A new approach to modelling process and building energy flows in manufacturing industry

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I. Abstract

Global conservation of energy and material has become a key topic among governments, businesses, local societies and academics. A point made by many on the subject of energy begin by stating the importance of conserving the earth's natural resources, and the need to reduce greenhouse gas emissions in a bid to reduce global warming. This research is no exception, concentrating on an energy and material intensive sector of the global economy; manufacturing industry.

This research formulates a methodology for modelling energy flows between a factory building, its manufacturing process systems and the materials used. The need for such an approach arises from the gap in knowledge between the understanding of energy consumed by factory buildings and process systems in manufacturing industry. Factory buildings are purpose built environments that house manufacturing processes, manufacturing plant, materials and occupants. Modern production lines are designed to optimise the flow of materials throughout a factory; to and from storage, production, assembly and distribution. Manufacturing production systems dictate the shape and size of factory buildings. This can lead to a high proportion of the overall energy consumption to be attributed to building services. The coupling of factory energy flows assists energy managers at both the facility and process levels, in order to identify efficiency improvements and reduce energy use and associated carbon emissions. A better understanding of the overall energy balance of a factory environment will allow energy to be used in a more sustainable manner.

Simulation tools are widely used in the disciplines of building design and manufacturing systems engineering. Traditional building energy flow paths are well documented and are handled within dynamic building modelling tools. Globally, manufacturing activities cover a wide field of industrial practice and use a range of simulation software packages such as flow diagramming packages, computational fluid dynamics, discrete event tools, direct coding, optimisation tools etc. The increasing use of simulation makes it difficult for a manufacturing systems analyst to choose a suitable approach for energy modelling. An important aspect of the methodology described in this thesis is the coupling of energy flows that occur internally (within a factory boundary) and externally (outside a factory boundary e.g. weather) in relation to time and location within and around a factory environment. Building modelling tools provide a structured and well defined approach to monitoring energy flows within traditional built environments.

The methodology extends the framework of an existing building modelling tool; the International Building Physics Toolbox (IBPT), to include the simulation of manufacturing process systems and material flow within a factory. There is a wide range of manufacturing processes used in industry so the scope of this research is reduced to thermal and electrical processes only. A

thermal process is considered to be an extension of a thermal zone (such as a room), as defined in building modelling tools. Two thermal processes are considered; processes that act on a volume of gas (i.e. air) and those that act on a volume of liquid. Material flow is represented in the model by time series. The lumped capacitance method is used to approximate the change in surface temperature of a material in relation to its stored energy, long wave radiation between the material and its surroundings, and convective heat transfer. To validate the use of the IBPT algorithms to model building physics, the results derived by using the IBPT are compared with those derived by using an industry standard trusted building modelling tool called 'Integrated Environmental Solutions Virtual Environment' (IES VE), in comparable areas of building modelling.

Three industrial case studies have been analysed, and these represent real scenarios from the automotive and aerospace manufacturing industry sectors. Two out of the three case studies include the simulation of the building (fabric and heating system), material flow and manufacturing process systems (air and liquid based). The third case study focuses on process modelling only, with future scope to include the factory building. Data obtained from industrial practice is used to validate the results of energy modelling using the proposed method. Results from the case studies demonstrate the capabilities of the proposed method of modelling factory energy flows and associated energy consumption at both facility and process level. Opportunities to reduce energy use and associated carbon emissions are also identified.

The methodology does have some limitations in the form of the number of manufacturing process types represented and the complex nature of modelling real energy flows that occur within factory buildings. However the findings of the research show that an integrated approach to modelling factory energy flows through development of a building modelling framework has real benefits for manufacturing industry. These benefits are very unlikely to be realised by modelling processes and buildings separately, as is the way current modelling methods are carried out by the separate discipline areas of building design and manufacturing systems. Factory energy managers and future factory designs are example areas in which the presented integrated tool would be most beneficial used. Future research within this area could include an extension of the framework to model moisture transfer, the inclusion of further types of manufacturing process systems and further investigation into the coupling of time-driven and event-driven hybrid modelling techniques to simulate material flow both in terms of locality and thermal behaviour.

II. Acknowledgements

This research was conducted at the Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK. The research formed part of the 'THrough life Energy and Resource Modelling' (THERM) project, in collaboration with Airbus UK, Toyota Manufacturing UK, Integrated Environmental Solutions Ltd, De Montfort University and Cranfield University (THERM 2012).

I would firstly like to thank my supervisors; Dr Andrew Wright, Dr Richard Greenough and Prof Li Shao, for their dedicated support and guidance throughout the PhD process. My gratitude is also extended to my friends and colleagues at the Institute of Energy and Sustainable Development of whom there are too many to mention here.

I would also like to thank the other members of the THERM project. Their enthusiasm and commitment to the project has made it an enjoyable experience. I greatly appreciate all of the help and guidance that each individual member has unselfishly offered to me throughout the three year project. I hope our paths cross again in the near future.

Last but not least, thank you to the loving support of my family. Especially to my amazing wife (Louise Oates), not only for enduring the ups and downs of the PhD process, but for also giving me a beautiful son.

With the exception of my supervisors, I have purposely not mentioned names as there are too many people to pay thanks to and do not want to miss anybody out. I gratefully appreciate all of the help that everyone has contributed.

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IV. Nomenclature

ACH	Air changes per hour
ASH	Air supply house
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
CNC	Computer numerical control
CO_2	Carbon Dioxide
DECC	Department of Energy and Climate Change
DES	Discrete event simulation
GUI	Graphical user interface
HVAC	Heating, ventilation and air conditioning
HX	Heat exchanger
IBPT	International Buildings Physics Toolbox
IEA	International Energy Agency
IES VE	Integrated Environmental Solutions Virtual Environment
JIT	Just in time
OCED	Organisation for Economic Co-operation and Development
PV	Photovoltaic
RH	Relative humidity
RMSE	Root mean square error
SCADA	Supervisory control and data acquisition
TBS	Technical building services
THERM	THrough life Energy and Resource Modelling
TM	Technical memoranda
TPS	Toyota Production System
TSB	Technology Strategy Board
UK SIC	UK Standard Industrial Classification of Economic Activities
WECD	World Commission on Environment and Development

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1. Introduction

1.1. *Research background*

1.1.1. Conservation

In 1986 the World Commission on Environment and Development (WECD) defined the need to conserve the earth's natural resources and reduce pollution and landfill as "development that meets the needs of the people today without compromising the ability of future generations to meet their own needs", better known as sustainable development (El-Haggar 2007). Conservation of energy and material has become a key topic among governments, businesses, local societies and academics. A point made by many on the subject of energy begin by stating the importance of conserving the earth's natural resources, and the need to reduce greenhouse gas emissions in a bid to reduce global warming. This thesis is no exception, concentrating on an energy and material intensive sector of the global economy; manufacturing industry. Since the start of the industrial revolution, access to materials and fossil fuel based sources of energy have been the backbone of industry (Hawken et al. 2010). Throughout this revolution the abundant use of material and energy across industry and other sectors (i.e. domestic and non domestic stock, transport and services) has been a linear flow, from extraction, processing, to use and finally disposal in landfill or incineration (Jelinski et al. 1992). Global energy consumption by industry equates to approximately one third of all the energy used globally and to almost 40% of global Carbon Dioxide (CO_2) emissions (IEA 2010). There is a limit to the earth's natural resources; land (surface area 149million km^2), water (1359million km^3), air, minerals (silicon, aluminium, iron etc) and other resources (Leonard 2010; Ecology 2012). Therefore, improvements in the way that industry uses energy and materials will have an effect on a global scale.

1.1.2. Built environment

A built environment protects and shelters inhabitants from changing external weather conditions. Residential, office and retail buildings are typical examples of purpose design and built structures that provide protection, shelter and stable internal environmental conditions, sometimes with the aid of heating, ventilation and air conditioning (HVAC), (BSRIA 2003). Through design and management of internal air temperatures, humidity and fresh air ventilation, occupants remain a focus of the internal environment (CIBSE 2006a). Poorly designed and underperforming buildings can result in increased health issues to the occupants. Sick Building Syndrome means that a building may be causing ill effects up on its occupants (McMullan 2007). A few conditions that occupants may experience are nausea, headaches and a runny nose. These conditions may be persistent or reduce in severity as the occupant leaves a particular environment.

1.1.3. Manufacturing industry

A main focus for manufacturing companies is to manufacture products at a minimum cost (Löfgren et al. 2011). The advent of Japanese production practices has been at the forefront of minimising cost, improving quality and performance of products (Sugimori et al. 1977; Schonberger 2007). The evolution of manufacturing process systems from manual to robotic and automation highlights the desire to increase speed and quality, whilst lowering cost such as material, labour and other non added value activities. Computer programmable manufacturing processes allow for more in-depth analysis of how these processes operate and how they consume energy. Studies by Vijayaraghavan and Dornfeld (2010) and Dahmus and Gutowski (2004) consider energy consumed by individual parts of a manufacturing process system e.g. spindle, actuators and electronics for a computer numerical controlled (CNC) machine. Metering and monitoring within industry is also becoming more widespread through the introduction of regulatory requirements (CIBSE 2006b; Goverment 2010a; Goverment 2010b; ISO 2011). The Chartered Institution of Building Services Engineers (CIBSE) (2006b) quotes:

> *The late Peter Drucker, renowned management 'guru', said, "If you can't measure it, you can't manage it". He probably did not have the energy use of buildings in mind when he said it, but it is as relevant to the measurement and management of building energy consumption as to any other resource use.*

Though most built environments are designed for occupants, factory buildings are not solely designed with the occupant in mind. A factory building houses large manufacturing processes, plant, material resource and occupants. The new £77m Bombardier aircraft factory is an example of how the manufacturing process systems shape the design of the building (Building.co.uk 2012). Building (2011) quote, "The wing design determines the type of manufacturing equipment needed, which affects the design of the building". The 27,871m² clean room facility also reflects the importance of the environment, not for human inhabitants, though they will benefit, but for the manufacture of temperature and particle contamination sensitive components. This level of high temperature and humidity control is more in line in the manufacture of medical and blue chip components. During the industrial revolution, access to low cost and perceived abundant energy and material resources were considered the norm (Hawken et al. 2010). The increasing cost of primary and secondary fuel supplies and materials is beginning to draw attention across economy sectors, even more so from industry, which rely upon these resources to provide products to their customers at competitive prices. Therefore the consumption of energy associated with both the factory building and manufacturing process systems is of most importance when trying to manage energy in a sensible and conservative manner. Within the UK, there is increased regulatory requirements to improve the performance of domestic and non-domestic buildings, through better insulation, improved lighting levels, and metering and monitoring (Goverment 2010a; Goverment 2010b). Older factory buildings are commonly constructed from a number of materials, red brick being a popular choice. These buildings are typically large in volume, have high roof levels and are poorly sealed, resulting in high infiltration rates. These conditions can lead to high heating demands over the colder seasons. Modern factory buildings are lightweight, constructed from thin prefabricated metal cladding (Carbon-Trust 2004a). The lightweight structure retains little residual heat within the wall construction, though advances in Building Regulations are seeking to improve thermal performance through improved insulation levels. Heat will be retained by the high thermal mass concrete floor (Waters et al. 1985). Even so, the internal air temperature of the factory building will follow more closely that of the external air temperature over a shorter period of time than that of a building constructed from higher thermal mass elements, in the case where there are no internal thermal gains from sources such as manufacturing process systems, lighting, occupants, materials, space heating etc.

1.1.4. Integrated approach

An integrated approach to saving energy within the manufacturing industry not only considers savings at a manufacturing process systems level but also at a facilities level. This can be achieved both in new design and refurbishment of factory buildings. The Toyota Tsutsumi plant in Japan (Toyota 2011) has been in operation since 1970. The plant has reduced CO_2 emissions by 50% on 1990 levels and is tackling environmental issues such as material, water and energy conservation. The plant has installed 50,000m^2 of rooftop solar photovoltaic (PV), developed its own type of green roof mounted grass, reduced water discharge by up to 50%, painted 22,000m^2 of exterior wall in photocatalytic paint, among a list of other environmental activities. The built environment remains an important aspect, in targeting further energy reductions. New factory buildings such as MAS Intimates, Thurulie (MAS-Intimates 2011), Nike, Ho Chi Minh City (Nike 2011) and McLaren's Technology centre, Woking (McLaren 2012) consider the internal environmental design of the building by applying natural ventilation and air conditioning strategies. Nike, Ho Chi Minh City, have designed and installed ventilation towers, to induce natural ventilation airflows from adjoining work shop areas. MAS Intimates Thurulie, apply a similar principle via large cross ventilation sectional openings, although air conditioning is still required during parts of the year. McLaren, Woking, use water from nearby lakes to cool the building via a network of heat exchangers and air conditioning system. There are many other examples of new and refurbished factory buildings aiming for a low energy and carbon emission future, (Herman-Miller 2011; Ford 2012; Herman-Miller 2012; Vanguard-Packaging 2012).

The above environmental strategies are based on energy conservation measures. However, what is known of the overall energy flows within a manufacturing facility? How much thermal energy is from solar gains, internal gains (e.g. people, lighting and office equipment), manufacturing process systems and material flow? If the layouts of manufacturing process systems are revised, process utilisation altered or turned off as a result of redundancy, how do these changes affect the internal thermal balance of the factory environment? How does this affect the energy consumption of the building services (i.e. heating, cooling, and ventilation)? What affects do these have on the energy consumption of neighbouring manufacturing processes? The energy interactions of a factory environment are complex and extremely difficult to evaluate, without an integrated approach. An integrated approach should consider the energy flows between the factory environment, manufacturing process systems, material flow and building services.

1.2. *Scope of the thesis*

This research forms part of the Technology Strategy Board (TSB) 'THrough life Energy and Resource Modelling' (THERM) sponsored project, in collaboration with Airbus UK, Toyota Manufacturing UK, Integrated Environmental Solutions Ltd (IES), De Montfort University and Cranfield University (THERM 2012).

The author has been working closely with the collaborators of the THERM project, contributing knowledge of building physics, software and building services, whilst gaining valuable experience from regular site visits to the industrial partner's facilities. The author assisted in the development of THERM tool prototypes, new data input methods into the IES software (i.e. free-form profiles) and development of THERM case studies through modelling and data management, see section 8.1. The author also assisted in the collection of data from the automotive and aerospace industrial partners of the THERM project forming part of the case studies used in this research.

Though the author has worked closely with the THERM project there are clear distinctions between the two pieces of work. The two approaches combine the disciplines of building design and manufacturing systems engineering into one integrated tool. However the limitations of current research, including THERM, are addressed in section 2.6. These limitations i.e. application and representation of liquid based manufacturing process systems, application and representation of material (product) flow that is thermally responsive to its local environment and case studies demonstrating actual or simulated opportunities to reduce energy usage at both a facility and process level, using a general model, are addressed by the research presented in this thesis.

The UK Standard Industrial Classification of Economic Activities (UK SIC 2007) classifies the variation in manufacturing sectors within the UK. The standard is used to classify business establishments and other statistical units by the type of economic activities they are engaged in

(ONS 2012). There are 23 manufacturing divisions, formed from manufacturing groups and classes (e.g. division 29 – Manufacture of motor vehicles, trailers and semi-trailers, group 29.1 - Manufacture of motor vehicles and class 29.10 - Manufacture of motor vehicles and division 30 – Manufacture of other transport equipment, group 30.3 - Manufacture of air and spacecraft and related machinery and class 30.30 - Manufacture of air and spacecraft and related machinery). From these classifications it is clear that the manufacturing sector covers a wide area of work. This thesis is focused on developing a technique in modelling energy flows between the factory environment, manufacturing process systems, material flow and building services. Through development of such a technique the work aims to be applicable to as many manufacturing sectors as possible.

1.3. *Research question*

Yin (2009) states that there are five types of research question: who, what, where, how and why. The primary research question that this thesis seeks to address is stated below:

> 'What type of technique is required to model energy flows between a factory building, its processes and materials, in order to reduce its overall energy use?'

Further to the literature review the primary research question is refined in section 2.7.

1.4. *Research focus*

The aim of the research is to devise a technique for modelling of energy flows within and between a factory building, its processes and materials. The coupling of energy flows can provide assistance to energy managers in assessing energy used at both facility and process level, in order to identify efficiency improvements and reduce energy use and associated carbon emissions. This is important as many manufacturing environments provide spacing heating, cooling and ventilation, which can make up a large percentage of the total energy balance of a factory. Through better understanding of the overall energy balance of an industrial factory environment, further effort can be made to use energy in a more sustainable manner. The main objectives of the research are listed below:

- Review current state of the art in building physics and manufacturing industry in areas of energy, simulation and integrated approaches.
- Develop a conceptual method for identifying macro and micro levels of energy flows that occur within a factory environment
- Define and develop a technique that is capable of modelling building energy flows, building services, manufacturing process systems and material flow within one integrated tool

- Use case studies formed from data obtained from the industrial partner's of the THERM project to test the methodology of the research

This work addresses the gap between the factory building (shell), manufacturing process systems and material (product) flow through the formulation of an integrated modelling technique.

1.5. *Thesis structure*

The structure of the thesis is as follows:

Chapter one provides an overview of the thesis which includes: research background, scope of the work and primary research question, aim and objectives.

Chapter two provides a literature review of the main research topics of the thesis. The chapter concludes with the research question being refined in line with the literature review summary.

Chapter three presents the methodology used to carry the research.

