This is a peer-reviewed, accepted author manuscript of the following research article: Mawson, V. J., & Hughes, B. R. (2020). Thermal modelling of manufacturing processes and HVAC systems. *Energy*, *204*, [117984]. https://doi.org/10.1016/j.energy.2020.117984

Thermal Modelling of Manufacturing processes and HVAC systems

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Abstract

The two main energy consumers within a manufacturing plant are the HVAC systems and manufacturing processes. Studies have predominately looked at energy demand associated with manufacturing a single product or a production line, as well as analysis of energy use within a building, but little work has investigated the interaction between manufacturing processes and the surrounding building. Dynamic time based building energy simulation was used to determine the thermal behaviour of the manufacturing facility. The study establishes the importance of analysing manufacturing energy flows alongside that of the building in order to capture all thermal and energy flows. The relationship between the energy demand of HVAC systems with manufacturing productivity is determined. The use of the current degree-day method of building analysis was proven inappropriate for manufacturing facilities, due to such significant heat gains from manufacturing equipment, and impact of equipment on indoor conditions. The need for a proactive HVAC system based on manufacturing demand is introduced, allowing for control of the environment prior to significant temperature or humidity changes.

Keywords: Energy modelling, Manufacturing energy analysis, Discrete event simulation, HVAC, Building energy analysis

Nomenclature:

$\dot{Q}_{mach}(t)$	Heat transfer rate (W)
$P_{elec}(t)$	Electrical power (W)
m	Mass (kg)
c_p	Heat capacity (J/g K)
T	Temperature (K)
ε	Emissivity
A	Surface area (m^2)
σ	The Stefan Boltzmann constant
Θ	Absolute temperature (K).

1. Introduction

Manufacturing is responsible for 55% of the world's energy consumption, and 21% of global greenhouse gas emissions, mainly accounting from fossil fuels burnt at on site facilities [1]. The UKs manufacturing industry is responsible for 17% of its energy demand, and holds a legally binding target of achieving an 80% reduction in carbon dioxide emissions by 2050 on 1990 levels [2]. The UKs Clean Growth Grand Challenge aims to put the UK at the forefront of industry, requiring a shift to low carbon [3]. With this increasing pressure to reduce energy consumption, manufacturing companies are faced with the challenge of reducing energy consumption whilst maintaining or increasing profits and productivity. However, at present, many facilities lack energy strategies [4], additionally over a third of manufacturing companies do not set energy efficiency targets nor have any means of measuring improvements [5]. Furthermore, energy costs are generally not accounted for by production managers, and are considered indirect costs to maintain facility operation [6].

With the emergence of Industry 4.0, the increase in automation, intelligent systems and complexity in systems requires a new outlook on optimising and analysing manufacturing procedures and processes. Thus, there is an increased focus on energy efficiency of manufacturing processes rather than renewable energy production, of which requires state of the art analytic tools to accurately capture all system dynamics. Manufacturing systems and plants differ considerably across companies, with the need for varying parameter considerations and no blueprint for achieving this understanding of all energy flows. Manufacturing processes and systems involve complex interactions between resources, water, compressed air, heat and energy, all of which are dependent on the machining process and state as well as control and operation. Determining and understanding energy use at every stage of the manufacturing process is critical for optimising the use of energy within manufacturing processes and facility management. Industrial facilities are charged for the greatest amount of energy they use over a 15-minute interval within a billing period, regardless of the total energy consumption. This spike in consumption can make up 30% of the monthly utility cost [7]. Studies have shown that investing in energy-efficient technologies and adopting technology to intelligently control energy uses can reduce energy consumption by 50% as opposed to making operational improvements, of which can reduce this by only 10 – 20% [8].

Additionally, the energy used within buildings for maintaining comfortable internal conditions, such as heating, ventilation and air conditioning (HVAC) is responsible for almost half of the UK's energy demand. HVAC is controlled by a Building Energy Management system (BMS), however currently, BMS is a reactive system based on CO_2 levels and air temperature, ideal for office and domestic environments where thermal comfort of occupants is a priority. Manufacturing facilities however, require production specific environmental conditions, of which are influenced by considerable heat and moisture gains from machinery. Humidity and temperature control, and therefore HVAC, can be vital for production quality control, and therefore manufacturing processes should be accounted for during control of HVAC systems.

Compared to other industries such as food production, pulp and paper, fuel, chemicals and pharmaceuticals, machinery is less energy intense, with energy consumption linked directly to production schedules based on manufacturing demands of customers and technological trends [9]. Therefore, it is predicted that the energy consumption of this sector will maintain a relatively flat energy consumption trend. With increasing customer demand and therefore production requirements, the requirement to adopt energy efficient management strategies is paramount to ensure the energy consumption of these facilities does not see an upward trend. With the increase in production requirements, yet need for energy reduction, consideration of the full facility is needed to achieve such a reduction, with the HVAC system holding great potential for reduction of energy demand in this sector.

Current building analysis involves calculations based on degree-days, a climatic indicator used to assess the impact of weather on energy consumption of buildings, where the base temperature is the temperature at which the building is thought to require heating or cooling. The CIBSE Guide for typical buildings has quoted the use of a base temperature of 15.5 °C [10], however this can be effected by building use, indoor temperatures, and heat losses and gains within the building. This method has been criticised in the past [11] [12], stating that building type specific base temperatures should be developed, however manufacturing facilities will not always fit to a specific building 'type' criteria. Building behaviour and use varies more so in manufacturing facilities as opposed to commercial building environments such as schools and offices, which operate at similar temperatures for occupants. Manufacturing facilities vary drastically in terms of size, productivity, application and required workshop conditions, and also have the potential requirement for refrigerated spaces and clean rooms. Equipment such as ovens may also contribute a significant amount of latent heat to the surrounding environment, thus effecting indoor humidity and working conditions. Such environments can also operate at irregular hours, such as throughout the night with daily shut down during peak energy hours, or with unmanned machining areas.

The Building Regulations 2010 highlights the requirement for 'adequate means of ventilation provided for people in the building', with a fresh air supply rate of 5-8 litres per second per occupant suggested [13]. The Workplace (health, safety and welfare) Regulations 1992 recommended a workplace temperature of at least 16 degrees Celsius, or 13 degrees Celsius if the work requires rigorous physical effort [14].

Recommended energy efficiency standards for non-domestic HVAC systems are based on kilowatt load [15], however in terms of industrial regulations, the Manual of Recommended Practice states that although ventilation rates are based on rate of contaminant generation, the primary function of heat control ventilation systems is to prevent the acute discomfort or illness of workers. It is therefore suggested that industrial heat control ventilation systems or other engineering control methods must follow a physiological evaluation in terms of heat stress for occupants, rather than control based on the manufacturing equipment or building use [16]. With the shift towards automated machining, the need for solely temperature and occupant thermal comfort based control of HVAC system is becoming less suited to the manufacturing industry.

Building Energy Modelling is extensively used to analyse a building envelope during both the design stage and through building optimisation for residential and commercial buildings. Simulation is key to modelling and analysing the complex non-linear nature of HVAC systems due to the large number of subsystems (chillers, boilers, fans and pumps, heat exchangers and pipes).

Discrete Event Simulation (DES) is commonly used in the manufacturing industry as a methodology of enhancing scheduling and system performance, identifying bottlenecks as well as process optimisation [17]–[19]. Simulation has been highlighted as the most appropriate method to model dynamic material and energy flows in a manufacturing environment due to the complexity of process interactions and large volume of variables [20]. However technical building services such as HVAC are more suited to the continuous paradigm, and with DES less suited to simulate this continuous nature of thermal building energy performance, it is consequently analysed in isolation to TBS (Technical Building Services).

