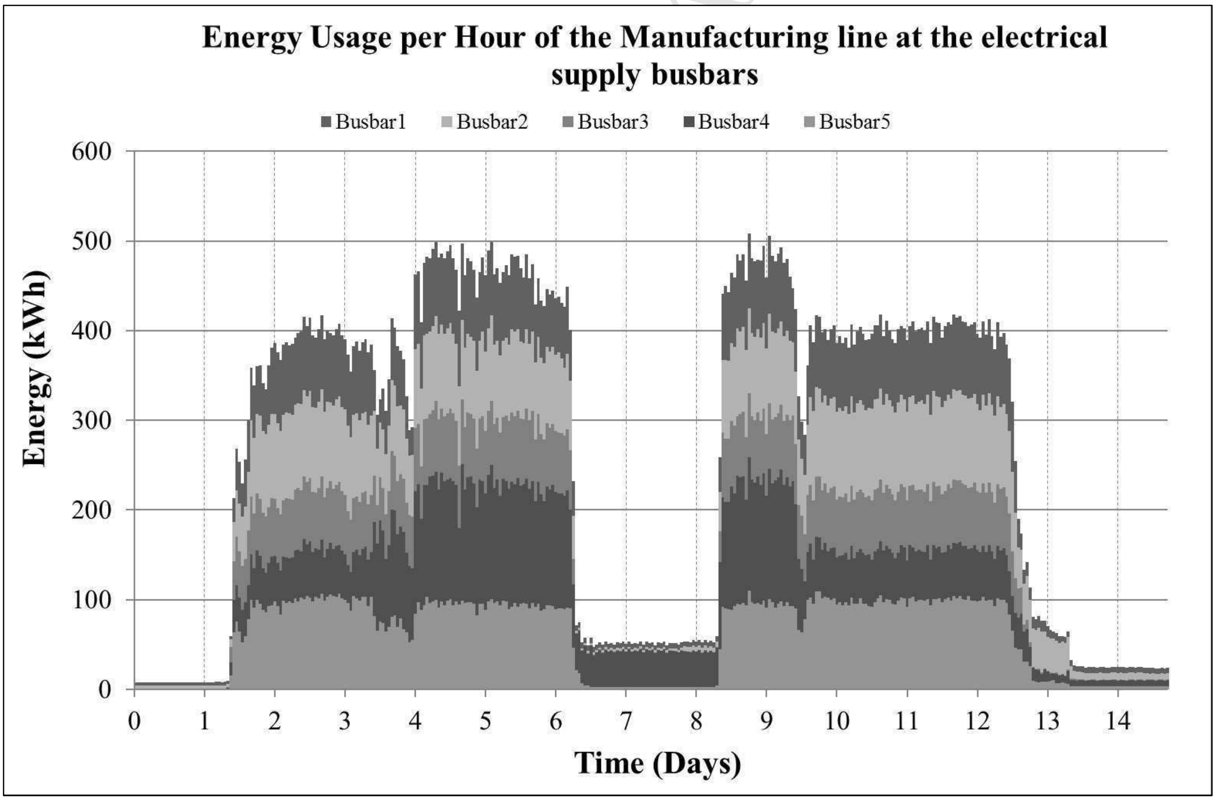


Figure 11: Total energy per hour for the real manufacturing line measured at the electrical supply busbars.

Data Source	Total Energy Used (kWh)	Total Parts	Specific Energy (kWh)	Error (%)
Real Result	179,452	18102	9.9	
Simulated Result	198,995	18752	10.5	5.9

Table 3: A comparison of the results from a 28day simulation run and a real manufacturing line study.

Given all of the assumptions mentioned above the error in the average simulated specific energy usage compared to the real data was approximately 6% for a 28day comparison. The simulation result over predicted the specific energy use by 0.6 kWh. This is contrary to Figure 10 and Figure 11 which indicate that the simulation was under predicting the energy usage per hour. Comparison of the hourly data showed that this anomaly was due to the number of non productive days which occurred during the 28 day real data sample, meaning that the real line was making more parts during productive hours than the simulation was predicting as the simulation was not matched to the exact same period as the real data.

In this case study there was no requirement to further improve the accuracy of the simulation results as the tolerance was set by the energy management team at 10%. This figure was considered sufficiently accurate as the team were primarily interested in using the tool to approximately predict the energy use of future projects and the magnitude of the percentage change due to potential energy savings hypotheses.

4.2 Energy Saving Hypotheses

Data Source	Total Energy Used (kWh)	Total Parts	Specific Energy (kWh)	Change (%)
Simulated Result	198,995	18952	10.50	
Simulated Result with Energy Saving	148,905	18376	8.10	-22.8

Table 4: A comparison of the results from a 28day simulation run with and without energy saving hypotheses.

With the simulated energy usage calculation result falling within the target tolerance it was possible to predict a theoretical potential energy saving of approximately 23% for the manufacturing line during the particular study period by applying the following hypotheses:

- Converting half of the idle time to energy saving time and adjusting the energy saving average power value to 10% of idle.
- Resetting the line balance to its full design capacity to reduce the idle percentage by changing shift patterns (Increasing value adding percentage).

In this case the manufacturing line was not running at its design capacity due to low demand, causing larger machine idle time percentages and therefore, larger potential savings were possible than would normally occur. These proposals were the most realisable of the hypotheses; however, even these would not be straight forward to implement in a complex manufacturing line. This problem is endemic within manufacturing as modern manufacturing lines are designed with the principles of lean manufacturing in mind where machine “availability” is paramount. It is not the intention of this paper to discuss the virtues of lean manufacturing but to find a potential theoretical energy saving figure to work toward, as you cannot change the dominant philosophy without a clear reason.

5. Conclusion

The method of energy simulation proposed in this paper is most beneficial to companies who have existing simulations of their manufacturing lines; however, the approach can be extended to new projects as the energy analysis is completed as a post process to the production simulation model development. Using simulation report data to approximate the energy usage of a complex manufacturing facility allows the modeller to complete the initial simulation validation without potentially cumbersome processes weighing the simulation down. However, as with all modelling the accuracy of the proposed approach is reliant on the availability of accurate input data and the validity of the model used.

The toolkit proposed in this paper introduces an interactive approach to the presentation of energy simulation results. It was noted during the case study process that the interactivity of the spreadsheet allowed manufacturing engineers and managers who had no previous involvement in manufacturing simulation to see the benefits of the discipline. As well as interactivity and simulation reuse the toolkit presented in this paper makes further contributions by including more useful machine energy use states and details a method of viewing how energy is being used by the simulated manufacturing line over time and by each state. This allows a clear comparison with the real line energy usage to be made while highlighting waste such as excessive energy use while machines are idle.

Further research in the area could extend the use of such a post processing toolkit to include environmental considerations which exist as a direct result of the manufacturing line being in operation. Due to licensing constraints this work was limited to the use of WITNESS but there is a need for a comparison of other simulation packages from an energy simulation perspective. Finally research is required into how accurate energy simulation should be, and at what point does the pursuit of accuracy incur more costs than the potential cost savings?

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Highlights

- An interactive manufacturing energy management tool is proposed
- Can predict potential complex manufacturing energy saving opportunities
- Accessible from management presentations and proposals
- Tool Interactivity provides an environment which facilitates hypothesis testing
- An industrial case study shows savings from energy usage reduction scenarios