Chapter four defines an integrated framework to representing energy flows within a factory environment through conceptual modelling.

Chapter five develops an integrated software tool in line with the research design and conceptual modelling framework. This chapter also includes a section on software verification between the integrated tool and a commercial building modelling tool in comparable areas of building modelling.

Chapter six describes three industrial case studies. The case studies are modelled using the framework of the research and are directed towards answering the research question(s).

Chapter seven concludes the work, discussing the outcomes of the research and contribution to knowledge.

Chapter eight discusses the potential of the research for further work.

References, publications and appendices: the final chapters include a list of research references and publications (Appendix A) by the author. Appendix B includes mathematical formulation for the drying manufacturing plant components modelled in Chapter 6. Material provided on compact disc (CD) is listed in Appendix C and D.

2. Literature review

The literature reviewed covers two largely unrelated areas, building physics and the manufacturing industry, sections 2.3 and 2.4. Brief introductions to both disciplines are given as the author is aware that the reader may not have prior knowledge of these areas. The drivers and the use of simulation within the fields are also discussed. Section 2.5 concludes the literature reviewed. This section discusses literature in the field which the author regards as core to the work in this thesis, covering the overlap of building physics and manufacturing processes and the need to consider the system as a whole to improve overall energy efficiency and energy conservation. The research question is refined in context to the literature reviewed in section 2.7.

2.1. *Approach*

The multi-disciplinary nature of the thesis necessitates a large area of previous work to be reviewed. Increased attention on environmental issues, such as diminishing natural resources, energy security and rising energy costs, has lead to more work in the following areas; energy efficiency, energy conservation, industrial ecology, and sustainable development. Keywords and filtering were used to narrow searches on building and industrial manufacturing related topic areas. The literature reviewed is taken from the following areas, peer reviewed journal papers, conference papers, professional accredited organisations, higher educational organisations, published books and the World Wide Web (WWW). Greater preference was given to peer reviewed journal papers as these are critically assessed and include research from pioneers in their field. The following keywords denoted by a letter of the alphabet and associated text strings were searched in multiple combinations in the following abstract and citation database engines, Scopus (Scopus 2012), Science Direct (Science-Direct 2012), Web of Knowledge (Web-of-knowledge 2012) and Zetoc (Zetoc 2012).

A. Building (design, services, physics)
B. Industrial (ecology)
C. Sustainable (Manufacturing, energy)
D. Factory (layout, building)
E. Process (layout, engineering, chain)
F. Energy (efficiency, conservation)
G. Manufacturing (system, engineering)
H. Simulation (dynamic, stochastic, discrete event)

Examples of combinations of the aphetically denoted keywords are shown below:

- A+D+E+F = (build*, design) AND(factor*, build*) AND(process, engineer*) AND(energy, conservation)

- C+E+F+H = (sustainab*, manufactur*) AND(process, engineer*) AND(energy, efficien*) AND(simulation, dynamic)

Keywords for new research published in the aforementioned abstract and citation databases have been carried out after the initial six month literature review stage. The keywords are from the identified research journal papers that closely resembled work undertaken in the thesis. The keywords are:

A. Sustainable manufacturing
B. Energy efficiency
C. Simulation
D. Process chain
E. Thermodynamics
F. Exergy
G. Manufacturing

Examples of combinations of alphabetically denoted alert keywords searches were also considered, shown below:

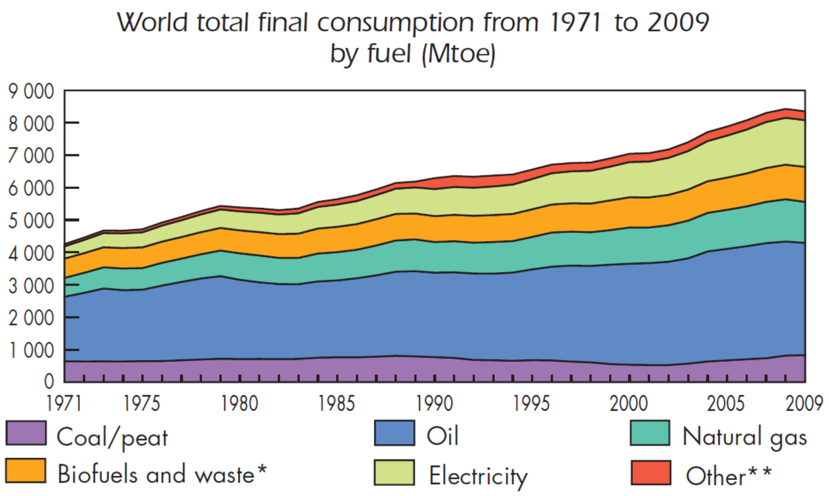
- A+B+C+D = (sustainab* manufactur*) AND(energy efficien*) AND(simulation) AND(process chain)
- E+F+G = (thermodynamics) AND(exergy) AND(manufactur*)

Keywords were also included for newly published documents citing core reviewed papers and newly published research undertaken by the pioneering authors in the field. More detail on core papers and authors can be found in section 2.5.

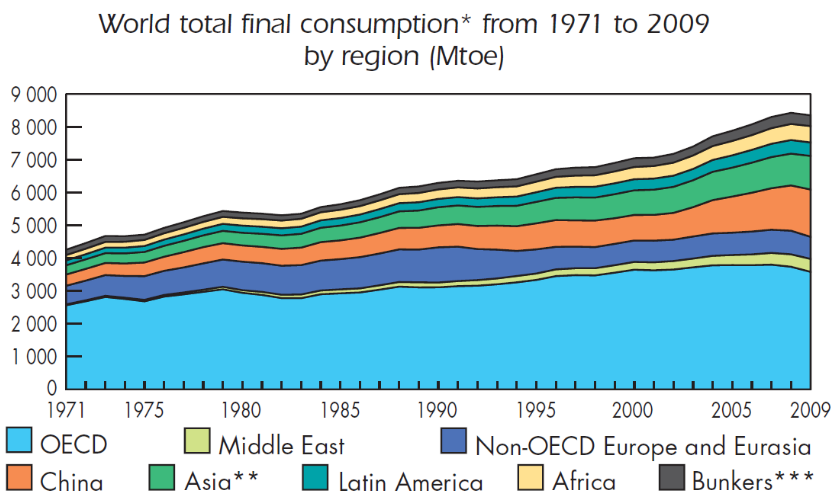
2.2. *Energy*

2.2.1. World energy

Since 1971 global energy consumption has approximately doubled from 4000 Mtoe (million tons of oil equivalent) to 8000 Mtoe in 2008, Figure 2-1. The IEA (International Energy Agency) World Energy Outlook 2010 press release (IEA 2010a) highlighted through formulation of global policy energy scenario that global energy demand could rise by nearly 36% by 2035, from 2008 figures. These figures reflect the growth and development of non-OCED (Organisation for Economic Co-operation and Development) countries, such as China and India.



a) Global energy consumption by fuel type



b) Global energy consumption by region

Figure 2-1 – Global energy consumption, 1971 to 2009, a) by fuel, b) by region (IEA 2011)

Figure 2-2 illustrates global fuel consumption by sectors of the economy, industry, transport, others (residential, commercial and public services, agriculture/ forestry etc) and non-energy use, from 1971 to 2009. In 2009 the percentage breakdown of global energy consumption for the industrial economy sector by fuel types were, coal (78.5%), oil (9.5%), gas (35.1%) and electricity (41.7%).

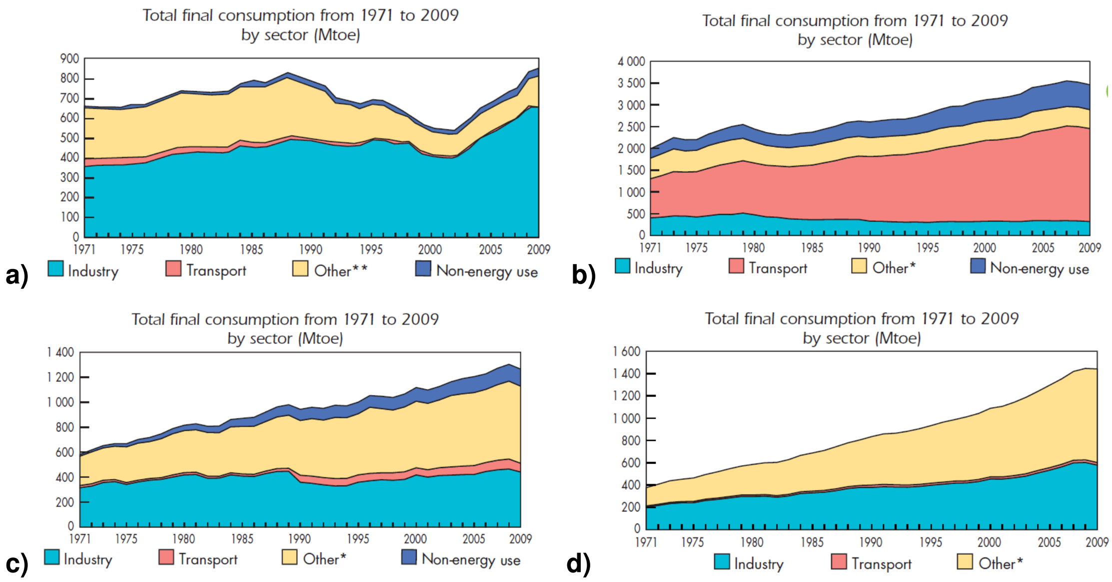


Figure 2-2 – Global energy consumption by sector, 1971 – 2009, a) coal, b) oil, c) gas and d) electricity (IEA 2011)

The cost of primary energy on a global scale has remained moderately consistent from early 1980s through to the early 21st century. Since 2000 the price of primary energy fuels (i.e. crude oil, oil products, coal and natural gas) have risen, with sharp fluctuations, peaking in 2008 as shown in Figure 2-3.

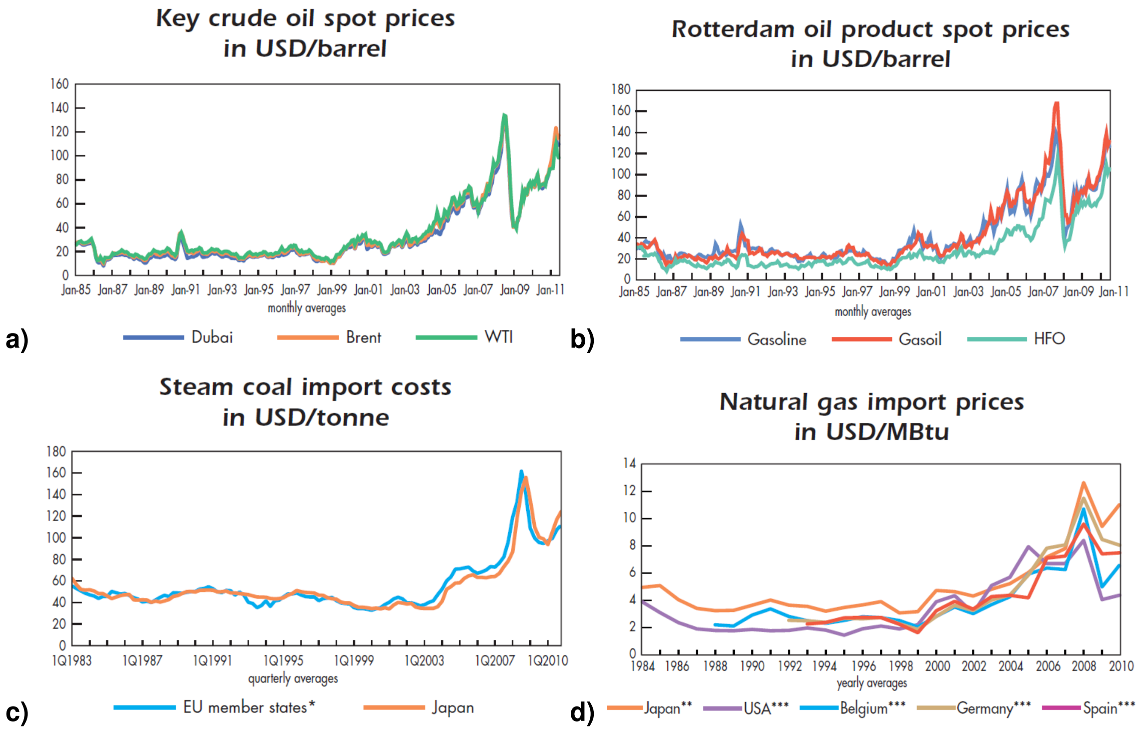


Figure 2-3 - Global energy prices, 1983 – 2011, a) crude oil, b) oil products, c) coal and d) natural gas (IEA 2011)

The future life expectancy for oil, gas and coal can be estimated from proven reserves. Statistical data from the 2011 BP Statistical Review of World Energy (BP 2011) indicates that there are 43 years, 59 years and 242 years, of oil, gas and coal reserves remaining respectively. These figures are based on 2010 energy consumption rates and proven reserves. They do not account for changes in future energy consumption, accessibility or explorations for further reserves.

2.2.2. UK energy by sector

This section gives a brief overview of the UK's energy consumption by sector of the economy, industrial sector and industrial processes. The UK Department of Energy and Climate Change (DECC) collected and analysed energy consumption data by economy sector (i.e. manufacturing industry, transport, domestic and services) for 2011 (DUKES 2012). These data show that almost a quarter of the UK's final energy consumption can be attributed to industry, Figure 2-4.

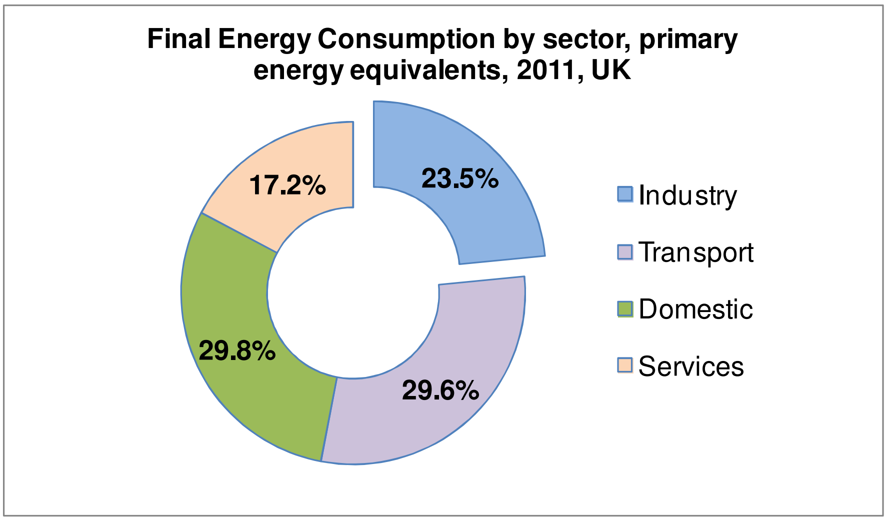


Figure 2-4 – UK industrial primary consumption by sector, 2011 (DECC 2012)

This thesis is concerned with the consumption of energy in the manufacturing industry. Globally, industry consumes one third of all the energy used in the world, amounting to nearly 40% of the global CO_2 emissions (IEA 2010). Depending on a country's manufacturing activity, the primary energy consumption of their industrial sector will vary in relation to the global average, e.g. China ≈48%, Germany ≈23%, USA ≈20% (IEA 2010). The high level of industrial energy use highlights the importance in reducing energy consumption in global industry, through improvement measures such as improved efficiencies, re-use of waste energy, and best practice. It is reported that the manufacturing industry can make potential savings of 25% by 2020. Improvement potentials reported are, process optimization (25-30%), optimised logistics (16%), integrated process chains (30%), development of new products (10-40%), intelligent motor drives (20-40%) and alignment with best performers (15%) (ICT 2008).

2.2.3. UK industrial energy

As shown in Figure 2-5, over 70% of energy in the UK industrial sector is consumed in the production of coke, fuels, chemicals, food and beverages, and other basic materials. Energy consumption figures for UK industrial sectors are shown in Figure 2-7.