In order to implement energy saving changes to HVAC and industrial machine usage in manufacturing, data visualisation is key to communicating areas of energy loss to realise additional benefits. Correlating energy use with key statistics and performance measures such as production output gives operators a greater understanding and context regarding end energy use. Pelliccia et al. [21] presented the advantages to visualisation techniques through virtual reality in energy analysis, displaying improvements in the effectiveness of energy optimisation processes.

The aim of this research was to determine the effect of manufacturing equipment on the energy consumption of HVAC systems and overall building energy consumption due to heat gains from machinery, in order to understand how the HVAC system can be operated alongside the manufacturing schedules for a reduction in HVAC energy consumption. Using manufacturing productivity and kilowatt-hours, rather than the traditional method of using temperature, to determine optimum HVAC controls is discussed. Process energy use was correlated alongside building energy use and key performance statistics. A review of previous related work provides a summary of attempts at holistic building and manufacturing analysis as well as the well-established methodologies of manufacturing energy analysis through the use of DES simulation.

Determining the interaction between manufacturing energy flows with that of the built environment, characterising heat and moisture gains from machining equipment and how the workshop environmental conditions are impacted by certain machining schedules can be used as the basis for further analysis into the buildings HVAC systems. The novelty in this study is the ability to combine such effects to determine the energy demand and requirements of the HVAC system based on manufacturing schedules, showing the need to include data at manufacturing process level in building energy simulation analysis. Such knowledge is required in order to ensure sufficient sizing of the HVAC system, as well as in determining optimum controls and set points to maintain a comfortable thermal environment. Furthermore, a novel methodology of proactively controlling HVAC based on manufacturing kilowatt-hours was developed.

1.1 Previous Related Work

High temperature industrial process is makes up 19% of the final energy requirement of the UKs industrial sector [22]. There is potential to utilise the environmental heat gains from manufacturing processes for energy recovery and management of the built environments HVAC systems, of which requires holistic analysis of heat flows between processes, the built environment and external conditions.

Oates [23] noted that large industrial processes and auxiliary equipment exchange large amounts of heat to the surrounding environment, and developed a framework to display how the energy use in manufacturing can be integrated with that of the building within simulation, however validation of such a method is required and development of such a software was described as ‘a major undertaking’ [24] [17].

Similarly, Gutowski et al. [25] developed a thermodynamic framework to characterise the work, heat and material flows within a manufacturing environment, and discusses the potential in exploring alternatives in order to reverse the inefficiencies and losses in current manufacturing systems.

Weeber et al. [26] proposed a model which assessed the impact of different forming processes on total energy demand accounting for both the process and building infrastructure. Machine load profiles were translated into internal heat gain curves using the thermodynamic model presented by Schlüter et al. [27], where Equation 1 represents the thermal balance equation for machine housing, and Equation 2 representing the thermal mass of the manufacturing process.

$$\dot{Q}_{mach}(t) = P_{elec}(t) - \left(\dot{Q}_{conv}(t) + \dot{Q}_{rad}(t)\right)$$

Equation 1- [27]

$$\dot{Q}_{mach}(t) = m\, c_p \frac{dT_{surf}(t)}{dt}$$

Equation 2- [27]

However the thermodynamic model assumed that 100% of the measured electric power was transformed into thermal energy, with constant environmental temperatures. The study concluded the necessity to specify heat gains from machines in building energy analysis, by increasing the quality and reliability of building simulations, as well as reducing safety margins in design.

Methodologies and frameworks for analysing energy consumption of a machine level using discrete event simulation (DES) is a common theme seen in literature [6], [28]–[31].

For example, Solding and Thollander [32] proposed a method of combing material flow analysis with energy and resource flows using DES, which was aimed at allowing reduction of peak loads and efficient production planning due to disregard for the dynamic nature of machining processes. Likewise, Keshari et al. [33] studied improving the energy efficiency of the paper and pulp industry by managing resources such as time, material processing, material flow to achieve a required a certain level of product quality. Mousavi [20] and Seow [34] however, both used state based approaches to determine energy consumption of a single product, using dynamic energy profiles for each process, through the use of DES.

The majority of studies focus on productivity and product quality, as well as efficient production management rather than energy saving potential.

Brundage et al. [35] stated that modern manufacturing facilities waste energy saving opportunities due to the lack of integration between the facility and production system. Efforts at combining manufacturing level analysis with that of the built environment to achieve a holistic understanding of energy flows has been seen [28], [29], [36]–[39].

Brundage et al. [35], utilised the concept of the energy opportunity window to allow machines to be turned off at certain periods of time without any decrease in production. Authors stated that if unused machines were switched from idle mode to off until next needed, there was potential for an 80% reduction in energy [40], [41]. The energy opportunity window was synced with the peak periods of energy demand from the HVAC system to optimise energy cost savings.

Dababneh et al. [42] proposed an analytical model on electricity demand response considering a combined manufacturing and HVAC system. The production schedule and HVAC set points were determined by solving the objective functions using General Algebraic Modelling. The aim was to provide an optimal production schedule for manufacturing operation, as well as a HVAC control scheme. However HVAC components and their thermodynamic properties were not considered. Focus of both these studies were on demand response and reduction in billing cost.

A large number of assumptions were made during model creation of discussed studies, due to unknown data and need for model simplification, as well as disregard for the dynamic nature of outdoor and indoor conditions. Predominately, the focus of studies is around determination of optimal scheduling and production planning for the reduction of peak loads and energy costs, rather than the accurate determination of energy demand and resource flows.

There is a scarcity of studies ([35] ,[26]) which address the combination of manufacturing production requirements and energy flows with the HVAC system and building. One study analysed thermal energy demand in industrial buildings using ESP-r and BuilOpt-VIE simulation tools, aiming to determine the temperature stratification in a manufacturing hall [43]. The study used the Austrian monthly balance method using typical internal heat gains, along with heat gains per unit area from machinery and lighting to determine thermal energy demand. The study concluded that methods used to determine thermal energy demand and temperatures in residential buildings is not suitable for analysis of industrial environments.

There were no studies found which analyse the effects of manufacturing equipment on indoor temperature and humidity, for environmental condition monitoring to ensure product specific working conditions for quality control, as well as linking manufacturing energy flows to building behaviour such as occupancy. Current work investigates energy demand of industrial buildings, and of individual machines, as well as attempts to combine manufacturing level analysis with that of the built environment, with a focus on cost reduction. However work has yet to be done looking into combining manufacturing energy flows with that of the built environment for analysis of indoor conditions and HVAC system requirements, with a view of manufacturing specific HVAC system analysis and requirements, of which is different to residential or commercial buildings.

This paper discusses analysing the energy flows of manufacturing facilities based on production environment requirements, production scheduling along with outdoor environmental conditions, allowing for more effective management of production environments and energy use of HVAC systems.

2.0 Methodology

IES-VE, a dynamic building energy management software, was used to build a simulation model of a manufacturing facility environment. IES-VE is a dynamic time based building energy simulation software for modelling of thermal zones and technical building services within a building shell [44]. Building performance can be modelled with the analytics tools provided, and take into account weather conditions and solar gains through the SunCast module, natural ventilation analysis through MacroFlo, thermal mass and building dynamics analysis through the Apache module, along with HVAC system implementation and analysis through ApacheHVAC. IES-VE has allowed the use of components within the model, which allows the user to model heat sources within a space, and user defined objects specified by heat gains or surface temperature. A manufacturing add-on tool has also been developed to allow for modelling of machines and corresponding heat gain profiles.

DES software, such as Lanners WITNESS [45], provides a predictive software used for creation of digital twins, business planning, risk management, planning strategies and sustainability. Lanners WITNESS provides tools for measuring resources such as water and energy, as well as providing statistics on energy efficiency. WITNESS has the ability to specify cycle time, mean time to repair and mean time to failure with great flexibility. WITNESS also offers the user the ability to define costings, such as energy, $C0_2$, fuel or currency.