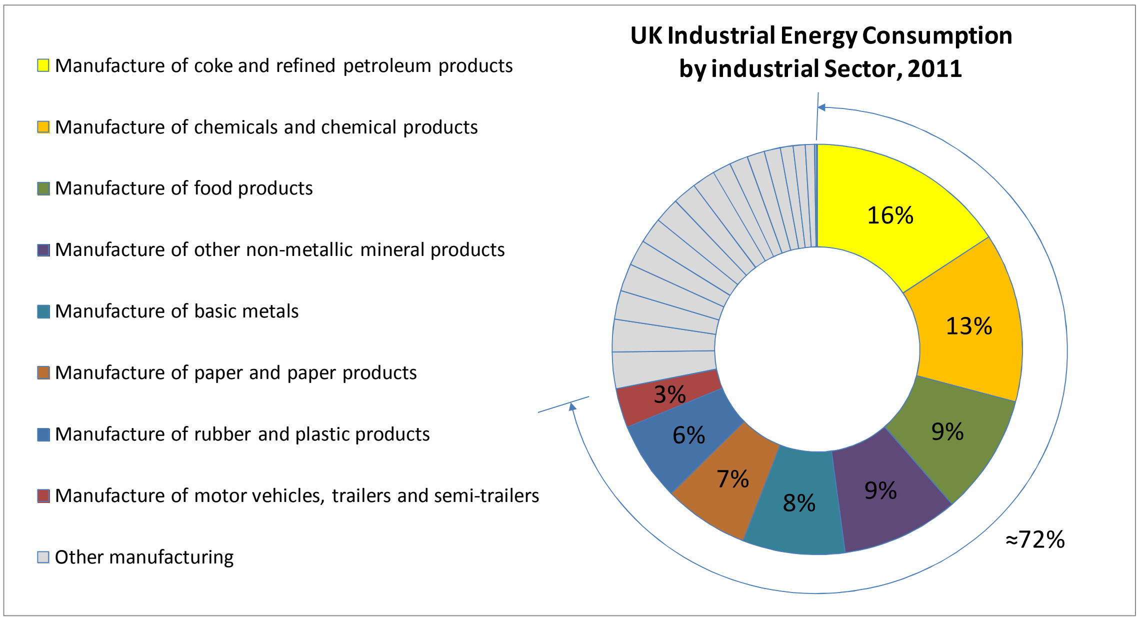


Figure 2-5 - UK industrial primary energy consumption by sector, 2011 (DECC 2012)

Highly energy intensive industrial sectors such as metals production consume large amounts of energy changing raw materials into workable/saleable end products (e.g. castings, sheet metal, wire rod). As highlighted in Figure 2-3, the global cost of primary energy has been fluctuating since 2000 and reached record highs in 2007-08. Figure 2-14 illustrates that, on average, 40% of the selling cost of a product is related to the manufacturing cost and that 50% of that cost is assigned to materials and 12% towards equipment plant and energy. The upward trend of energy prices reflects market value and the realisation that fossil fuels and natural resources are becoming more scarce and more dangerous and costly to source (BBC 2011).

Primary energy consumed within the UK manufacturing by industrial sector can also be broken down into end process uses, Figure 2-6. The figure shows that approximately 48% of end process use is accounted for by heat processes. Percentages will vary between industrial sectors.

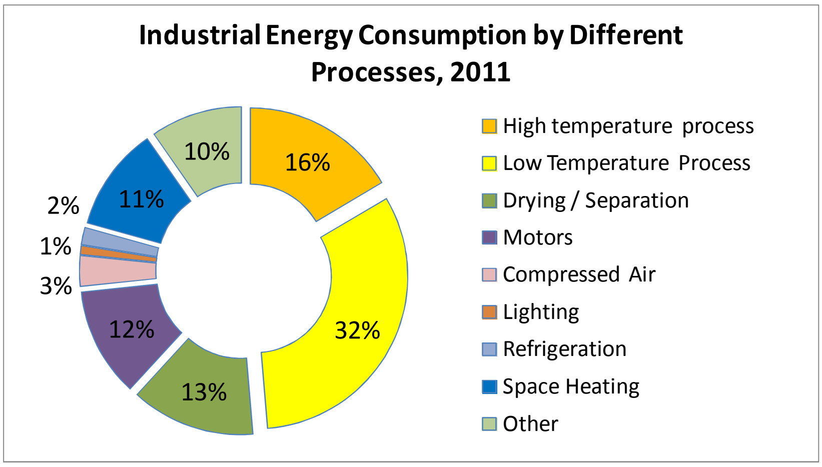


Figure 2-6 – UK industrial primary energy consumption by process, 2011 (DECC 2012)

Figure 2-7, illustrates industrial energy consumption by end use within the UK industrial sector for 2011. The figure illustrates both oil equivalent and percentage energy consumed by energy end users for 25 sectors of the UK industry. The oil equivalent is based on primary and secondary energy sources, e.g. electricity, natural gas, oil and solid fuel. The end users of energy are, space heating, lighting, high temperature process, low temperature process, drying/separation, motors, compressed air, refrigeration and others. The left side of the figure, oil equivalent, shows the gulf between energy consumed from different industrial manufactures within the UK, discussed in section 2.2. The right hand side of Figure 2-7 is the percentage breakdown of energy consumed by end user. It is clear that space heating and lighting can constitute to a large percentage of the overall end energy use, consuming as much as 40% to 60% for some UK industrial sectors e.g. manufacture of motor vehicles, medical, radio, electrical machinery, office machinery and equipment etc. The data is sourced from historical surveyed information and will vary in relation to independent manufacturing organisations. The figure may be considered as an approximate guide to establishing end energy users in industry. For example, there is no space heating or lighting attributed to the manufacture of food products and beverages. The manufacturing of chemicals sector only indicates a small proportion of energy for space heating. Within these typical process driven industries, process integration and re-use of waste heat is common, due to the nature of continuous production schedules (Kemp 2006). Therefore, waste heat streams are often re-utilised to pre-heat incoming production lines or space heating systems. There is also the possibility that some of the energy defined under the title of other, could be attributed to space heating and lighting. Another observation from Figure 2-7 is that all but a few of the industrial sectors utilise a combination of high and low temperature processes. As a result these two end users have become dominant overall energy users for most of the industrial sectors, with the exception of space heating.

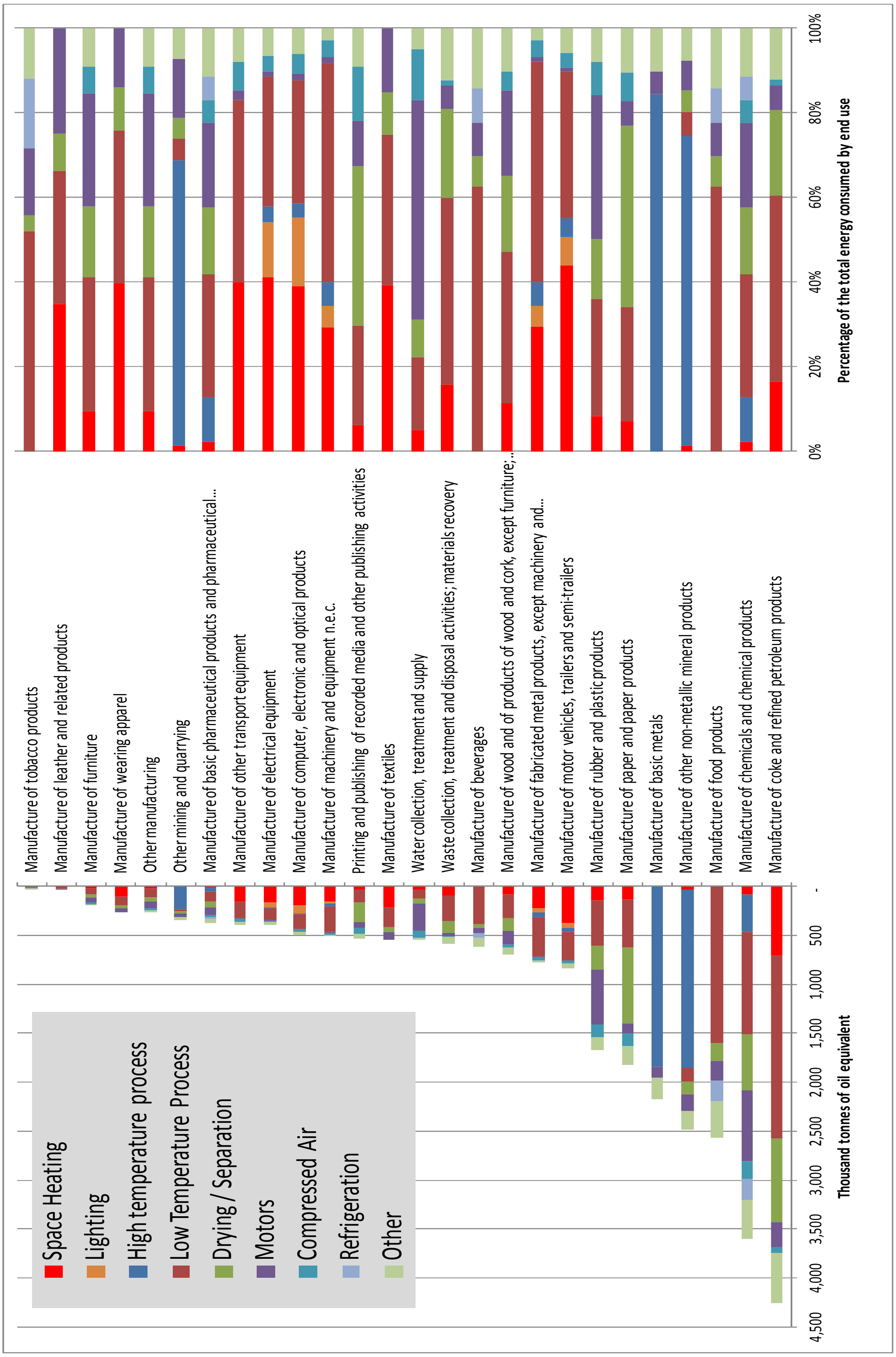


Figure 2-7 – UK Industrial energy consumption by end use, 2011 (Left – oil equivalent, Right – percentage split by process type), (DECC 2012)

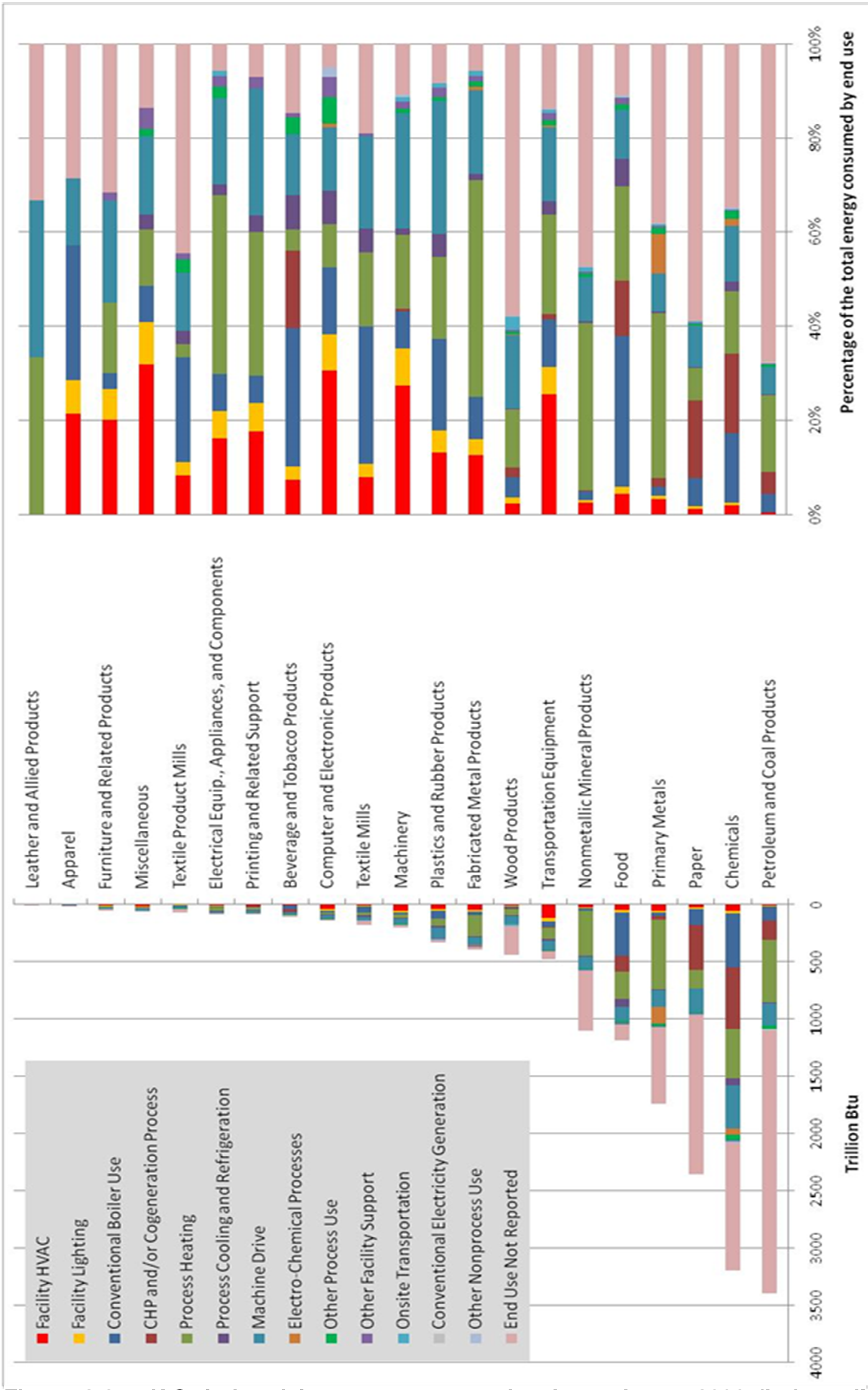


Figure 2-8 – U.S. Industrial energy consumption by end use, 2006 (Left – oil equivalent, Right – percentage split by source of energy use), (EIA 2006)

Industrial energy consumption by end use in the U.S. for 2006 is shown in Figure 2-8. Similar judgements to the UK end energy users can be made. Unfortunately a large proportion of the end user of energy is not reported. This disproportions the reported energy consumption per end user for a considerable number of the manufacturing industries. For manufacturing industries such as, computer and electronic products, machinery, transportation equipment, furniture and related products, the facility HVAC and lighting on average constitutes to between 20 and 40% of the overall energy use.

2.3. *Buildings*

This thesis draws on knowledge from the two disciplines of building design and manufacturing process systems engineering. The thesis focuses on thermal energy flows between manufacturing process systems, material and the built environment. For this reason, the thesis does not discuss in detail the design and construction of buildings (McMullan 2007). The following section discusses the principles of building physics and dynamic building simulation.

2.3.1. Energy balance

The energy balance of a built environment or zone (living space, office, factory etc.) can be considered in the form of an electrical analogue (i.e. resistance and capacitance circuit model), Figure 2-9 (IBPT 2012). Clarke (1986) states that fluid and capacity volumes are characterised by one or more variables of state such as temperature or pressure, the equivalent of voltage in an electrical network and that regions possess capacity and are linked by time-dependent resistances through which heat flux can flow, equivalent to current.

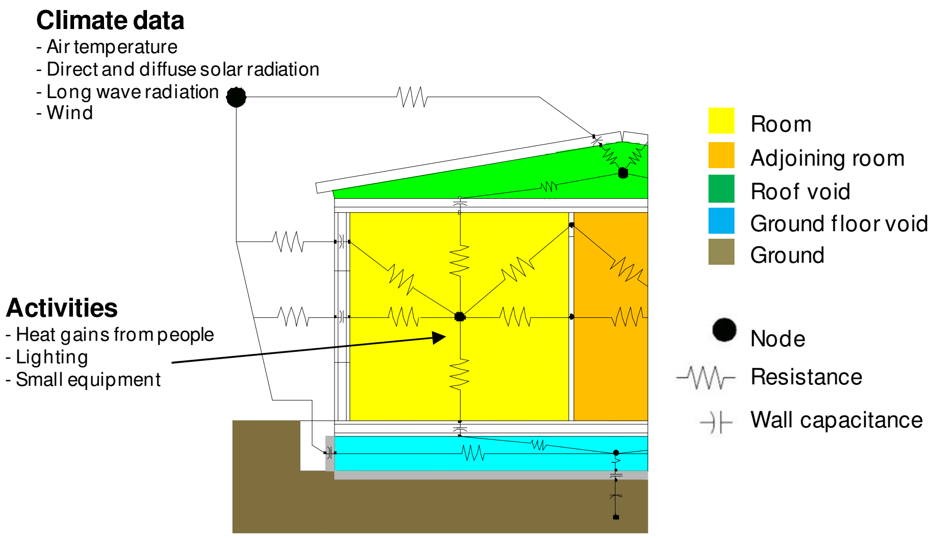


Figure 2-9 – Electrical circuit analogue of a built environment (IBPT 2012), redrawn

A bulk air flow model calculates the properties of air at a single air mass node per zone e.g. temperature and humidity, (coloured yellow in Figure 2-9). Opaque constructions such as walls and roof absorb solar electromagnetic waves in the form of shortwave radiation, as well as releasing and absorbing long wave radiation from surrounding objects. Transparent constructions (i.e. glazing), reflect, absorb and transmit short and long wave radiation. Internal surfaces absorb transmitted radiation from transparent surfaces and openings, resulting in an exchange of long wave radiation between internal surfaces. Radiant heat transfers do not have a direct effect on the internal air temperature of a zone. Long wave radiation is transferred out to absolute space, through transparent constructions, openings and from external surfaces. The absorption of radiation increases internal and external surface temperatures. Heat transfer via conduction occurs at construction materials, based on the 2nd law of thermodynamics. The rate of conduction through a construction is dependent on the number of layers and construction properties such as conductivity, specific heat capacity, density etc (wall capacitance, Figure 2-9). The absorption of moisture in construction materials and changing phases of materials (i.e. phase change materials) is a specialised area of building physics, though applications are becoming more widespread (Evola et al. 2011; HAMlab 2011). Air movement, not show in Figure 2-9 from intentional (forced) or unintentional (natural) ventilation flow paths, over internal and external boundary surfaces result in convective heat transfer between the surface and the adjacent air layer. Heating and cooling building services are designed and installed to offset thermal heat losses or gains to a thermal zone. Ventilation strategies (i.e. natural, mechanical or mixed) can also be implemented to increase or decrease the air temperature of a thermal zone. Internal gains from people, lighting and equipment can also occur in sensible (long wave and convective heat transfer) and latent (occupants and equipment) forms. As illustrated in Figure 2-9, thermal energy flows from adjoining rooms (orange), voids (roof void, green and floor void, blue) and ground floor (brown) can also have influence on neighbouring thermal zones. The change in air temperature of a thermal zone is the resultant balance of the convective energies and the thermal capacity of the zonal air control volume. The in-depth mathematical expressions for the energy flow paths in a typical built environment are widely covered (Clarke 2001; CIBSE 2006a).

2.3.2. Simulation methods and tools

The physics of a building can be modelled using different simulation methods, depending on complexity, accuracy and overall requirement. A quasi-dynamic (e.g. admittance method) procedure assumes that all internal and external load fluctuations can be represented by the sum of a steady state component and a sine wave with a period of 24 hours (CIBSE 2006a). This approach is useful as a first assessment tool, but can overestimate required plant capacity as a single frequency sine wave does not take into consideration load changes and long term heat storage in construction materials (thermal mass). Dynamic simulation tools fall into two categories, response function method and finite difference. Finite difference is a more widely used tool within building simulation modelling due to its ability to solve time varying, non-linear equation systems without the need to assume equation decoupling as a computational convenience, as the response function method does (Clarke 2001). The response function method is an exact analytical technique, and can predict temperatures and heat fluxes at any point within the system of interest (CIBSE 1998).

The 1970s oil crisis led to advancements in the development of theories of energy estimation based on the fundamentals of building physics (Kusuda 2001). Prior to the development of low cost computer power in the 1980s, a sequential approach to simulation modelling was used as shown in Figure 2-10. The technical constraint of computer memory meant that each part of the building environment had to be analysed separately with the results from each stage of the analysis feeding the next stage. The lack of interaction between analysis of load, system and plant, can lead to inaccuracies and questionable results (Al-Homoud 2001).

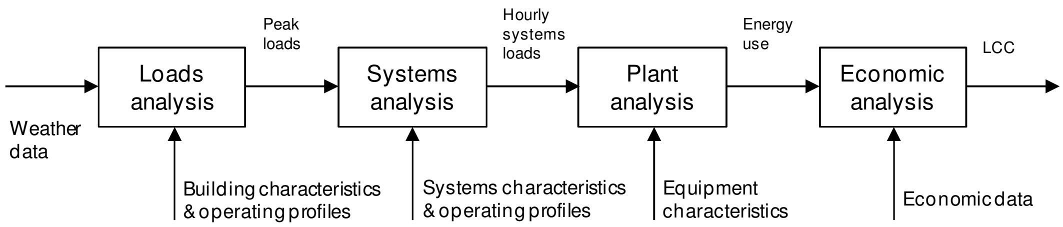


Figure 2-10 – Sequential simulation approach (Al-Homoud 2001)

As computer memory and processor power improved during the 1990s, smaller time increments could be used and interactions between different parts of the building simulation could be modelled simultaneously. Figure 2-11 illustrates the concept behind the simultaneous simulation approach. The interaction and feedback of the simultaneous simulation approach produces more accurate and reliable results than was possible using the sequential approach.

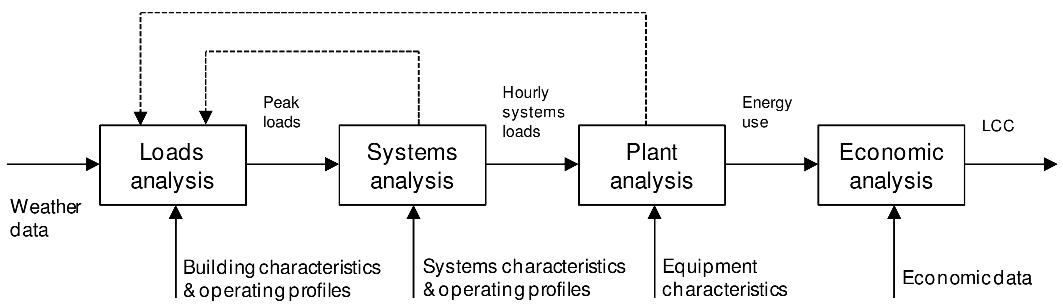


Figure 2-11 – Simultaneous simulation approach (Al-Homoud 2001)

The availability of low cost computer power has enabled software engineers to develop advanced dynamic simulation models producing more accurate and reliable results than ever before. Operating systems such as Microsoft Windows, Mac, and Linux etc have made the graphical user interfaces (GUI) of building modelling tools more user friendly and accessible to building design engineers.

There are many different dynamic building modelling tools available on the market from commercial, academic and open sources. IES VE (Integrated Environmental Solutions Virtual Environment) (IES 2012a), EnergyPlus (EnergyPlus 2012), and ESP-r (Environmental Systems Performance Research) (ESP-r 2012) are to name but a few. A list of building simulation software tools can be found at (DOE 2012). Building modelling tools also exist in equation based and block flow diagram tools such as, Modelica and Matlab/Simulink respectively. Modelica is a non-proprietary (i.e. open source), object-oriented, equation based language capable of modelling complex physical systems (Modelica 2012). Matlab, an acronym for Matrix Laboratory, is a high-level language and interactive environment that claims to perform computationally intensive tasks faster than traditional programming languages such as C, C++, Fortran etc (Matlab 2012). Simulink is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems (Simulink 2012). Simulink is a product module that operates alongside Matlab within the Mathworks environment. Descriptions of the aforementioned softwares have been obtained from their webpages. The author has identified two open source building modelling toolboxes that exist within Modelica and Matlab/Simulink environments, Buildings library and the International Buildings Physics Toolbox (IBPT), respectively. Further information on the toolboxes can be found at the following references, Modelica 'Buildings' library (Wetter et al. 2011) and IBPT (Rode et al. 2002; IBPT 2012). The main advantage to using a toolbox within the Modelica or Matlab environment is that no knowledge of traditional computer programming languages is required. The toolboxes are open source, well documented and freely accessible to academics. Therefore, the user's time and resources can be best used to understand the physics of the problem rather than understanding computer programming language and making revisions to graphical user interfaces that may be required if using a traditional building modelling tool. These are important capabilities of the toolboxes that distinguish them from other building modelling tools.

2.3.3. Simulation inputs

Figure 2-12 illustrates the flow path of data input required to perform a building simulation model and analysis (IES 2010). In most situations the simulation software provides generic databases of inputs, for example:

- Weather file (Location, altitude/ azimuth, dry bulb air temperature, wind speed etc.),
- Construction (Standard constructions, thicknesses, properties etc.),
- Geometry (graphical user interface (GUI)),
- Room templates (occupancy, lighting, equipment etc. profiles),
- HVAC system (predefined system components, inputs, efficiencies, fuel source etc),
- Simulation (Simulation options (heat transfer coefficients etc. and reporting outputs)

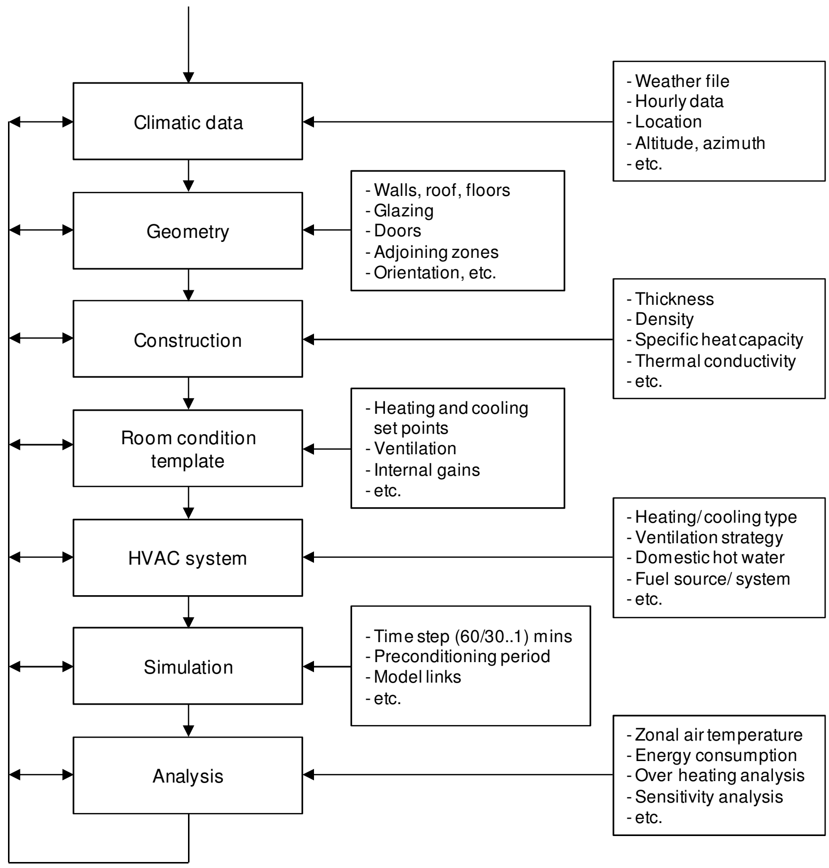


Figure 2-12 – Building simulation input flow path

The database of information provided within the building modelling software enables the user to run models on limited information as an early design tool. The user can amend input data to reflect the design decisions that closely match that of the building. Equally, early stage design simulation within a building modelling tool may influence and drive building geometry, orientation, glazing percentages, construction properties etc., reducing energy consumption and improving the internal environment conditions for human occupants.

The simulation of buildings in a building modelling tool is deterministic. For example, the climatic data, building physics, internal gains etc inputs are all implemented into a dynamic model by use of deterministic profiles feeding into the model at time step intervals. If the parameter profiles in the model stayed unchanged, the tool would produce the same output for multiple simulation runs. Though in reality this is not the case in real buildings and will vary stochastically e.g. occupants and weather conditions

2.4. *Manufacturing industry*

The term ‘industry’ is used in this thesis to describe organisations that manufacture physical products (i.e. goods as opposed to services (ICT 2008). To some extent, this is an artificial distinction, since many manufacturers also offer services such as finance, insurance and maintenance. Though concentration is on engineered goods, findings could be applicable to other industries such as food production, as it is not uncommon for manufacturing equipment to be used across a broad spectrum of manufacturing industries.

2.4.1. Manufacturing system

Figure 2-13 illustrates the flow and interconnections within a production system. The external customer of the goods is the driver of the system, i.e. demand of the market. This thesis concentrates on a small proportion of the system i.e. the manufacturing system. The manufacturing system is a form of operational management and has been concerned intrinsically with operational data in the form of rates utilisation etc and not energy. It is important to note that the manufacturing facility (i.e. factory building) is not considered in the analysis of the flow of materials within a manufacturing system. This is not unusual as the building is a shell that surrounds and protects the manufacturing process systems, materials and workers. DeGarmo et al. (2003) breaks down the departments that constitute the production system, in relation to the selling price of a product, Figure 2-14. Manufacturing costs, further divided into four areas, are indicated at approximately 40% of the overall selling cost. Subassemblies, component parts and other materials section are the second largest cost, at 20% of the overall selling cost. Indirect labour cost, quantify building costs, in the form of heating and lighting, equate to around 10% of the total selling cost. Figure 2-14 provides a snapshot overview of the breakdown costs of a typical production system. These figures will vary across different manufacturing industries and organisations.

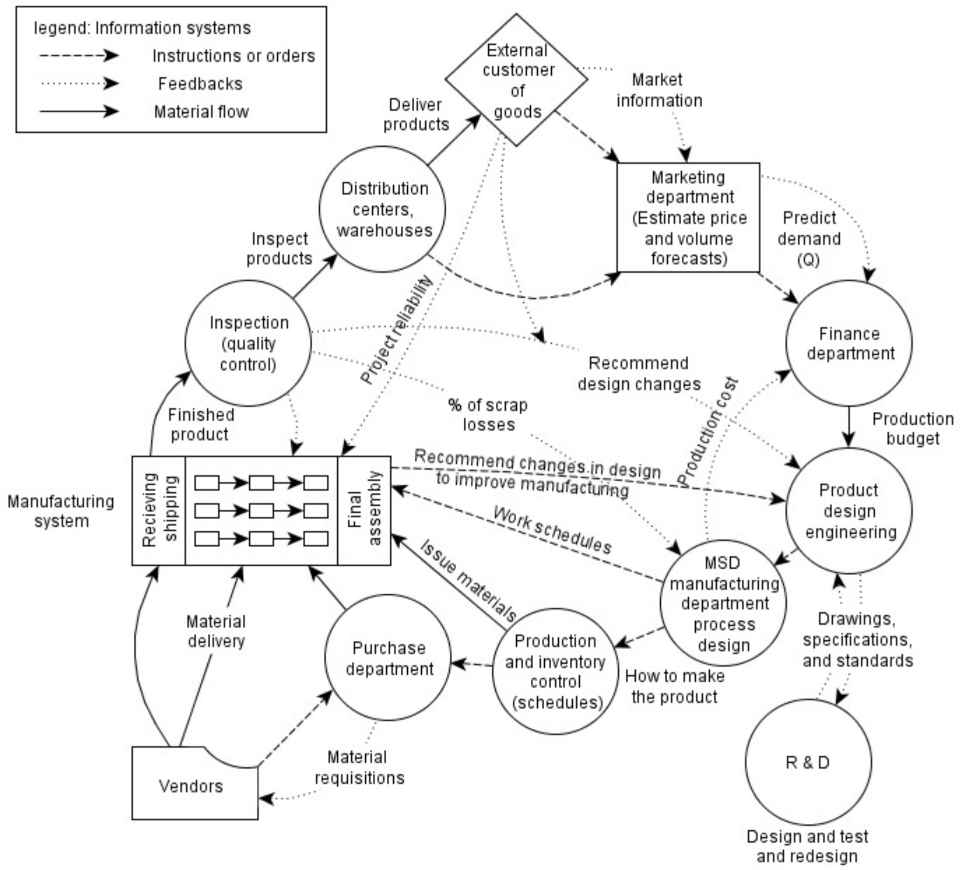


Figure 2-13 – Illustration of the flows and interconnections in a production system (DeGarmo et al. 2003), redrawn

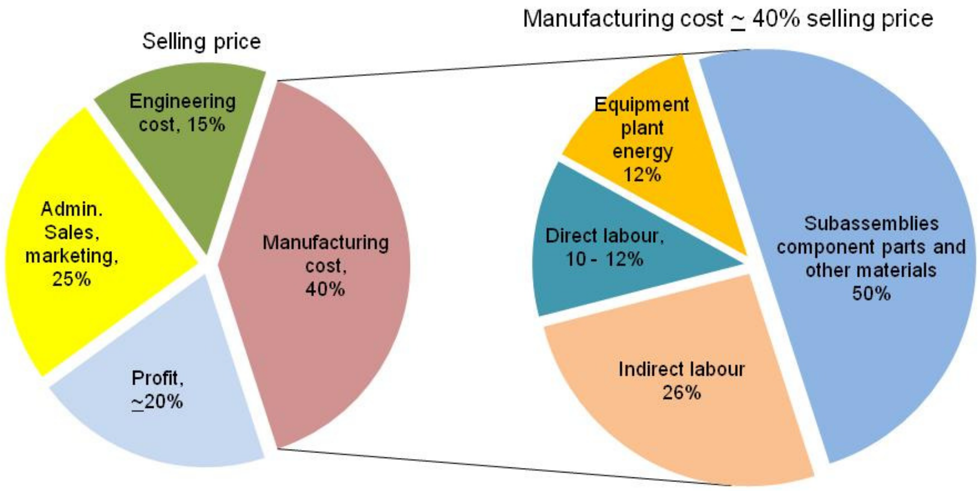


Figure 2-14 – The breakdown cost of the production system (adapted from (DeGarmo et al. 2003))

2.4.2. Manufacturing processes

Manufacturing industries utilise manufacturing process machinery to change the shape, surface finish, appearance or physical properties of material in order to add value. Since the development of the earliest industries, the manipulation of material into a different shape and changing of properties were achieved through heat and application of force (e.g. by using an anvil, hammer and a forge). The fundamental physical principles of many of today's manufacturing processes have not greatly changed but the introduction of machinery and automated processes have led to an increase in productivity and quality. Figure 2-15 illustrates the seven basic manufacturing processes used in industry. This typology is not exhaustive and not limited to single products or processes (CO_2PE 2012). The basic processes can be linked in sequence or combined with each other.