IES-VE, being predominately a building services analysis tool, does not provide the capabilities to specify machining variables such as cycle times, set up times, machining states and corresponding energy requirements in certain states which WITNESS provides. However, IES-VE does have the ability to analyse the manufacturing components alongside the built environment through the use of the Manufacturing View add on package, whereas WITNESS solely analyses the manufacturing components.

In order to determine the accuracy of the IES VE manufacturing tool at analysing energy consumption of manufacturing equipment, the shop floor was modelled in WITNESS, a commonly used tool for manufacturing energy analysis and established method in the field, and compared with results from IES VE in a feasibility study. Results from the comparison study are found in Section 3.3.1.

After determining the suitability of IES-VEs manufacturing add on tool for analysis of the shop floor, IES-VE was used to fully model the manufacturing facility along, building use and occupant behaviour together with machines on the shop floor. Figure 1 displays the modelling methodology.

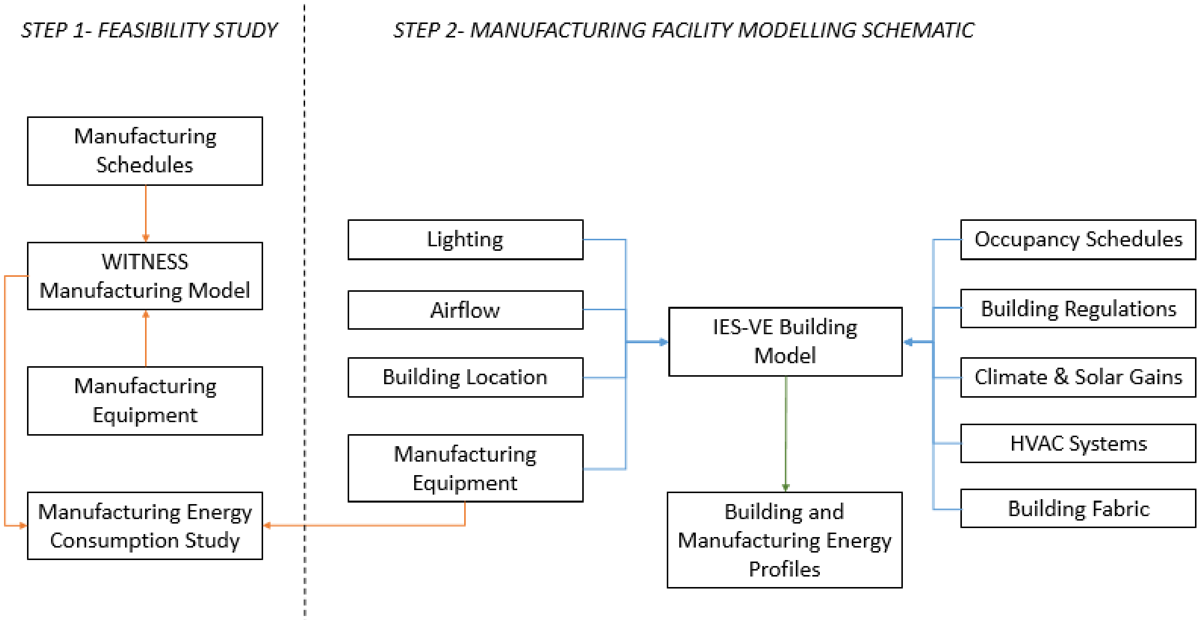

Figure 1- Modelling Methodology

Such a model was used in order to determine spikes in energy consumption, building and machining energy profiles, workshop environmental conditions and also to determine the interaction between manufacturing processes and HVAC systems.

2.1 IES-VE Thermal Calculation Methods

IES-VE is based on first principals of heat transfer processes occurring in and around a building. Conductive, convective and radiative heat transfer for all elements within the model are analysed at user defined time intervals. Room heat gains are integrated with building fabrics, air exchanges and the building plant.

IES-VE performs heat loss and heat gain calculations based on the procedures and principles stated by the Chartered Institution of Building Services Engineers (CIBSE), whereas heating and cooling load calculations are performed according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Heat Balance Method.

2.1.1 Heat Conduction and Storage

Temperature distribution in a solid is governed by the principles of conduction heat transfer and heat storage. A finite difference discretisation approach is adopted, with conduction that is discretised in both time and space. Temperatures are calculated at a number of discrete nodes distributed within each element (wall, roof, ceiling etc). The model assumes building elements to be uni-dimensional, with individual element thermal conductivity, density and specific heat capacity a constant.

2.1.2 Convective Heat Transfer

Both natural and forced convection are calculated in IES-VE. For external forced convection, a wind speed dependant convective heat transfer coefficient is used. A number of methods are available in IES-VE for calculation of the heat transfer coefficient, including a fixed coefficient and coefficients as functions of surface orientation, air-surface temperature difference and mean room air velocity, of which are iteratively calculated throughout the simulation due to their dynamic nature.

2.1.3 Heat Transfer by Air Movement

Buildings are subject to constant air exchanges such as infiltration, natural ventilation or mechanical ventilation. Such airflows can be specified prior to simulation, as either fixed values, profile based or adopt dependency upon conditions such as air temperature or humidity. Air exchange between different rooms within the building and thermal zones is also possible. IES-VE also accounts for water vapour gain associated with air supply as well as carbon dioxide gains.

2.1.4 Radiative Heat Transfer

The total radiation emitted by a plane surface is determined by Equation 3.

$$W = \varepsilon A \sigma \Theta^4$$

Equation 3- Radiative Heat Transfer

IES-VE adopts the mean radiant temperature model, which simplifies computation and assumes the emissivity's of surfaces bounding the enclosed areas do not differ greatly.

2.1.5 Solar Radiation

IES-VE calculates direct solar radiation, diffuse solar radiation and solar altitude and azimuth based on the location of the site. Solar flux is calculated at each time step of the simulation. Solar shading and tracking is also modelled using the SunCast module, using data based on solar exposure of interior and exterior building surfaces.

2.1.6 Casual Heat Gains

IES-VE allows sensible and latent heat gain specification for individual components to be specified as absolute values or on a floor area basis, with values modulated by a profile. Radiant fractions are specified for each component, with the remainder as convective gains. Each piece of manufacturing equipment was modelled individually, with its own heat losses profile specified based on machining use, schedule and power rating of the machine.

2.2 Data Acquisition

Machining and manufacturing data was provided through interviews with shop floor staff, machine booking and schedule databases and also from manufacturing data booklets, whereas data regarding the energy consumption of the built environment was provided by management from pre-installed energy data collection systems. Facility layout and floor plans were obtained from management, with layout further detailed by observation.

Information regarding heat generation of machines is difficult to obtain without extensive physical measurement. Sun et al. [39] used the assumption by Brundage et al. [35] which adopted a heat emission fraction to determine machine power and heat emissions. This suggested that 30% of the power consumption of the machines is given off as radiant heat.

Weather data was provided as part of the IES VE ApLocate weather and location editor. Such data included solar radiation, solar altitude and azimuth for calculation of solar shading and solar heat gains.

3.0 Case Study

The method was applied to a case study of a medium sized manufacturing environment, a 6400 sq.m facility, in South Yorkshire, UK, which focuses on machining research, with state of the art machining centres and laboratory space to allow companies to develop and trial new technologies. Manufacturing systems are manual with production schedules varying according to customer demand.

A model of the built environment was built in IES-VE (Figure 2).

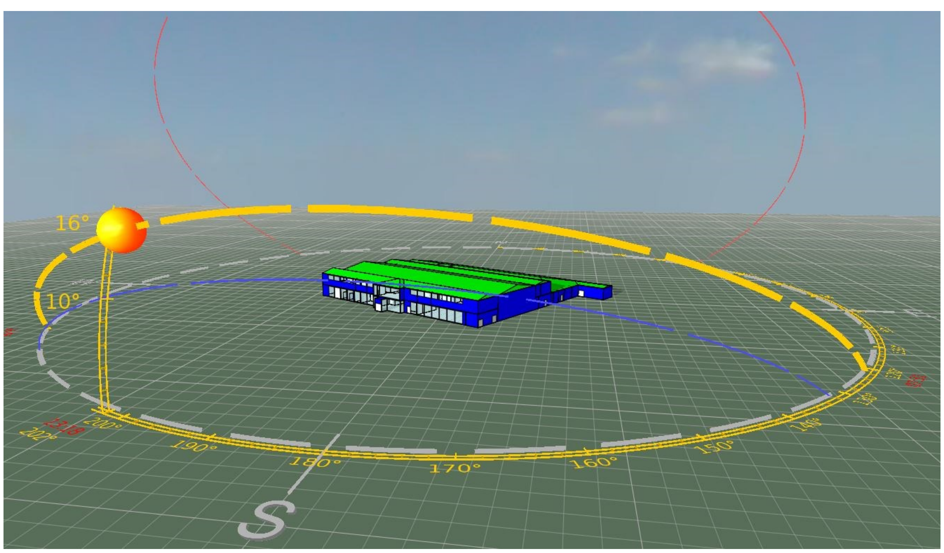

Figure 2- Building model in IES-VE, displaying the solar path around the building

The model was separated into 59 different thermal zones corresponding to rooms within the building. Each room was specified with its own thermal profile dependant on use, lighting, occupancy and required temperatures, as well as specifying behaviour effecting airflows, such as whether windows and balcony doors can be opened and door positioning. Zoning was used to implement different thermal conditions to spaces within the facility, however air and heat exchanges occur across these zones.

The site is part of a larger industrial estate compromising of 5 sites. These sites are supplied with a 11kV electricity supply, which is supplemented with a 950 kW wind turbine. Currently, the site is monitored using simple electricity meters, collecting data regarding energy consumption at hourly intervals of which is transmitted to loggers using internal GPS. HVAC systems are set to operate 24hrs a day, based on the thermal comfort of occupants, and controlled with a thermostat. The HVAC system is a Schneider PM200 system. No windows are present in the manufacturing workshop and therefore the only source of cooling in the workshop is mechanical.

3.1 Boundary Conditions

Construction material properties used in the simulation can be found in Table 1. Boundary conditions such as HVAC systems, occupancy schedules and internal gain assumptions used in the model are displayed in

Table **2**. Such assumptions follow manager guidelines at the site, as well as industry guidelines [46].

Table 1- Building construction materials

Parameters	**Specification**	**U- Value (W/m^2 K)**
Roof	154.4mm insulation – 0.1mm membrane – 100mm concrete deck – 50mm cavity – 12.5mm plasterboard	0.18
Internal Ceiling/Floor	20mm chipboard – 50mm cavity – 50mm screed – 100mm reinforced concrete – 50mm cavity – 12.5mm plasterboard	1.09
External Wall	3mm rainscreen – 50mm cavity – 81mm insulation – 12mm cement bonded particle board – 50mm cavity – 12.5mm plasterboard	0.26
Internal Partition	12.5mm plasterboard – 50mm cavity – 12.5mm plasterboard	1.79
Ground Floor	98mm insulation – 100mm reinforced concrete – 50mm cavity – 20mm chipboard flooring	0.22
Window External	8mm outer pane – 12mm cavity – 8mm inner pane	1.59
Window Internal	10mm glazing	3.85
Doors Internal	30mm plywood	2.20
Doors External	8mm outer pane – 12mm cavity – 8mm inner pane	1.59

Table 2- Building boundary conditions

Parameters	Values
HVAC set point	23 °C for all zones except workshop – 21 °C
Hours of Operation	24hr
Occupancy Schedule	Mon- Thurs 50% workers 07:00-08:00 100% occupancy 08:00-16:00 50% occupancy 16:00- 17:00 Friday 50% workers 07:00-08:00 100% occupancy 08:00-14:00 50% occupancy 14:00- 16:00 10% occupancy 16:00-17:00
Internal Gains Lighting People Misc Equipment- computers & monitors Machines	 5 W/m^2 90 W/person sensible 60 W/person latent 125 W/ computer + monitor Dependent upon power rating
Air exchanges per hour	0.2

Thermal bridging is accounted for by implementing a coefficient expressing heat loss as a function of wall area. A default U value of 0.035 W/m^2 K was implemented as stated as national standard in NCM documentation [47]. The MacroFlo module within IES-VE is responsible for simulating the flow of air through gaps in the building envelope, an example of such within this model were doors and windows.

Building simulation studies commonly use a default time step of 60 minutes [48], however a study by Albatayneh et al. [49] on the use of simulation for the thermal performance of buildings suggested the use of smaller time steps for shorter simulation periods (weeks or months) for an improvement in accuracy. Data collected from meters at the case study site was only available in 60 minute intervals, therefore, the time step used throughout the simulation study was set to 10 minutes with a 60 minute reporting interval.

18 pieces of equipment were modelled on the shop floor, ranging from 5 axis CNC machines and large mill turn centres to simpler lathes and gear grinders. All machines on the shop floor were high-powered machining equipment for processing of metals and composites.

The radiative fraction, a value between 0.0 and 1.0 is used to characterise the amount of radiant heat given off by equipment in a room or thermal zone. A typical value is between 0.1 and 0.5 [50].

Waste heat from manufacturing equipment can occur in multiple forms. In this study, lower temperature waste heat was prevalent, occurring from exhaust streams and cooling water systems, as well as the conversion related waste heat (conversion from electrical sources).

This study adopted the methodology of Sun et al. [39] and Brundage et al. [35] using a heat emission fraction to determine machine power and heat emissions. Simulations were run for a period of 12 months with radiant fractions of 0.1, 0.3 and 0.5 to determine effects of differential values on boiler and chiller energy (Table 3).

Table 3 - Effect of radiant fraction on boiler and chiller energy

Radiant Fraction	Total Boiler Energy (MWh)	Total Chiller Energy (MWh)
0.1	208.01	205.80
0.3	207.80	205.74
0.5	207.74	205.69

As the radiant fraction increased from 0.1 to 0.5, differences in boiler and chiller energy for each radiant fraction over the 12 month period was seen as negligible with the highest obtained error at 0.13 % for the boiler load. An error of 0.05 % was obtained for the chiller system. As the chiller system is prone to larger fluctuations in energy consumption, these differences were seen as negligible. The default value of 0.1 specified by IES-VE for radiant fraction was utilised throughout the study.

The boiler and chiller energy demands are that of the full building facility, and thus also work to combat effects of occupants, solar gains and building fabrics. Therefore, any effects of manufacturing radiant fraction variations play a small part towards total boiler and chiller requirements.

A thermal imaging camera was also used to determine surface temperatures of machines, as well as to investigate heat dissipation from each machine.

The Verein Deutscher Ingenieure (VDI), [51], an association of German engineers setting standards in engineering, suggest the use of 15-20% of the machine load as internal heat gains. Such a standard was also used in the assessment of factory energy efficiency by Weeber [26], and was also adopted in this study.

The location of the factory was specified, as well as building orientation, geography of the surrounding area and height from sea level to determine effects of external conditions and solar gains. Weather conditions such as cloud cover, outdoor temperatures, relative humidity and wind speed were provided by Met Office databases at time intervals of 1 hour. The simulation was initially run in IES-VE without any manufacturing equipment present, and then also run with the manufacturing equipment. This second simulation aimed to approximate heat gains to determine the effect of adding manufacturing heat gains to the built environment.