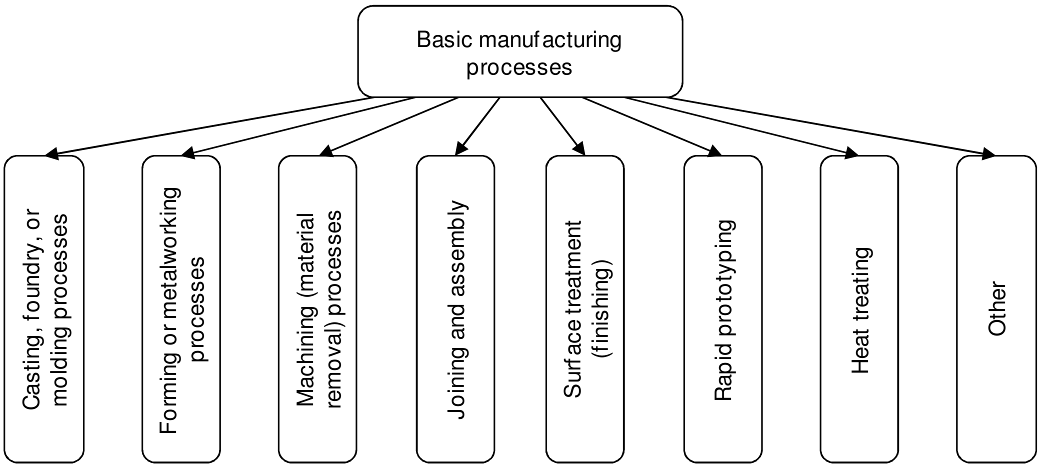


Figure 2-15 – Basic manufacturing processes (DeGarmo et al. 2003)

This thesis does not discuss the operation and capabilities of manufacturing processes and material properties, unless required. DeGarmo et al. (2003) and Ashby et al. (1996), discuss the use of manufacturing processes and materials properties in greater detail than covered in this thesis. The flow of materials within a manufacturing system is an important aspect of the trade-off triangle, time, quality and cost (Pugh 1990). The layout of a manufacturing production line is greatly affected by the trade-offs of the triangle. DeGarmo et al. (2003) identifies five manufacturing system layouts, job shop, flow shop, linked cell shop, project shop and continuous process. The job shop, groups similar manufacturing processes together and is the most widely used in manufacturing industries. The linked cell shop is a batch system that sequences the material flow within a production system into a cell of arranged machinery to increase productivity, improve quality and reduce work in process. This is a similar analogue to a project team, consisting of one of each discipline working together. More than one project team can consist within the organisation. The flow shop is a line of specialised machinery designed to maintain a consist flow of material along the production line, e.g. automotive and aeronautical industries. The continuous process relates to high volume flows of liquids, chemical and powders, e.g. pharmaceutical, oil refinery etc. The variation in production lines relates to the product being manufactured and the type industry, e.g. continuous or batch, high or low volume, high or low quality etc.

2.4.3. Manufacturing energy flow paths

The process of mapping and understanding the operation of a manufacturing industrial environment can be complex (Oates et al. 2011a). The changes in energy and resource flows in the internal environment of a factory building can be linked to the energy flow paths within a factory built environment, discussed in more detail later. Equipment inefficiencies, dynamic energy requirements and energy conversions (e.g. electrical energy into mechanical and thermal energy) of large industrial process systems can lead to the generation of large amounts of heat to the surrounding environment. The addition of moisture to the surrounding environment can be commonly found within certain manufacturing industries e.g. pulp, paper, wood. Heat from material (product) moving between manufacturing processes is released into the building environment. Manufacturing energy flow paths considered are:

- Facility level
- Process level
- Material level

2.4.3.1. Facility level

Energy flow path data at a factory gate or departmentalised factory building is commonly metered at time step intervals of 30 minutes or greater by utility providers (i.e. electricity and natural gas). Data granularity at 30minutes or greater is termed as macro level data within this work, micro for less than 30minutes. The consumption of coal and oil may be determined from mass and gross caloric values. Little may be known about the energy usage of activities (e.g. manufacturing production systems, heating, and lighting) that may occur within a given boundary such as, factory, workshop, and office. Depending on the level of metering and monitoring the energy consumption of individual buildings and departments may be hard to determine. An advantage to analysing energy data at a macro level is that it provides the energy manager with an abstract overview of energy usage on site. A main drawback is that this level of data does not indicate in detail where and how energy is being consumed and potentially wasted (Turner et al. 2012). Figure 2-16 illustrates five combinations of on-site metering: direct, hours run, indirect, by difference and estimation (CIBSE 2006b). The five levels are based on: reliability (less to more accurate), cost (less to more expensive) and installation (ease to harder design). The highest level of the triangle, direct metering, can apply at any level from site facility to machine apparatus. Metering and monitoring of energy data can help identify and assist in energy efficiency saving measures (Bombardier 2009; JCB 2009; Heinz 2010; Morrisons 2010).

The Carbon Trust, have published good practice and energy consumption guides that demonstrate methods of auditing and analysing on-site energy data (Carbon-Trust 2002; Carbon-Trust 2004b).

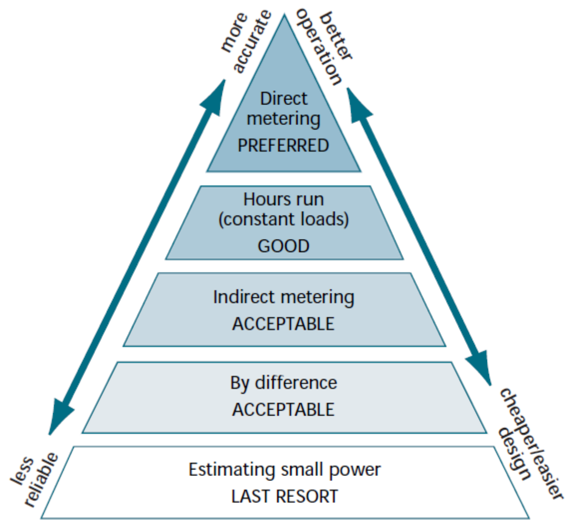


Figure 2-16 – Five methods for determining energy consumption (CIBSE 2006b).

Sankey diagrams are another method of understanding the flow of energy and material, from source(s) or sink(s). The flow is dictated by the directional flow and width of the arrow (Schmidt 2008). Figure 2-17 is an example of a Sankey energy flow chart for the UK in 2010. The flow chart illustrates the flow of primary fuels (i.e. production and import), transformation of energy and end economy sector users (i.e. domestic, industry transport and others).

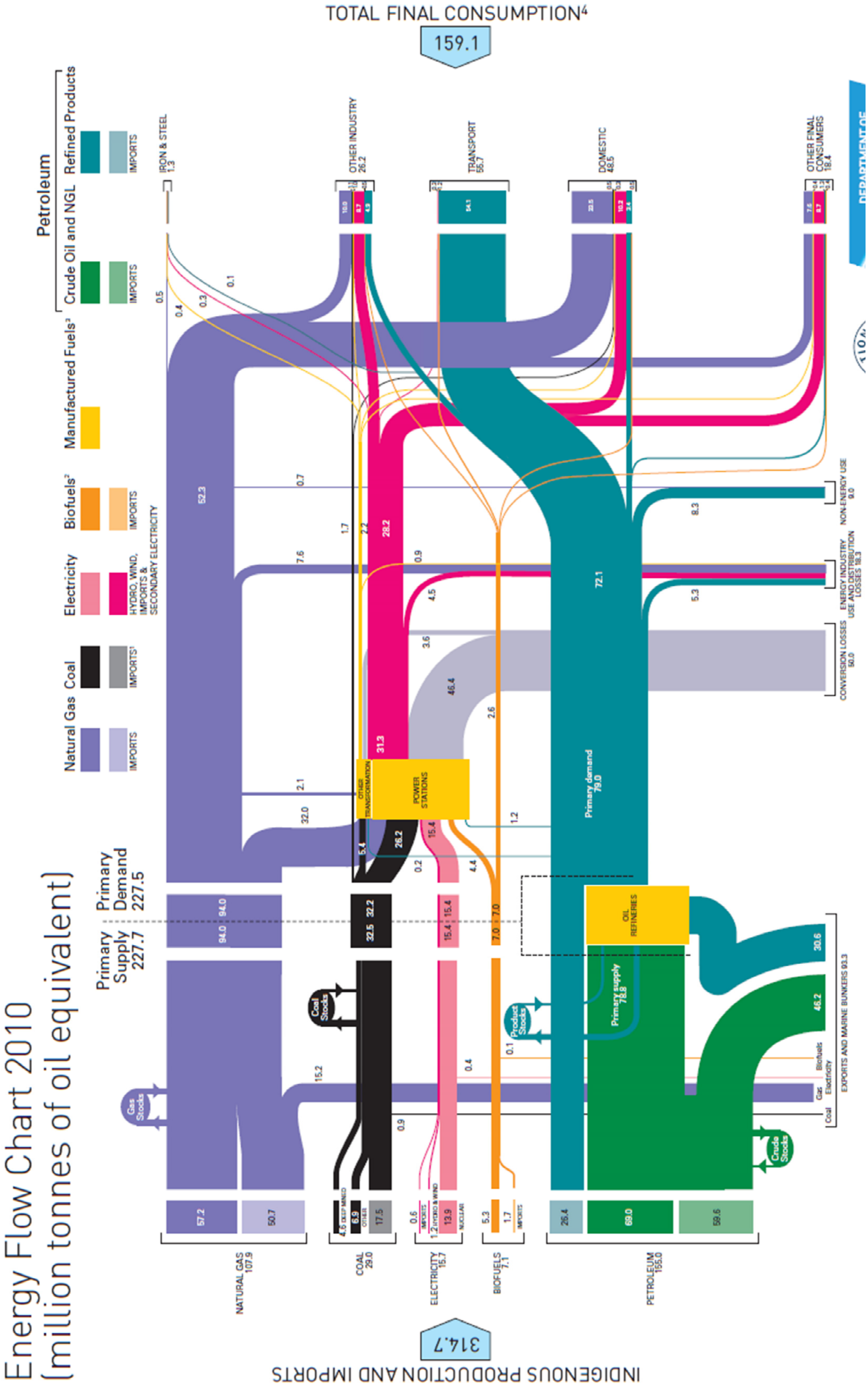


Figure 2-17 – Sankey energy-flow chart 2010, UK (DECC 2011b)

2.4.3.2. Process level

Dahmus and Gutowski (2004) discuss at process level the energy consumption of three machining tools during operation. The machining processes, two automated and one manual milling machine, are illustrated in graphical form and demonstrate that the energy required during machining does not equate to the total energy consumed by the process. Figure 2-18 illustrates the energy breakdown of a 1998 Bridgeport automated milling machine with a 5.8 kW spindle motor. The figure shows that 13.2% of the energy breakdown of the milling machine is required during constant start-up mode (i.e. auxiliary equipment such as computer, fans, pumps, servos) and 20.2% is during constant running mode (e.g. spindle, tool change). The machining of the part constitutes to the remainder of the energy breakdown. Dahmus and Gutowski (2004) state that between 30% and 50% of the energy required is spent on auxiliary equipment, depending on the machine duty cycle. The analysis of the machining process and the breakdown of energy consumed whilst in operation provide process designers and energy managers with higher resolution data of the energy consumed during machining cycles. This level of detail identifies potential improvement areas to conserve energy e.g. more efficient auxiliary equipment when in standby or during non cutting states.

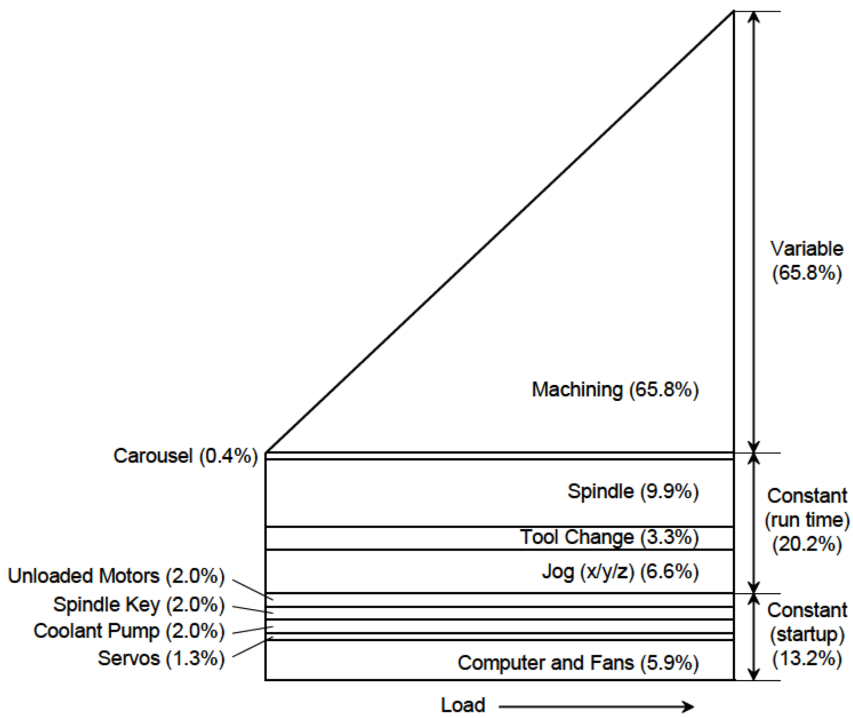


Figure 2-18 – 1998 Bridgeport automated milling machine energy use breakdown (Dahmus et al. 2004)

Vijayaraghavan and Dornfeld (2010) consider environmental improvements through monitoring of energy consumption patterns in machine tools. Figure 2-19 illustrates the temporal scales of monitoring and analysing energy consumption patterns. The figure illustrates the scales of monitoring energy consumption from enterprise level to tool-chip interface on scales of m-seconds to days. Dietmair and Verl (2009), model the energy consumption behaviour of machines and plants based on a statistical discrete event formulation. The approach is similar in that it identifies events that occur during machining (i.e. start-up, utilisation, warm down), but with a view to predicting energy consumption for different configurations of machining events and scenarios (Dietmair et al. 2009).

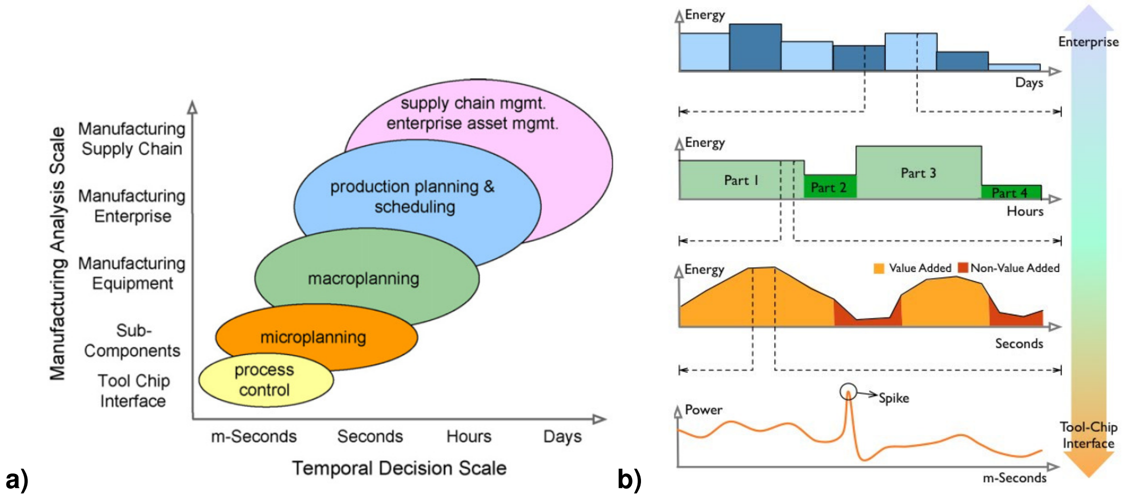


Figure 2-19 – Energy monitoring of machine tools, a) temporal decision scales, and b) analysis over cross temporal scales (Vijayaraghavan et al. 2010)

Studies that consider energy consumption at a process level include: machine tool (Avram et al. 2010), press brake and milling machine (Devoldere et al. 2007), injection moulding (Thiriez et al. 2006), die casting (Dalquist et al. 2006), grinding (Baniszewski 2005), sand casting (Dalquist et al. 2004) and abrasive water jet (Kurd 2004). Further studies can be found (Ciceri et al. 2010). Thermal energy flows within industrial environments, include, equipment surfaces, opening of doors, infiltration, exhaust streams (considered as a possible waste stream) etc. The capture of waste heat from heat generation processes, through installation of heat exchangers such as recuperators, regenerators, heat pipes, economizers and heat pumps, is more common practice in continuous process industries (Kemp 2006). Table 2-1, Table 2-2 and Table 2-3 list a range of industrial processes with the potential for heat recovery, low temperature (27 - 232℃), medium temperature (232 – 650℃) and high temperature (650 – 1650℃).

Table 2-1 – Typical low temperature waste heat from industrial source (BEE 2010)

Source	Temperature (°C)
Process steam condensate	55 – 88
Cooling water from: Furnace door	32 – 55
Bearings	32 – 88
Welding machine	32 – 88
Injection moulding machine	32 – 88
Annealing furnaces	66 – 230
Forming dies	27 – 88
Air compressors	27 – 50
Pumps	27 – 88
Internal combustion engines	66 – 120
Air conditioning and refrigeration condensers	32 – 43
Liquid still condensers	32 – 88
Drying, baking and curing ovens	93 – 230
Hot processes liquids	32 – 232
Hot processed solids	93 - 232

Table 2-2 – Typical medium temperature waste heat from industrial source (BEE 2010)

Type of device	Temperature (°C)
Steam boiler exhausts	230 – 480
Gas turbine exhausts	370 – 540
Reciprocating engine exhaust	315 – 600
Reciprocating engine exhaust (turbo charged)	230 – 370
Heat treating furnaces	425 – 650
Drying and baking ovens	230 – 600
Catalytic crackers	425 – 650
Annealing furnace cooling systems	425 - 650

Table 2-3 - Typical high temperature waste heat from industrial source (BEE 2010)

Type of device	Temperature (°C)
Nickel refining furnace	1370 – 1650
Aluminium refining furnace	650 – 760
Zinc refining furnace	760 – 1100
Copper refining furnace	760 – 815
Steel heating furnaces	925 – 1050
Copper reverberatory furnace	900 – 1100
Open hearth furnace	650 – 700
Cement kiln (dry process)	620 – 730
Glass melting furnace	1000 – 1550
Hydrogen plants	650 – 1000
Solid waste incinerators	650 – 1000
Fume incinerators	650 - 1450

The Cooperative Effort on Process Emissions in Manufacturing (CO_2PE) project, is an initiative to coordinate international efforts to document, analyse and improve the environmental footprint for a wide range of available and emerging manufacturing processes with respect to their direct and indirect emissions (CO_2PE 2012), see Figure 2-20. The CO_2PE project has 4 main objectives (CO_2PE 2012):

1. Study the environmental footprint of manufacturing processes with energy consumption/CO2 emission as first priority. Scope limited to discrete part manufacturing.
2. Develop a methodology that allows to provide data in a format useful for inclusion in LCI dbases.
3. Identify opportunities for improved process design in close cooperation with machine tool developers. Derive design rules and guidelines in support of eco-design of machine tools.
4. Draft a proposal for an eco-label system for machine tools.