3.2 Validation

The results for the building shell analysis in IES-VE, both with and without manufacturing equipment, were compared with the real metered energy data for a simulation period of 1 year (Table 4). No metered energy breakdown was available from the building due to lack of sensors in the facility; therefore, total energy consumption was used for comparison.

Table 4- Building Energy Analysis- IES-VE and Metered data

	With manufacturing equipment (MWh)	**Without manufacturing equipment (MWh)**	**Metered data (MWh)**
Total System Energy (HVAC and chillers)	856.40	712.33	-
Lighting	58.24	58.24	
Misc Equipment (eg computers)	261.34	261.34	
Fan and Pumps Energy	72.03	30.31	-
Manufacturing Energy	282.83	-	-
Total Energy	1458.81	1031.90	1588.33

The IES-VE model underestimated total energy consumption for a simulation period of 1 year by 8.15 % in comparison to metered data. Monthly data was also analysed, with an average error of 13.5 % for monthly energy consumption between simulated and metered data (Table 5).

Table 5- Building Energy Analysis- IES-VE and Metered data- Monthly analysis

Month	**IES Simulation Total Energy (MWh)**	**Metered Data Total Energy Consumption (MWh)**	**Error (%)**
January	148.46	164.41	9.70
February	110.49	165.60	33.3
March	132.42	190.89	30.6
April	118.54	152.15	22.1
May	116.46	108.57	7.27
June	111.87	116.85	4.26
July	116.90	124.12	5.82
August	108.72	120.15	9.51
September	112.90	113.01	0.10
October	123.36	109.64	12.5
November	123.54	109.49	12.8
December	135.14	135.14	19.1

These errors are likely to arise due to the unavailability of data for building construction materials, estimated occupancy patterns, lack of data regarding machining times and length of certain machining jobs, lighting data and also lack of knowledge on occupant behaviour. For example, the IES-VE model assumes lights are switched off overnight, with no machinery left running. In reality, stochastic and unpredictable occupant behaviour can have a significant impact on building energy consumption, of which is unquantifiable in simulation without real detailed metered data within the model. From simulation, it was concluded that manufacturing processes accounted for 29 % of the total energy use of the facility comparing an environment with equipment to one without. Comparatively, the UK Department for Business, Energy & Strategy's report on energy consumption in the UK states that space heating is responsible for 30% of energy consumption in manufacturing facilities [52]. This emphasises the importance of obtaining accurate machining schedules, understanding of worker and machine behaviour for a more accurate simulation of manufacturing equipment.

The model was calibrated by comparing total building electrical energy data from the simulation model with the metered data from the facility every hour, for a sample of data over one month (672 samples). Following the method utilised in a similar study by Weeber [26], the validation of the model is based on statistical indices; the coefficient of variation in root mean square error (CV(RMSE)). Weeber quotes the ASHRAE Guideline (2002) for monthly validation criteria, the level of CV(RMSE) acceptance is 15%. The CV(RMSE) was 0.05% for the model utilised in this study.

3.3 Analysis of results

3.3.1 Feasibility Study Results

The shop floor was modelled in both WITNESS and IES-VE to determine manufacturing energy consumption. A typical working month was selected to carry out the feasibility study. A total of 18 machines were simulated for 4 weeks, with a preconditioning of 4 weeks.

The results from analysing manufacturing equipment energy consumption using WITNESS and IES-VE were compared, looking solely at energy consumption from manufacturing processes (Figure 3).

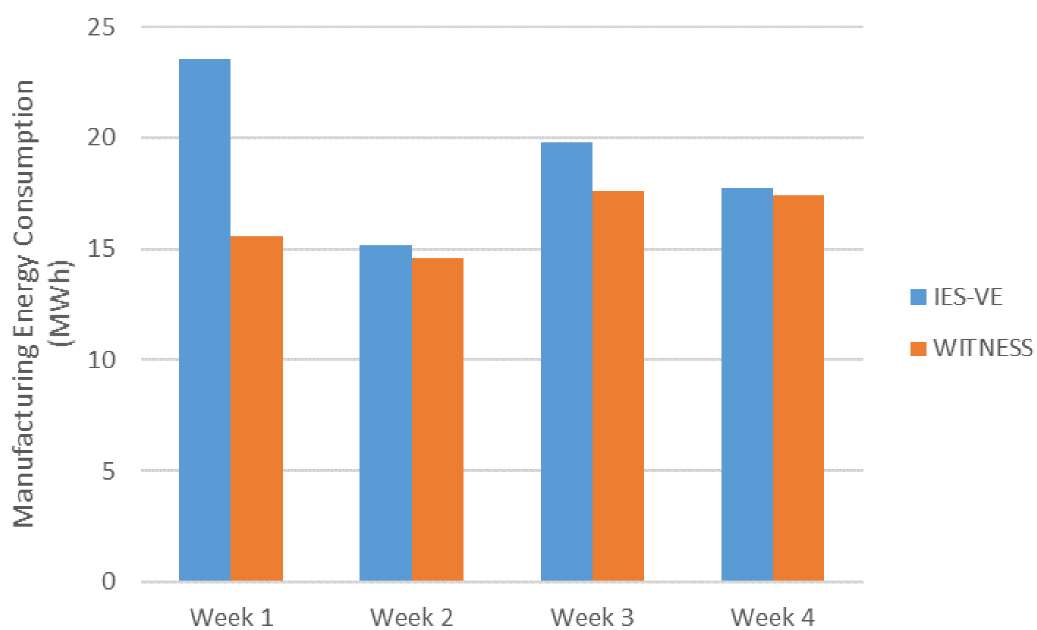

Figure 3-Weekly Manufacturing Energy Consumption from IES and WITNESS

There was an average error of 12% between the IES-VE and WITNESS model. It was concluded that the inability to specify set up and down time in IES-VE would have resulted in slightly larger values for energy consumption due to the assumption that the machinery is on 100% operation mode throughout the majority of the working day.

For this study, focus was predominately on interaction between manufacturing processes and HVAC systems along with ensuring optimum environmental conditions for production. Therefore, the manufacturing add-on tool in IES-VE was used to model the machines on the shop floor during holistic analysis of both the manufacturing environment and processes.

3.3.2 IES-VE Manufacturing Facility Results

The full building was analysed with and without manufacturing equipment (Table 6). Metered data from the case study facility was only available on a building level, with no data collected for individual zones (e.g. the Workshop). It should be noted that only variables influenced by manufacturing processes and therefore variables of interest are displayed in the table.

Energy from additional sources such as lighting and computers is not effected by manufacturing demand and therefore not included in the table; however such factors contribute towards the final energy requirement of the facility.

Table 6- Simulation results for the Building

	February		**August**	
	With manufacturing equipment	**Without manufacturing equipment**	**With manufacturing equipment**	**Without manufacturing equipment**
Total System Energy (MWh)	74.03	70.63	58.78	44.98
Boilers Energy (MWh)	32.55	35.02	1.02	1.07
Chillers Energy (MWh)	9.67	5.32	19.45	9.21
ApSys Heat Rejected (Fans/Pumps Energy) (MWh)	3.38	1.86	6.82	3.22
Total Energy (MWh)	110.49	95.27	108.72	71.68

In order to ensure thermal comfort within the facility throughout the year, a workshop temperature threshold was set between 19-21 °C. Likewise, a relative humidity threshold was set at 40-70 % for thermal comfort. Boiler systems were still required for the summer months, in the early hours of the morning to ensure the facility was at a comfortable working temperature for when the workers arrived.

Less energy, 7.30 and 5.48 % for winter and summer months respectively, was consumed from the boiler systems when manufacturing equipment was present, due to the additional heat gains provided by the machining equipment which acted to warm the space. A 58.0 % and 71.6 % increase in energy required from chiller systems was seen in winter and summer months respectively. Although chiller systems are not required in winter to combat significant solar gains, a large increase in energy from the chiller system in the winter months was found to be due to inefficient use of the HVAC system. The boiler systems were set at a high level to provide a comfortable environment for the workers at the start of the day, however due to unanticipated heat gains from the equipment, the chiller systems were required to combat a significant amount of heat from the boiler systems as well as the manufacturing equipment.

Such patterns in HVAC control demonstrates the need for a proactive based HVAC system which takes into consideration manufacturing equipment, and the heat gains from machines based on machine usage and upcoming schedules. Thus, HVAC controls can be set to anticipate heat gain fluctuations due to an increase or decrease in machining demand, along with HVAC requirements due to external weather conditions.

Despite the energy savings from the boiler system due to the presence of manufacturing equipment, the facility with manufacturing equipment required 4.71 % and 26.6 % more energy from the HVAC system in the winter and summer months respectively, compared to a facility without such equipment.

As seen from Figure 4 there were significant fluctuations in boiler and chiller system energy consumption, as they work alongside manufacturing demand and process heat output. The chiller energy consumption profile follows the manufacturing schedule profile, working to combat excess heat in the environment as a result of intense manufacturing activity. Boiler system energy consumption reduced, as boiler systems were no longer needed to heat the environment during times of machining.

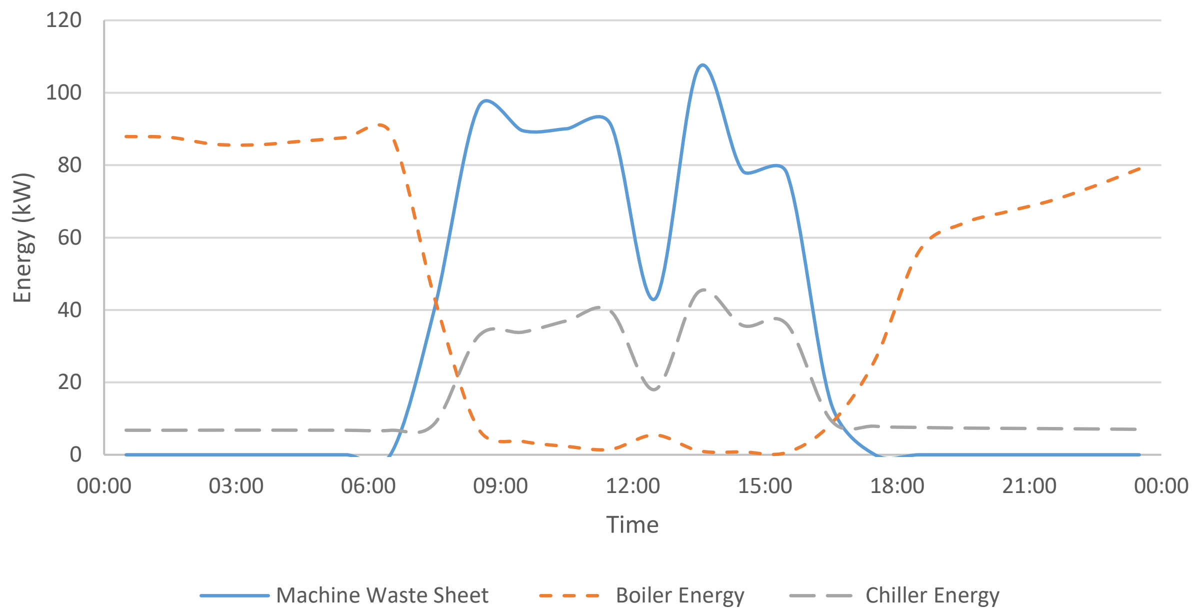

Figure 4- Waste heat output from machinery alongside energy required for boiler and chiller systems

There is also a spike in demand for heat in the space when machines are not operating and additional energy required for fans and pumps to remove heat from the air during times of high machining activity (Figure 5). Such an effect was prominent as the waste heat output reached 20kW (corresponding to machining equipment with an energy consumption of 19 kW).

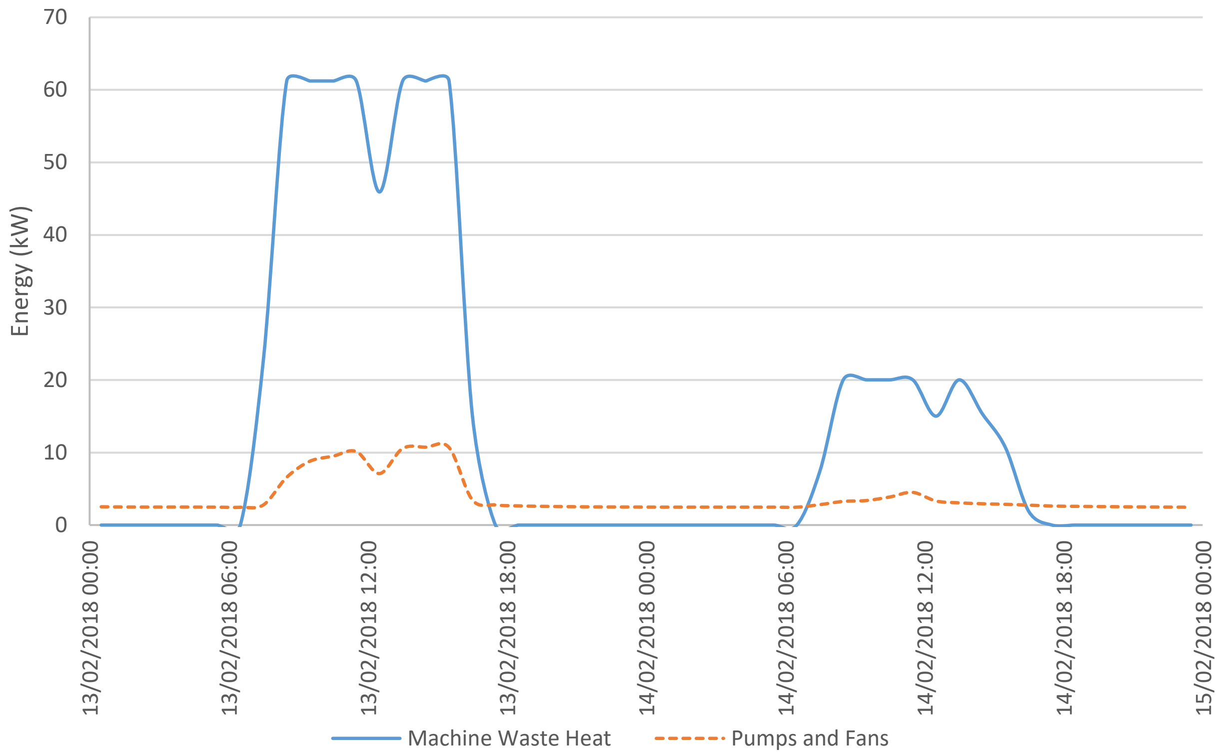

Figure 5- Waste heat output from machinery alongside energy required for environmental pumps and fans

Spikes and such operation in the HVAC system is inefficient, and based on a reactive system- when machining demand increases, waste heat increases, the boiler and chiller systems then react to compensate. Due to the dependency on machining schedule, a HVAC system with controls based upon machining demand as well as workshop conditions could provide a less oscillatory energy profile.