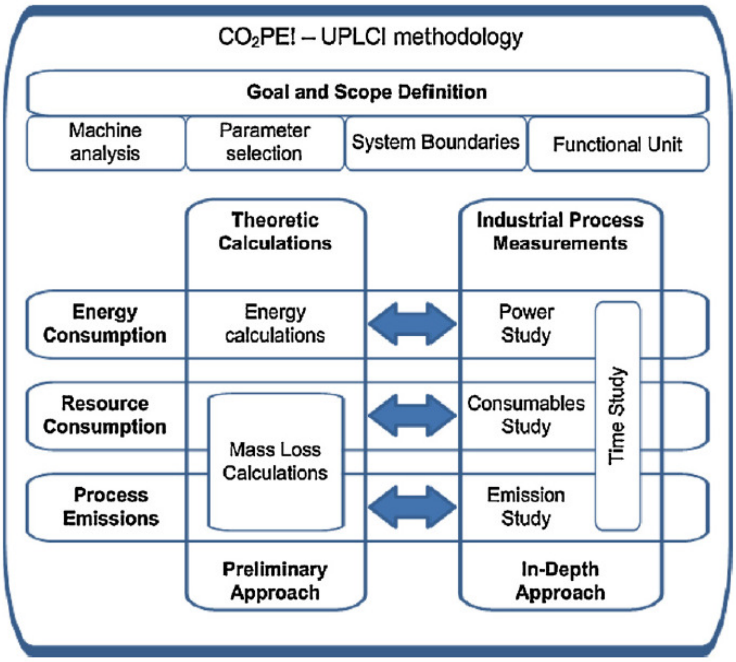


Figure 2-20 - CO2PE! – UPLCI methodology

The first objective is of interest to this research. The following works are from authors actively reporting on the research of the CO_2PE initiative. Duflou et al. (2012) applies a structured approach to distinguishing different system scale levels for discrete manufacturing: unit process, multi-machine, factory, multi-facility and supply chain levels. The unit process level is shown in Figure 2-21. The authors (Overcash et al. 2009; Duflou et al. 2011; Seow et al. 2011; Duflou et al. 2012) discuss methods for life cycle inventory analysis of production processes using theoretic equations to calculate the energy and resource consumption as well as waste and process emissions at a unit process level.

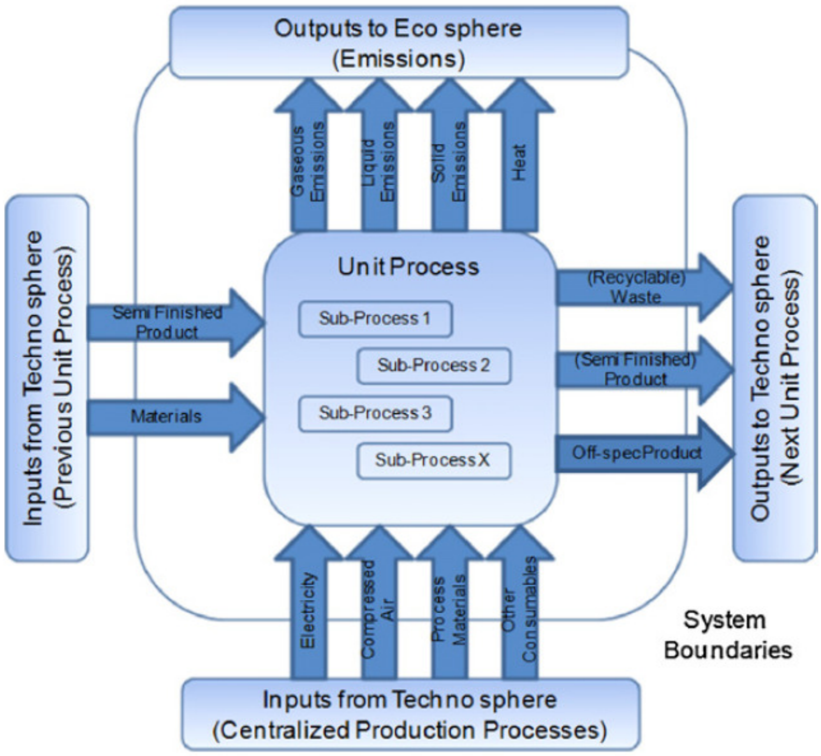


Figure 2-21 - System boundaries of a unit process

2.4.3.3. Material level

During the processing of material, energy is converted during the forming or breaking of bonds within materials (either at the molecular or physical level), and collateral use or production of electromagnetic radiation, sound, and heat. A cutting process is a typical example of these transforms. During the cutting process, forces from the tool piece are used to break bonds in the material. The temperature of the tool piece, chip formation and workpiece are elevated during the cutting process, Figure 2-22. The primary shear zone, where plastic deformation occurs at the chip formation, is a major heat source. The secondary shear zone, at the tool/chip interface generates heat from friction, and at the flank, due to rubbing between the tool and workpiece (DeGarmo et al. 2003). Dependent upon the cutting parameters (tool/workpiece material, cutting speed, chipping thickness, chip angle, flank angle etc) a varying proportion of the thermal heat generated can end up in the chip formation (Dorn et al. 2011).

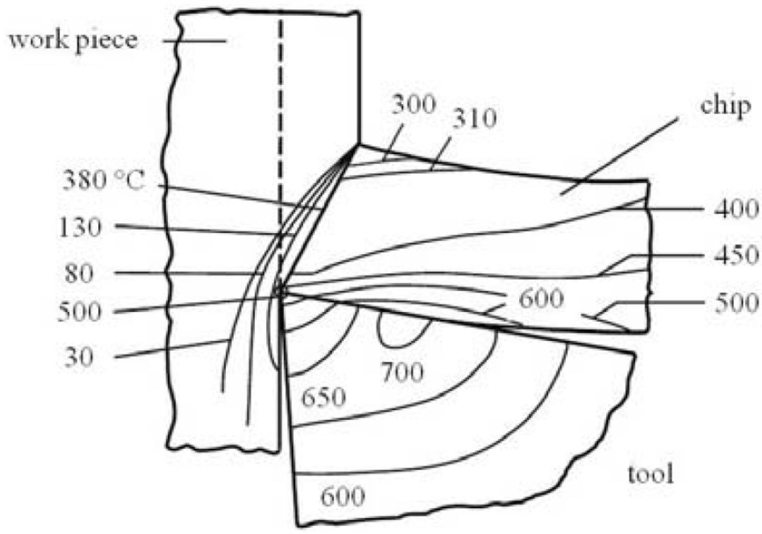


Figure 2-22 – Thermal behaviour of a cutting process (Dorn et al. 2011)

The transfer of thermal energy onto a worked material (i.e. heat affected zone) during a laser cutting study, was attributed to the parameters of: laser power (64%), cutting speed (21%), pulse frequency (11%) and gas pressure (4%) (Stournaras 2009). Another study into the thermal analysis of grinding, states that for a conventional abrasive wheel applying a shallow cut, typically 60% to 80% of the grinding energy is transported to the workpiece. For deep creep-feed grinding, cooling fluids and high thermal conductive abrasives reduce the transfer of heat to the material to approximately 5% (Malkin et al. 2007).

2.4.4. Thermodynamics and exergy

The first and second laws of thermodynamics are relevant to industrial energy use. The first law states that energy can be neither created nor destroyed but can only be changed from one form to another (Boustead et al. 1979). It is more commonly known as the conservation [of energy] law. The first law does not make a distinction between different energy forms, it merely states equilibrium, between the inputs and outputs of a system, in heat and work. The first law also takes no account of the energy source in terms of its thermodynamic quality (Hammond 2007). The second law of thermodynamics (i.e. law of increased entropy) states that heat flux is directional and will flow spontaneously from a higher to a lower temperature. The first and second laws of thermodynamics take into account the ability to convert energy into a quantity of heat. However the laws do not take into account the quality of an energy carrier. Gool (1987) discusses the use of exergy analysis to quantify the amount of high quality work from an energy carrier using an ideal conversion device. Hammond (2007) describes exergy as the available energy for conversion from a donating source (or reservoir) with reference to a specified datum, Figure 2-23.

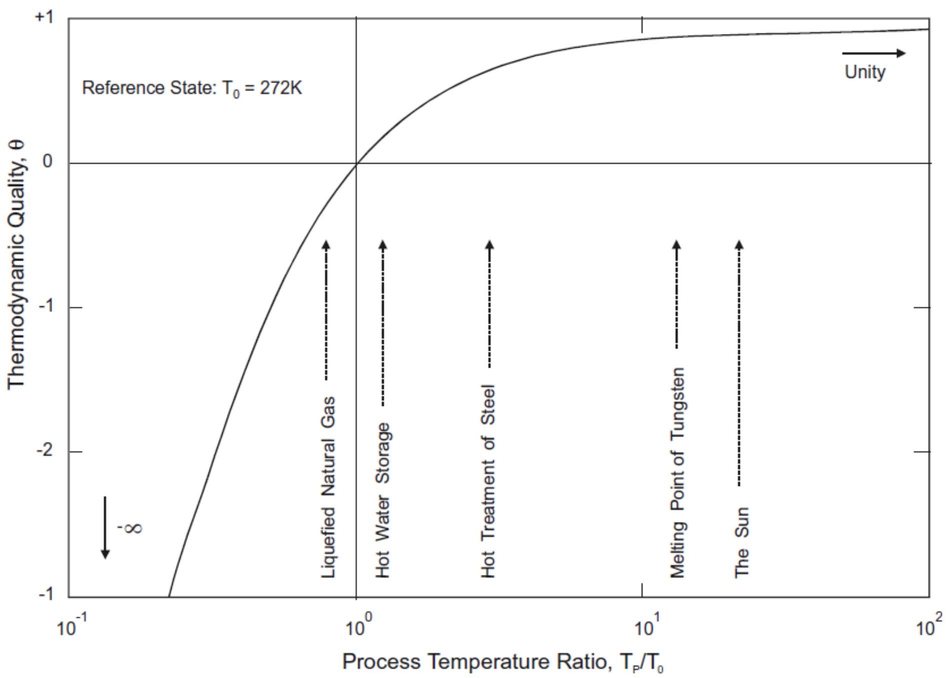


Figure 2-23 - Temperature dependence of thermodynamic quality (Hammond 2007)

The figure illustrates the thermodynamic quality of an energy carrier with reference to a specified datum (i.e. reference state $T_o = 272K$) and is calculated using Equation 2-1.

$$\theta = 1 - \frac{T_o}{T_p}$$

Equation 2-1

Where T_o is reference state and T_p is process temperature. Energy carriers with a high thermodynamic exergy quality (θ) value such as electricity (i.e. θ = 1) should not be used to heat low thermodynamic exergy carriers. For example, a low temperature process at 70°C (342K) would have a thermodynamic exergy quality of θ = 0.2 (i.e. 1 – (272/342)). Note, the reference state for the figure is 1℃ (i.e. 272K). The reference state can vary between examples (Gool 1987; Hammond 2007; Yildiz et al. 2009).

Both Van Gool and Hammond discuss the application of exergy in terms of heat cascading. Heat cascading considers the possibility of using higher quality thermodynamic waste streams (available energy) to heat energy carriers that fall just below the thermodynamic quality potential of the carrier. The ability to quantify the quality of the energy carrier enables energy supplies to be matched with the energy demands of a system (Sakulpipatsin 2008). In the cascading of heat, if energy carriers can be matched by time, location and demand, the overall exergy efficiency of a system can be greatly improved, reducing the demand for naturally depleting energy sources. Table 2-4 identifies a number of possibilities of utilising waste source in terms of the quality of the available energy.

Table 2-4 – Potential heat recovery opportunities from waste sources (BEE 2010)

N.o.	Waste source	Quality
1	Heat in flue gases.	The higher the temperature, the greater the potential value for heat recovery
2	Heat in vapour streams.	As above, but when condensed, latent heat also recoverable.
3	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheats.
4	Heat losses in cooling water.	Low grade – useful gains if heat is exchanged with incoming fresh water.
5	Heat losses in providing chilled water or in the disposal of chilled water.	High grade if it can be utilized to reduce demand for refrigeration Low grade if refrigeration unit used as a form of heat pump
6	Heat stored in products leaving the process.	Quality depends upon temperature
7	Heat in gaseous and liquid effluents leaving process.	Poor if heavily contaminated and thus requiring alloy heat exchanger

2.4.5. Simulation in manufacturing

The manufacturing industry uses a diverse range of simulation software packages. Cameron and Ingram (2008) surveyed the industrial sector to gain further understanding of the simulation tools used in the process industry, Figure 2-24.

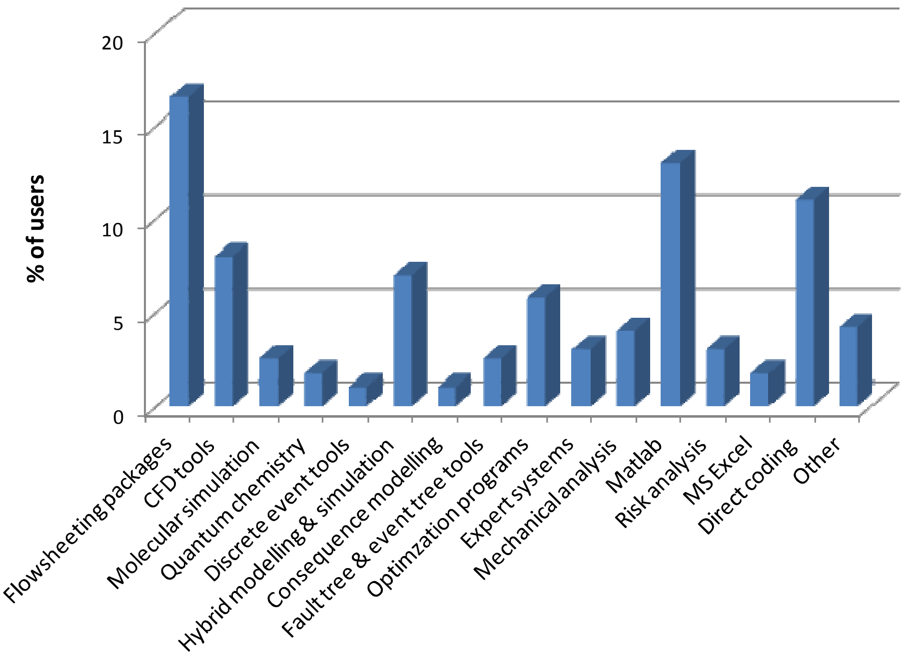


Figure 2-24 – Principal industrial process tools used for modelling and simulation (Cameron et al. 2008)

It is outside the scope of this research to describe and explain the multitude of simulation software packages used by the manufacturing industry. However some manufacturing simulation tools have features that are of interest to this research. The manufacturing industry as well as other industries such as, retail, financial service, healthcare etc, use a simulation method called discrete event simulation (DES) to account for objects flowing through a process at discrete events in time. DES can be both deterministic and stochastic. Stochastic simulation allows the user to integrate statistical data (i.e. probability distributions) into the simulation, as many systems behave stochastically (Pidd 2004). DES tools are used within the manufacturing industry to determine outputs such as, machine utilisation, machine queue times/length, bottlenecks etc. Another key feature of DES is the software's ability to move the simulation clock forward to future events in time, if nothing is scheduled to happen in the simulation time prior to the next event happening. This feature of DES creates a future event list, enabling the software to effectively miss out time steps in the model, reducing simulation time (Schriber et al. 2007). Larger and complex process systems may benefit from features of DES, in providing a stochastic element of uncertainty into the simulation analysis phase. Both time-driven (dynamic) and event-driven (discrete event) simulation have been combined in a complex hybrid simulation method (Clune et al. 2006)

2.5. *Factory environment - energy balance*

The above literature sections have covered industrial energy consumption on a global scale and relevance to the UK. The literature has also provided background information in regard to building physics and the manufacturing industry. The following section considers areas of research that are core to the aim and objectives of the thesis.