Spikes in energy consumption from fan and HVAC systems can have a considerable effect on the total energy consumption of the facility and the price in which the facility is charged for its energy consumption. Avoiding large spikes in consumption is essential to avoid larger tariffs for energy that is not necessarily used. Identifying the spikes in consumption and then subsequently the relationship between building energy management systems such as HVAC and machining processes can identify means of more effectively and efficiently controlling the system, and provide a pathway to spike reduction.

The energy required from the HVACs chillers systems for the facility without any manufacturing equipment for a week in July, increased with outdoor air temperature as predicted, with a maximum requirement of 44.62 kW. However, when manufacturing equipment was present, the energy requirement from the HVACs chillers system had to account for both a rise in outdoor air temperature, as well as heat gains from manufacturing equipment. The additional heat gains from equipment, the peak energy requirement reached 107.58 kW; a 141 % increase in energy requirements from the chiller system due to machining heat gains (Figure 6). Such a comparison displays the increase in chiller energy from a non-operating to an operating facility is independent of outdoor temperature.

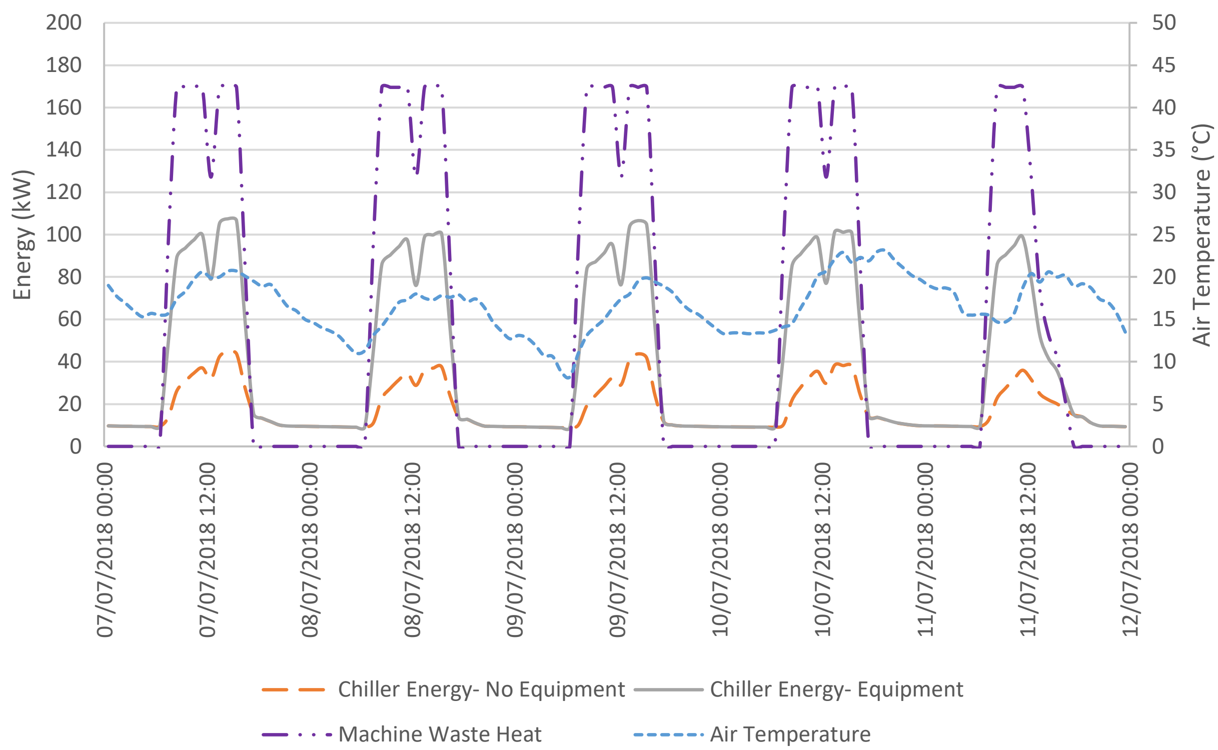

Figure 6- Chiller energy requirements for a the facility with and without equipment, plotted alongside outdoor air temperature and machine waste heat

Considering that the manufacturing equipment is only present in the Workshop, the workshop was also analysed in isolation to the rest of the building for a cooler month (February) and a warmer month (August) of the year (Table 7). In order to ensure thermal comfort within the facility throughout the year, a workshop temperature threshold was set between 19-21 °C and relative humidity threshold set at 40-70 %.

Table 7- Simulation results for the workshop

	February		August	
	With manufacturing equipment	**Without manufacturing equipment**	**With manufacturing equipment**	**Without manufacturing equipment**
Heating Plant Sensible Load (MWh)	26.04	28.01	0.81	0.86
Cooling Plant Sensible Load (MWh)	26.11	14.36	52.59	24.86
Mean Air Temperature (°C)	19.8	19.6	19.8	19.6
Mean Humidity	53.0 %	53.6 %	53.0 %	53.6 %

The requirement to analyse manufacturing equipment alongside the built environment was concluded from the simulation. Due to equipment heat gains, the workshop with manufacturing equipment required 7.31 % less energy to warm the space (heating plant sensible load) in February, however required over 58 % more energy to chill the space (cooling plant sensible load). In the warmer months, only 0.05 MWh, 5.48 %, of heating energy was saved due to heat gains from manufacturing equipment, however 71.6 % more energy was required to chill the workshop.

Understanding the impact on HVAC systems due to manufacturing equipment and production schedules can enable companies to utilise the concept of waste heat recovery, with the potential to optimise machining schedules based on outdoor weather conditions. To meet the UKs 2050 climate change target and reduction in emissions, emissions from building need to be near zero, with action taken on industrial processes. Furthermore, process heating in manufacturing remains the largest consumer of energy [9], and the need for a policy regarding Future Framework for Heat in Buildings having been proposed emphasises the importance of reducing the energy consumption from heater systems [53]. Along with optimised HVAC management, it has been reported that process optimisation and redesign is another factor holding potential to reduce energy consumption in manufacturing facilities [9]. For example, during the summer, at midday when temperatures are at their peak and excess heat in the facility is a disadvantage, intense machining could be scheduled for later on in the afternoon.

3.3.3 Process Energy Visualisation

Production output for a single machine, Bumotec, a turnmill, was correlated with its energy use for a 5-day working period (Figure 7).

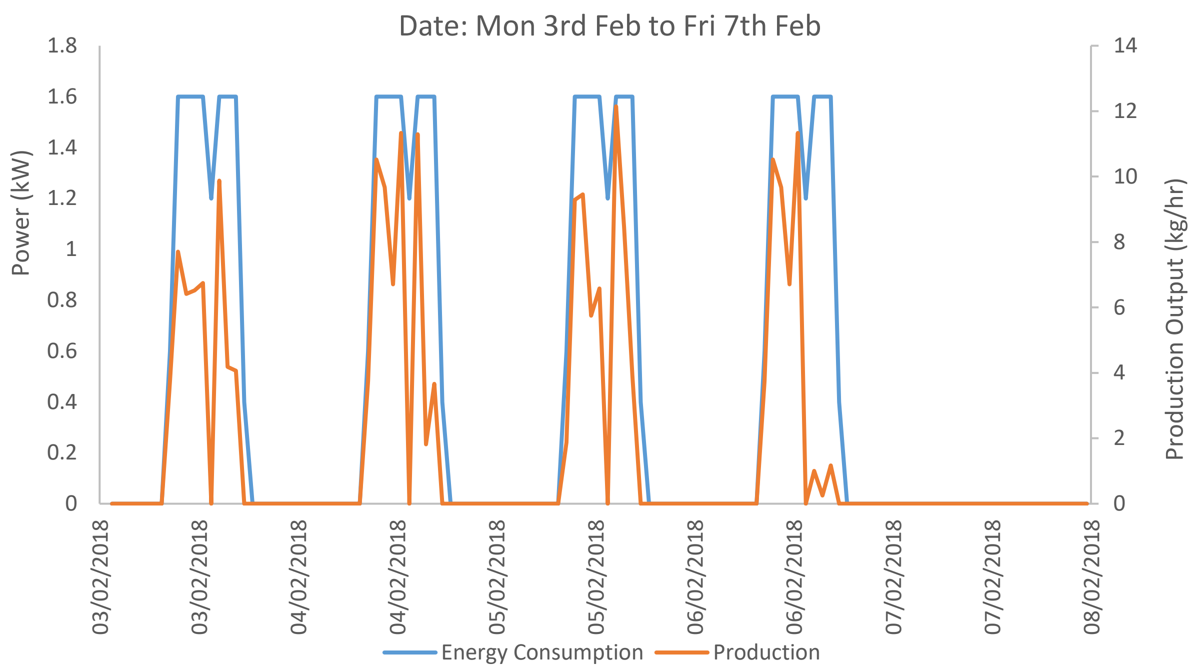

Figure 7 - Energy Use VS Production Output for Bumotec Turrnmill

The machine was not scheduled for operation on the Friday, however for the operating period of Monday to Thursday, the machine was booked in both the afternoon and morning slots, and therefore kept on all day, with the machine switched to standby during the lunch break. Gutowski et al. [54] stated that only 14.8% of a machines energy use is used for machining, likewise, Figure 7 shows that the machine is continuously using a large amount of energy regardless of production output. Similarly, fluctuations in energy consumption during machining periods is insignificant compared to the amount of energy the machine is using just to run. Displaying such statistics to the operator can give an indication of energy losses through machine usage as well as the ability to highlight issues with a machine. On the 06/02/2018, displayed in Figure 7, production output was significantly lower than the rest of the week, despite no drop in machining energy consumption, suggesting machine operational fault or insufficient use of machining time. From such energy visualisation, optimisation techniques can be adopted to reducing machine energy use, such as by increasing throughput rates, suggested by Gutoswki et al. [54] to be a significant energy saver.

Degree-days can be defined as the sum of the difference between the base temperature and outdoor temperature over a specified time period. The use of degree-days is commonly used to determine the effect of weather conditions on energy demand to plan energy systems, prediction seasonal load demands and to determine weather related variations in energy demand. Such a method is considered an index of the energy consumption of buildings and represents a method of estimating heating and cooling requirements of HVAC systems [55]. However, this means that the resultant building energy performance is a function of degree-days, and therefore outdoor temperature, whereas in reality, buildings energy demand can fluctuate greatly dependent upon use, occupant behaviour and internal gains. The latter being a considerable factor in manufacturing environments. As previously shown in Figure 6, chiller energy fluctuating to extreme levels due to manufacturing equipment, suggesting the inability of degree-days to predict energy consumption of manufacturing HVAC systems. As seen from the negligible correlation between building energy consumption and degree-days, the use of degree-days in manufacturing facility energy analysis does not provide an accurate account of building or HVAC consumption (Figure 8).

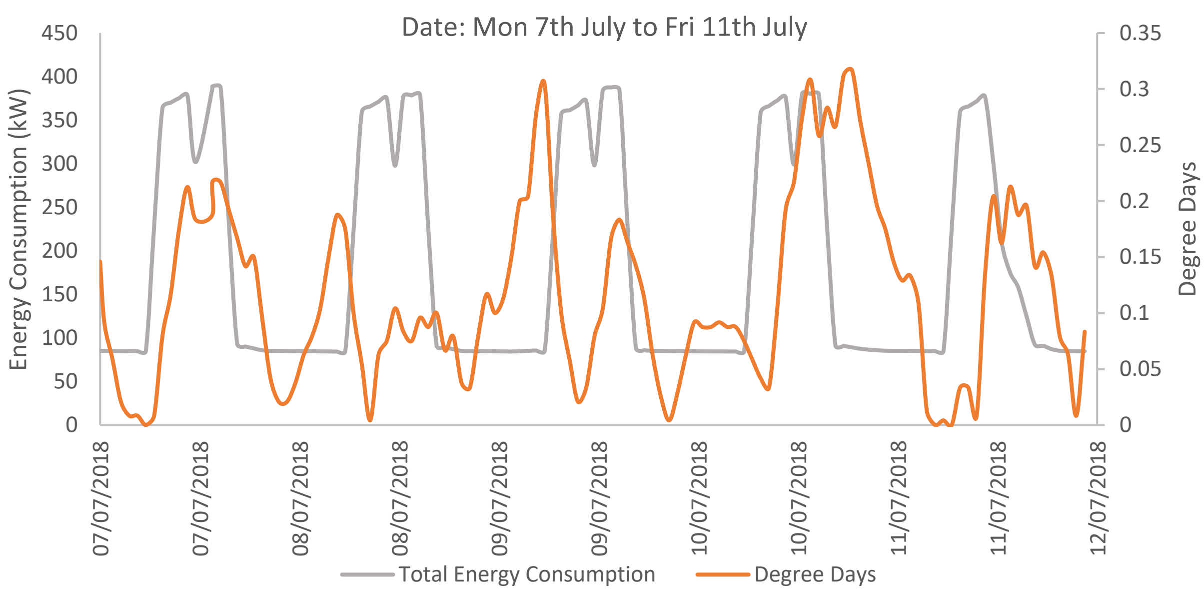

Figure 8- Building energy consumption alongside degree days

4.0 Conclusions

This project demonstrates the importance of analysing manufacturing energy flows alongside that of the building in order to capture all thermal and energy flows. Similar to the study on manufacturing heat gains and building energy analysis by Weeber et al. [26], this study showed the relationship between the energy demand of HVAC systems with manufacturing productivity, with a 26.6 % increase in HVAC system energy requirements, and a 71.6 % increase in energy requirements from the chiller system due to the use of manufacturing equipment in summer months. Such an increase in chiller energy from a non-operating to an operating facility is independent of outdoor temperature. Results show that the current methodology of modelling buildings with the degree-day system is not suitable for manufacturing facilities due to its use of a set base temperature, of which is dependent on building use, however machine use and required workshop conditions significantly influencing control and efficiency calculations of the building.

With significant spikes in energy profiles from boiler and chiller systems in response to manufacturing demand, this study has demonstrated the need for a proactive based HVAC system, responding to manufacturing demand, rather than a reactive temperature based system due to the significance of manufacturing equipment on HVAC energy demand. Proactive manufacturing based systems allows HVAC systems to respond in accordance to machining use, allowing control of the environment prior to significant temperature or humidity changes. Thus, allowing for a reduction in spikes in energy consumption from HVAC systems.

Energy visualisation techniques in manufacturing enables the primary focus of building level energy to also include system and product level, allowing for both energy awareness and continuous improvement of end energy use. The knowledge surrounding interactions between manufacturing and HVAC energy consumption alongside energy flows, resources, occupants and the architecture of the building allows for better decision making regarding control of HVAC systems, as well as for optimising machining shift pattern management.

Although building energy management software has the capability to model manufacturing equipment on the shop floor, along with its interaction with the surrounding environment, the software is predominantly building analysis based rather than manufacturing energy based and therefore cannot model machining energy profiles with high accuracy. Although radiative heat losses from equipment are known, no research was found determining convective heat transfer from machines to the surrounding environment. Determining convective heat losses as well as radiative would give a more accurate representation of heat transfer between machines on the shop floor and the surrounding environment. The ability to import machining power profiles would capture a more accurate model, with additional parameters implemented such a machining state, cycle times and set up times, all of which may hold a different energy profile.

Acknowledgements

The authors would like to acknowledge the financial contribution provided by the Engineering and Physical Sciences Research Council (EPSRC) and the University of Strathclyde that has enabled the production of this paper.

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