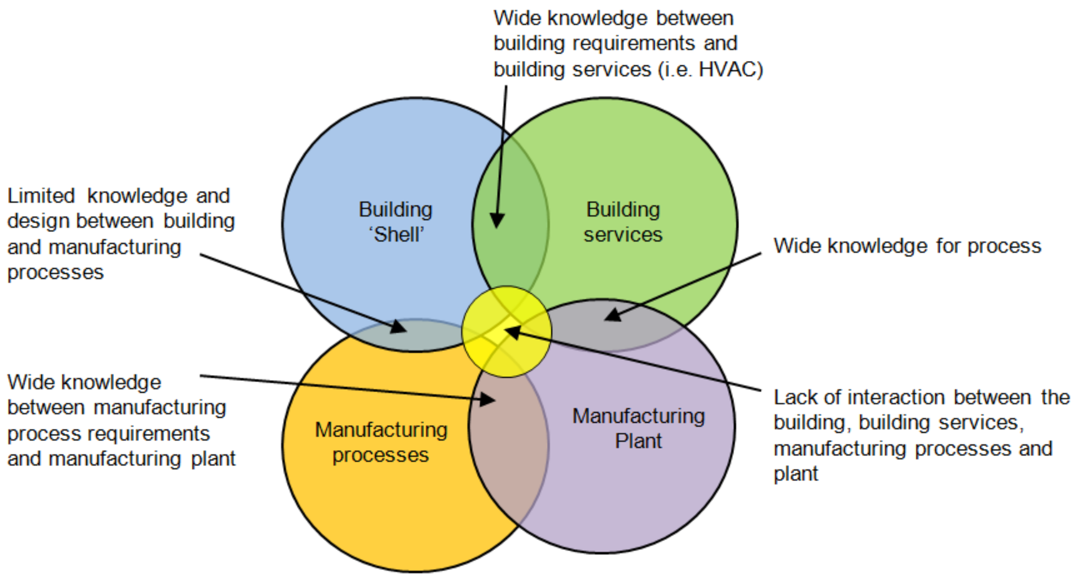


Figure 2-25 – The overlap of building, building services and manufacturing (adapted from (Wright, Oates and Greenough (2012a))

Figure 2-25 gives an overview of building and process related energy domains that exist in manufacturing. The figure overlaps four areas, building (top left, blue circle), building services (top right, green circle), manufacturing process systems (bottom left, orange circle) and manufacturing plant (bottom right, purple circle). The overlap in knowledge between the four domains related to the use of energy in the buildings and processes of manufacturing. The buildings technical services (HVAC) are designed to meet the requirements of the internal environment of the building i.e. temperature and humidity. The technical services may also share common elements with the manufacturing plant (e.g. hot/cold water circuits, steam etc) facilitating manufacturing processes (Oates et al. 2012). There is limited knowledge and design effort regarding the interaction between the building shell and manufacturing processes and also the coupling of the four domains (the central yellow circle) (Wright et al. 2012a). Material (product) flow, not shown in Figure 2-25, resides in the overlap of the building 'shell' and manufacturing processes.

The following journal papers discuss the overlap between building physics, manufacturing process systems and the factory environment. Hesselbach et al. (2008) examine the possibility of integrating four separate simulation tools, HKSim (building services), TRNSYS (Building simulation), SIMFLEX/3D (Production machines and material flow) and AnyLogic (Production management), into one integrated tool, Figure 2-26b. This states that the coupling of the four simulation tools will support the energy efficient design and management of production facilities and technical building services.

Figure 2-26a, illustrates the emission of waste heat and exhaust air from production machines into the production area environment. This has a direct influence on the technical building services that treat the production environment. There is no mention within the journal paper of accounting for heat flux from product flow into the factory environment. The paper states that isolated approaches are insufficient in overall design of a sustainable production facility. It is the impression of the author that the coupling and integration of four individual purpose designed software will be difficult to achieve. To date, more recent papers from the authors have not resulted in the demonstration of a fully operational tool that integrates four separate simulation tools together (Herrmann et al. 2009; Herrmann et al. 2011; Thiede et al. 2011). Herrmann et al. (2011), propose a variant approach to Figure 2-26b by presenting energy oriented simulation model for planning of manufacturing systems by dynamically coupling, DES, technical building services (TBS) simulation and an evaluation tool. Outlook for future work to include, the addition of TBS modules, automated life cycle costing/assessment routines and integration with the industrial data environment. The reviewed papers include no detail of material (product) flow interacting with its environment before, during and after being processed, in terms of, locality of material and reciprocal thermal energy flows to and from the material to the factory environment. Case studies presented consist of electrically operated manufacturing process systems only, aluminium die casting and weaving mill.

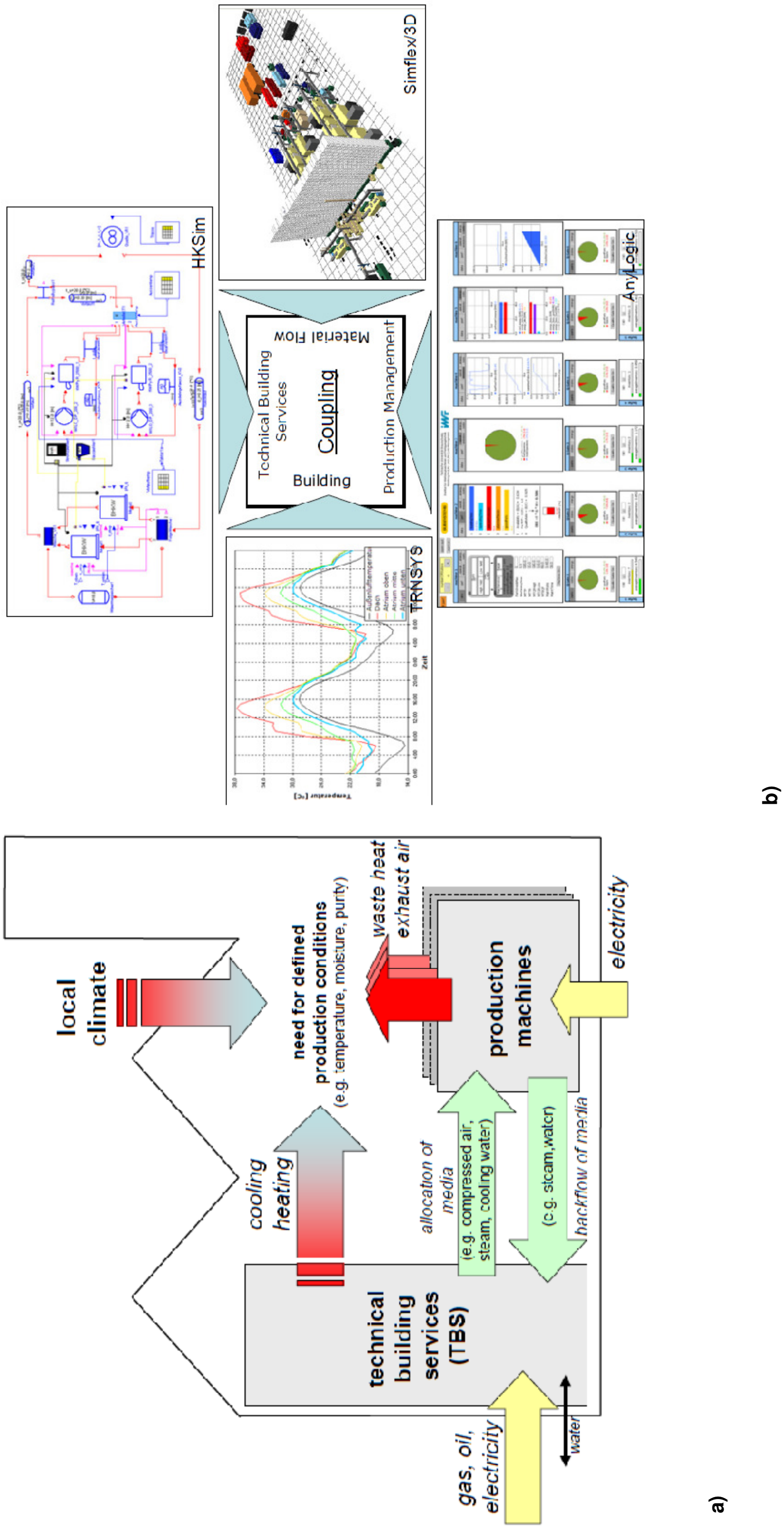


Figure 2-26 – a) Interdependencies between production and technical building services, and b) coupling of four simulation tools (Hesselbach et al. 2008)

Gutowski (2009) has studied the use of thermodynamics to develop a framework that accounts for process work, heat and material flows within a simplified manufacturing system boundary, Figure 2-27.

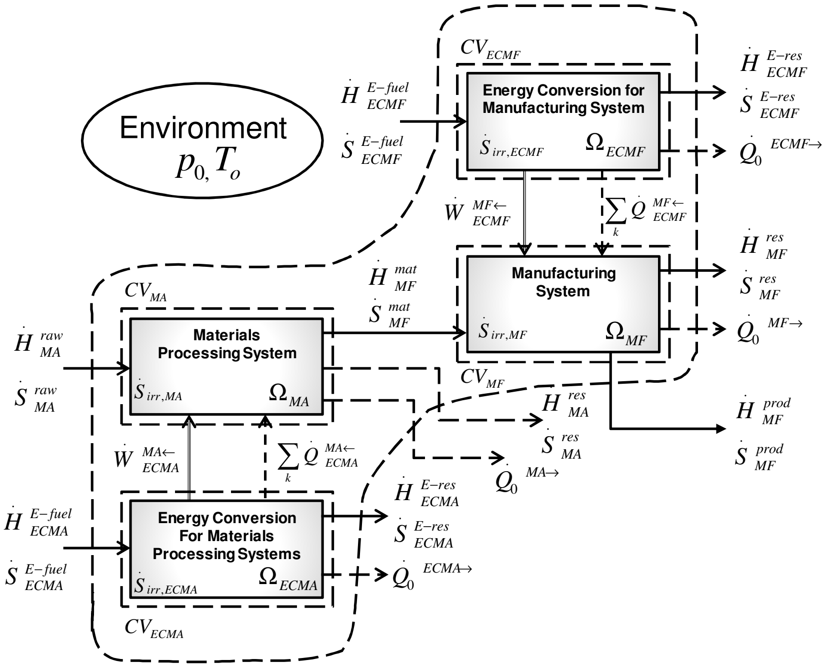


Figure 2-27 - Thermodynamic analysis of a manufacturing system (Gutowski et al. 2009), redrawn

The manufacturing system boundary illustrated includes mass, energy and entropy flows into and out of the manufacturing sub system (Ω_{MF}) from the manufacturing system energy conversion subsystem (Ω_{ECMF}) and materials processing subsystem (Ω_{MA}). The materials processing subsystem (Ω_{MA}) has work (W), heat (Q) and material flow interactions from the materials processing energy conversion subsystem (Ω_{ECMA}). The manufacturing system boundary can be extended to encompass further complex networks of inputs and outputs. Each subsystem interacts with the surrounding environment outside the system boundary at some reference temperature (T_o), pressure (p_o) and chemical composition, accounting for the inevitable system losses to the environment through irreversible processes, entropy (S). The thermodynamic framework is extended to exergy analysis of the system. The framework does not consider the interaction of the surrounding environment with external weather inputs, interactions of long wave and short wave radiation from transmitted solar radiation via internal/external surfaces. The closed system also does not consider thermal energy interactions from other surrounding manufacturing systems. These are important interactions that will affect the performance and energy consumption of manufacturing process systems and building services treating the local environment.

Dorn et al. (2011) and Kovacic et al. (2011) apply a systemic approach to modelling a production facility through holistic modelling of production, building and energy within the building modelling tool EnergyPlus. Figure 2-28 illustrates heat emitted from the machine components, tool, work piece and chip formation. Simulated case studies modelled in EnergyPlus do not include heat emission from the work piece, tool or chip formation to the surrounding environment. Thermal energy gains from the machine components are simulated via deterministic profiles at 37W/m² for laser machines and 49W/m² machine centres. The paper considers an electrically operated manufacturing process system only.

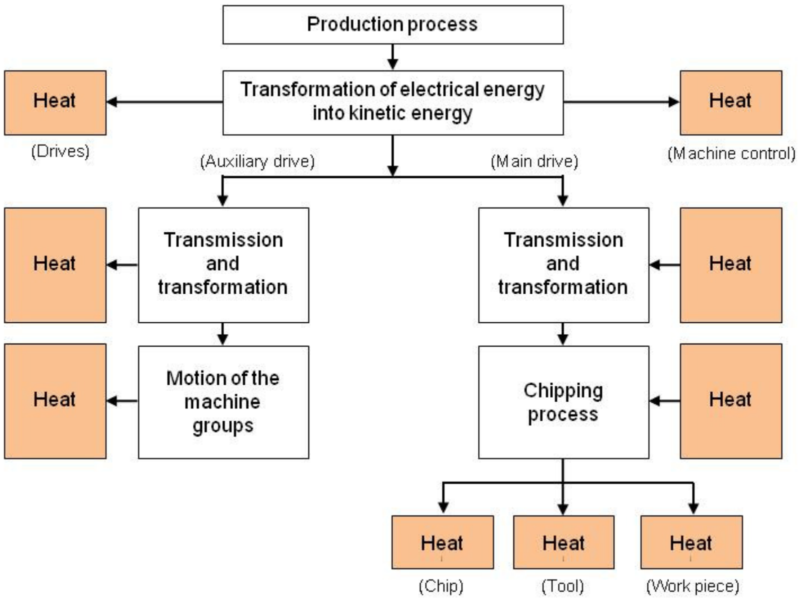


Figure 2-28 – Thermal transformation of machine components (Dorn et al. 2011), redrawn

Devoldere et al. (2007) discuss the energy consumption of two discrete part producing machines. The paper highlights the emission of heat from a machine that could potentially reduce the heating load of the building services in the production hall. It is not uncommon for heat gains to be ignored in the design of building technical services treating an environment, especially in dwellings. For example, in determining the heating system load of a occupied dwelling, solar gains and internal gains from occupants, lighting and small equipment are not considered in the heat balance analysis, as these gains may be negligible during the colder seasons and during morning pre-heat (BSRIA 2003; CIBSE 2006a).

Oates et al. (2012) discuss the integration of 'Sustainable Building Design' tools and 'Sustainable Manufacturing Process' tools to achieve an 'Integrated Sustainable Manufacturing' tool. The integrated tool resides within a building energy modelling suite and can help identify resource efficiency improvements via its library of tactics (Ball P. D et al. 2011; Despeisse et al. 2012; Ball et al. 2012a; Ball et al. 2012b; Despeisse et al. 2013). Liquid based manufacturing process systems are not modelled within the tool. Material (product) flow is not thermally responsive to its local environment. Thermal gains from material flow to its surrounding environment are represented through temperature decay time driven profiles.

Oates et al. (2011b) propose a methodology for representing manufacturing processes and supporting equipment in a graphical form. The graphical representation of manufacturing processes uses a system of interconnecting nodal networks to represent the inputs and outputs of material and energy flows through a manufacturing system. The nodal network of energy flows from a manufacturing process system can be extended to the local surrounding environment, and vice versa.

Oates et al. (2011a) describe the development of a modelling approach which combines the energy use in industrial production, with the energy flows relating to the building. The paper identifies three types of manufacturing processes, thermal 'gas' process (oven), thermal 'liquid' process (vat) and electrical processes (motor). Material (product) flow is also discussed, accounting for product heat flux and dispersion upon the overall energy balance of the system, before and after leaving a manufacturing process system. Simulation has been demonstrated within the Matlab/Simulink environment.

2.6. *Summary of the literature review*

The multi-disciplinary nature of the research has provided the author with a large area of existing research to review. However there is a dearth of literature on the interaction between the building environment 'shell' and the manufacturing process systems. The majority of papers that have been identified in this field are from a small group of authors, i.e. Ball, Despeisse, Dorn, Gutowski, Herrman, Theide, Oates, Wright.

Different approaches have been applied, such as simulation tools that model thermal energy interactions between the production machine, technical building services and the facility (Hesselbach et al. 2008; Herrmann et al. 2009; Dorn et al. 2011; Herrmann et al. 2011; Kovacic et al. 2011; Thiede et al. 2011). Other simulation tools that include the modelling of three types of manufacturing processes and material flow within an integrated factory tool (Oates et al. 2011a). As well, there are tools that seek to achieve an 'Integrated Sustainable Manufacturing' tool alongside helping to identify resource efficiency improvements via a library of tactics (Oates et al. 2012). Gutowski et al. (2009) details a thermodynamic framework that includes heat emissions into the production environment from both the machinery and input/output material flows from a manufacturing bounded system.

There is a growing interest in the field of building and manufacturing process system integration, design and analysis, though with the exception of papers authored and co-authored by the thesis author, research so far does not adequately cover the following areas:

- Application and representation of liquid based manufacturing process systems
    - Thermal interaction between manufacturing processes and the surroundings
- Application and representation of material (product) flow that is thermally responsive to its local environment
    - Thermal interaction between material and the surroundings
- Case studies demonstrating actual or simulated opportunities to reduce energy usage at both a facility and process level, using a general model

2.7. *Refined research questions*

The literature review identified several approaches to an integrated factory environment, section 2.5. It is clear that there has been some discussion on the formulation of an integrated software tool (Hesselbach et al. 2008). To the author's knowledge, no simulation tool exist that goes some way to integrating building and manufacturing process energy flows within one software tool. The literature reviewed also outlined shortcomings in present approaches to modelling an integrated factory environment, e.g. liquid based manufacturing process systems and material (product) flow, section 2.6. Further to the findings of the literature review, the primary research question (section 1.3) has been revised and is stated below.

Research question:

> 'How can a software tool combine the modelling of energy flows between a factory building, its processes and materials, in order to identify efficiency improvements and reduce energy use and associated carbon emissions?'

Based upon the research question to 'identify efficiency improvements and reduce energy use and associated carbon emissions', the literature reviewed in section 2.3.1 and 2.4.3 identifies the scales and levels at which energy flows and data exist within theory and practice. From this a subsidiary question has been formulated.

Subsidiary question:

> 'What is the appropriate level of detail for a practical integrated energy modelling tool for use in factory design?'

Through addressing the above research questions, this research seeks to make an original contribution to knowledge.

3. Methodology

This chapter discusses the methodology of the research. In section 3.1 the aim and objectives of the research have been modified and restated in line with the literature reviewed. A brief introduction into research methodology, framework and philosophies that are available to a researcher are discussed in sections 3.2 and 3.3. Sections 3.4 and 3.5 focus on the research design used within the thesis, conceptual modelling, software tool, case studies and validity.

3.1. *Refined aim and objectives*

Further to the literature review (Chapter 2) and refined research question (Section 2.7) the aim and objectives of the research have been modified. The aim of the research is to develop a software tool that is capable of modelling energy flows within and between a factory building, its processes and materials. The objectives of the research are listed below:

- Develop a conceptual method for identifying macro and micro levels of energy flows that occur within a factory environment
- Define and develop a software tool that is capable of modelling building energy flows, building services, manufacturing process systems and material flow within one integrated tool
    - The tool is to be capable of modelling different types of manufacturing process systems, equipment and plant
    - The tool is to model thermal interaction between manufacturing processes and their surroundings
    - The tool is to model thermal interaction between material flow and their surroundings
    - The tool is to include modelling of technical building service systems
- Use case studies formed from data obtained from the industrial partner's of the THERM project to test the methodology of the research
    - The author is to assist in the collection of data from the industrial partners of the automotive and aerospace industrial partners of the THERM project

The coupling of energy flows can provide assistance to energy managers in assessing energy used at both facility and process level, in order to identify efficiency improvements and reduce energy use and associated carbon emissions. Through use of an integrated tool, energy managers can identify and plan to optimise facility and process energy flows. The tool can also assist in the design of factories of the future, through modelling of building design and manufacturing systems in an integrated approach, to which these disciplines are currently modelled separately, missing vital opportunities to minimise energy use and associated carbon emissions.

3.2. *Research methodology*

The term research methodology has many definitions across different disciplines, and these can be contradictory (Lehaney et al. 1994). The Cambridge dictionary on-line definition for research is, *to study a subject thoroughly, especially in order to discover (new) information or reach a (new) understanding* (Cambridge_dictionary 2011). The definition of methodology is, *a system of ways of doing, teaching or studying something*. Robson (2011) states that research should be carried out, systematically, sceptically and ethically. From many definitions there seems to be an agreement that, research is a process of enquiry and investigation, It is systematic and methodical, and increases knowledge (Amaratunga et al. 2002). Amaratunga et al. (2002) list the basic elements of scientific research methodology:

- **Laws** – verified hypotheses, used to assert a predictable association among variables, can be empirical or theoretical
- **Principles** – A principle is a law or general truth which provides a guide to thought or action
- **Hypotheses** – Formal propositions which, though untested, are amenable to testing, usually expressed in casual terms
- **Conjectures** – informal propositions which are not stated in testable form, nor is a casual relationship known or even necessarily implied
- **Concepts and constructs** – concepts are inventions of the human mind to provide a means for organizing and understanding observations, they perform a number of functions, all of which are designed to form logical and systematic relationships among data
- **Facts** – Something that exists, a phenomenon that is true or generally held to be true
- **Data** – The collection of facts, achieved either through direct observations or though gathering of records, observations are the process by which facts become data

3.3. *Research method*

Real world research offers a number of philosophies and paradigms that are available to a researcher (Lehaney et al. 1994; Yin 2009; Robson 2011). Traditionally there have been two ways of carrying out research, quantitatively and qualitatively (Bryman 2006; Bryman 2007). Amaratunga (2002) considers a mixed method approach of combining quantitative and qualitative methods within built environment research, stating that the strengths and weakness of each approach compensate for each other. Though research philosophies offer different perspectives on how research can be carried out, Yin (2009) states that every research method can be used for all three purposes of – exploratory, descriptive and explanatory. Robson (2011) describes the difference between deductive research (in which theories are tested by observations) and inductive research (in which observations lead to theory development). Robson (2009) states that when considering open systems (e.g. a non-laboratory situation representative of the real world), the researcher is only in a position to explain an event after it has occurred, although they are unable to predict it. This is in contrast to a closed system (e.g. a controlled laboratory experiment), whose behaviour can be predicted based on observations of past behaviour.

3.3.1. Research method used in this thesis

The methodology of this research follows an inductive (observation to theory) approach. Observations have been made during site visits to the factories of the industrial partners of the THERM project that include manufacturing process systems (e.g. scale, size and complexity) and product flow (e.g. production lines, transportation, storage etc). The work also includes observations made from the author's working background as a draughtsperson for a steel balustrade manufacturer, shop floor assistant for an electromagnet manufacturer and a mechanical engineer for a global building design organisation. The research makes use of existing theory from the disciplines of building design and manufacturing process systems engineering to create a new integrated modelling tool based on observations of real manufacturing processes and buildings. A large body of theory is embodied within the existing building modelling tool, the International Building Physics Toolbox (IBPT), which this research utilises in the development of a new simulation approach, as discussed in chapter 5. The overall methodology is designed to answer the research questions outlined in section 2.7.

3.4. *Research design used within this thesis*

Yin (2009) states that research design is a 'blueprint' for research, dealing with at least four problems: what questions to study, what data are relevant, what data to collect, and how to analyse the results. The main research question (section 2.7) is directed towards the development of a conceptual model and a software tool that is capable of modelling energy flows between a factory building, its production systems and material (product) flow.

3.4.1. Conceptual model

The conceptual model is a description of the model that is to be developed, that is not software-specific, and which describes the objectives, inputs, outputs, content, assumptions and simplifications of the model (Robinson 2004). Robinson (2006) states that conceptual modelling is one of the most vital parts of a simulation study and lists:

- Conceptual modelling is about moving from a problem situation, through model requirements to a definition of what is going to be modelled and how.
- Conceptual modelling is iterative and repetitive, with the model being continually revised throughout a modelling study.
- The conceptual model is a simplified representation of the real system.
- The conceptual model is independent of the model code or software, while model design includes both the conceptual model and the design of the code
- The perspective of the client and the modeller are both important in conceptual modelling.

3.4.2. Software tool

The model design includes both the conceptual model and the design of the code (Robinson 2006). Maria (1997) lists 11 steps to developing a simulation model, Table 3-1. The steps are in a logical order.

Table 3-1 - 11 steps in developing a simulation model (adapted from (Maria 1997))

Steps	Development of a simulation model
1	Identify the problem
2	Formulate the problem
3	Collect and process real system data
4	Formulate and develop a model
5	Validate the model
6	Document model for future use
7	Select appropriate experimental design
8	Establish experimental conditions for runs
9	Perform simulation runs
10	Interpret and present results
11	Recommend further course of action

3.4.3. Case studies

Holistic and meaningful characteristics of real-life events can be retained by the investigator through case study methods (Yin 2009). Yin (2009) also states that there are four types of designs for case studies, (Type 1) single-case (holistic) designs, (Type 2) single-case (embedded) designs, (Type 3) multiple-case (holistic) designs, and (Type 4) multiple-case (embedded) designs, Figure 3-1. The holistic design for single and multiple case studies address one general issue. The embedded design may address the general issue as well as a subunit or subunits of connected issues.

Yin (2009) also states that multiple-case designs have distinct advantages and disadvantages in comparison to single-case designs. The evidence from multiple cases is often considered more compelling, and the overall study is therefore regarded as being more robust.

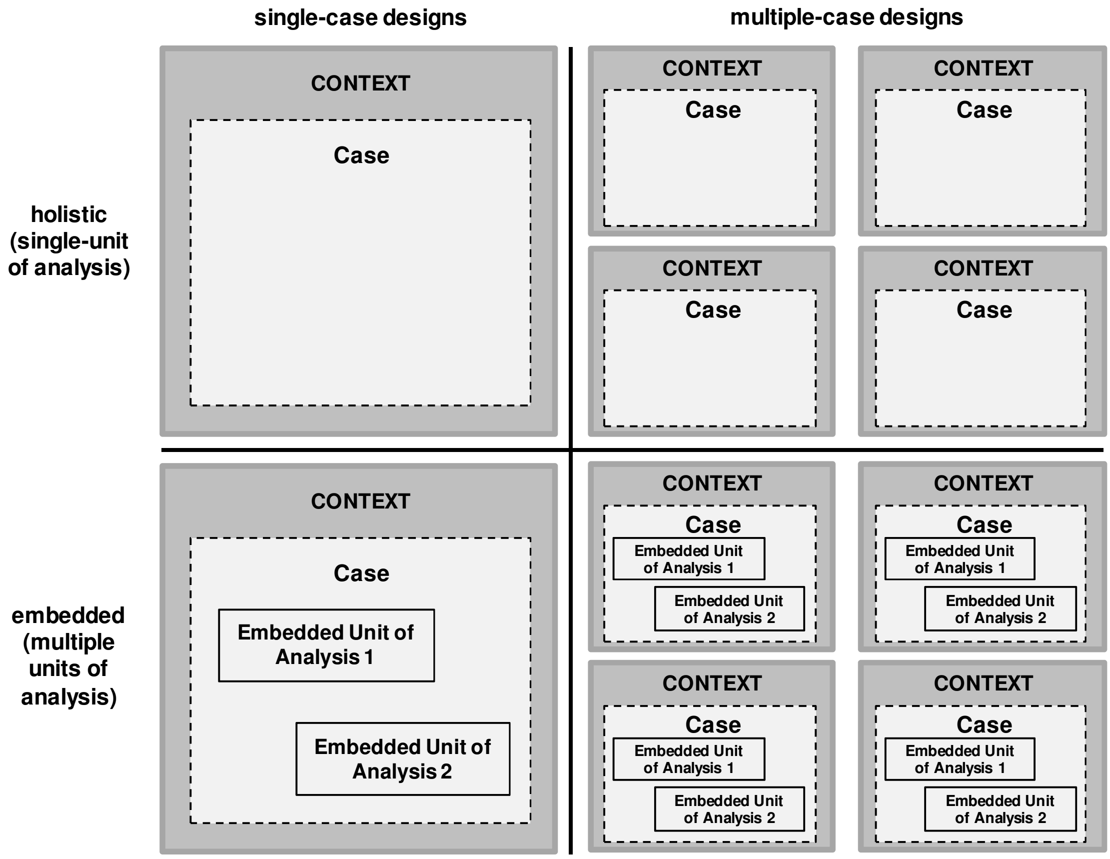


Figure 3-1 - Basic types of designs for case studies (Yin 2009)

3.4.4. Validity

The value of research is defined by the validity of its results and the extent of its contribution to knowledge (Amaratunga et al. 2002). Yin (2009) lists four tests that are commonly used to validate the results of research:

- *Construct validity*: The suitability of the operational measures used for the concepts being studied.
- *Internal validity:* This strength of the causal relationships in which certain conditions are believed to lead to other conditions.
- *External validity:* The degree to which the findings of the research can be generalised.
- *Reliability:* The degree to which the research can be repeated, with the same results.

3.5. *Research structure*

Figure 3-2 outlines the structure of the research. The research problem, literature review and problem definition are covered in chapters 1 and 2. Conceptual modelling, model design and tool verification are discussed in chapters 4 and 5. Case studies and results, conclusions and further work are discussed in chapters 6, 7 and 8. Throughout the work the THERM project has had several links to the research. Case studies from the industrial partners have been selected from real life industrial production processes, see section 3.6. The author assisted in the collection of data from the automotive and aerospace industrial partners of the THERM project.
Knowledge gained throughout the research and results from the case studies have assisted in the development of the THERM tool, see section 8.1.

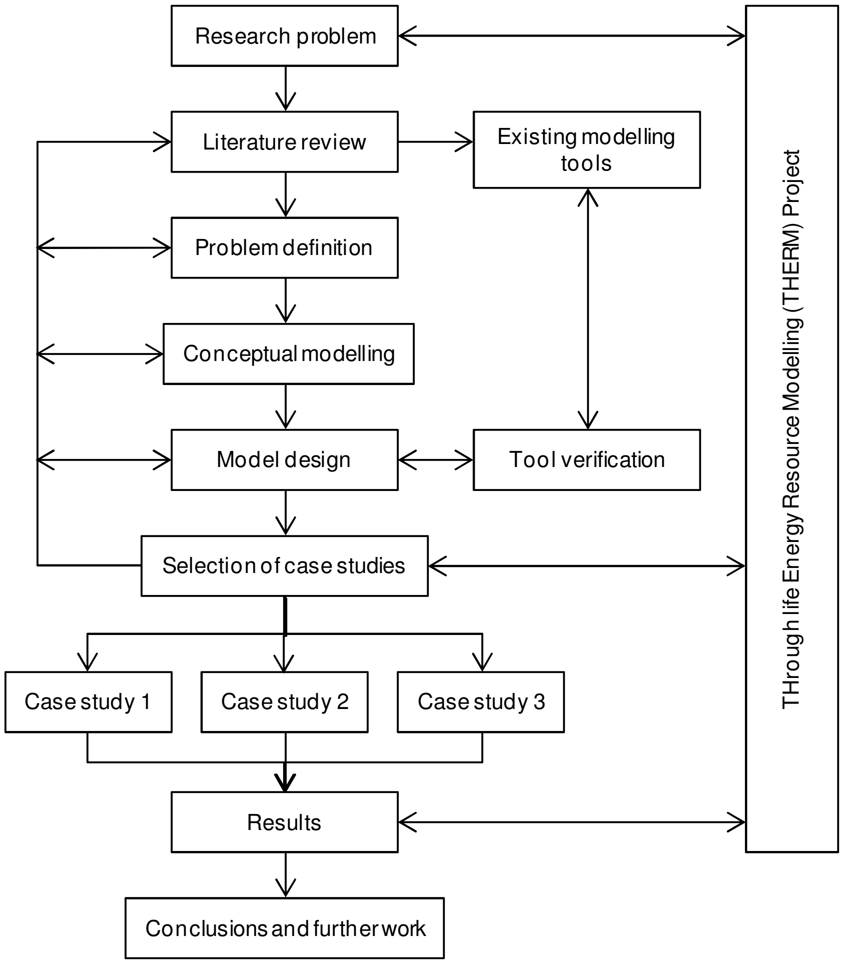


Figure 3-2 – Research structure

3.5.1. Conceptual modelling

Prior to the development of a software tool, a conceptual model was created to represent factory related energy flows. The creation of this model was based on knowledge from the disciplines of building design and manufacturing process systems engineering, as described in chapter 4. The conceptual model follows an inductive (observation to theory) approach to research and is the framework for the development of the software tool, chapter 5.

3.5.2. Model design

Sections 2.3.1 and 2.4.5 consider existing building and manufacturing software tools. A software tool capable of coupling building and manufacturing related energy flows is novel, section 2.5. Traditional building energy flow paths are well documented (Clarke 2001) and are commonly coupled within dynamic building modelling tools (EnergyPlus 2012; ESP-r 2012; IES 2012a). Building modelling tools simulate energy flows that occur internally (e.g. factory – office, retail) and externally (e.g. outside the building boundary – weather) to a built environment, based on fundamental building physics. The manufacturing industry within the UK covers a wide field of industrial practices. Figure 2-24 lists a number of simulation tools that are used by manufacturing industry. Although there are a number of simulation tools that are capable of modelling energy flows, it is understood that these tools in general are focused on improving productivity, reliability and quality. Applications in energy analysis are limited to reducing process energy consumption, particularly in the chemical and pharmaceutical industries (Kemp 2006). At the time of writing there has been little research into modelling thermal energy interactions between the factory environment, production systems and material (product) flow.

The 11 steps to developing a simulation model listed in Table 3-1 are in line with the methodology of the research. The many approaches to simulation make it hard to decide which modelling approach is best suited to the problem situation. Throughout the early stages of the research (i.e. the first 6 months) the author investigated and worked through several examples using different software tools from the disciplines of building design and manufacturing process systems engineering. A software should be chosen on the basis of understanding the conceptual model (Robinson 2004). An important aspect of the conceptual model is the coupling of energy flows that internally (within a factory boundary) and externally (outside a factory boundary – weather) in relation to time and location within and around a factory environment. Figure 2-9 illustrates energy flow paths that occur within a traditional built environment (e.g. office, domestic dwellings, retail etc). These energy flow paths are simulated in current building modelling tools. Building modelling tools provide a structured and well defined approach to modelling energy flows within traditional built environments. Initial exploratory work was carried out using the building modelling tool; Integrated Environmental Solutions Virtual Environment (IES VE). A building model representative of the THERM industrial partner's factory building and processes was created in IES, Figure 3-3. The purpose of the exercise was not to simulate material and energy flows that occur within the factory, but to explore the requirements and capabilities of modelling a factory building and its processes within the framework of an existing building modelling tool. Each production process was created as a thermal zone (i.e. single interior air mass node per zone) as IES VE currently only models gas (i.e. air), grey blocks in Figure 3-3. This was a simplification of reality as processes were not only air based such as an oven, but also consisted of paint spray booths, liquid tanks, assembly lines etc. The model was cumbersome, time consuming and required modelling expertise.

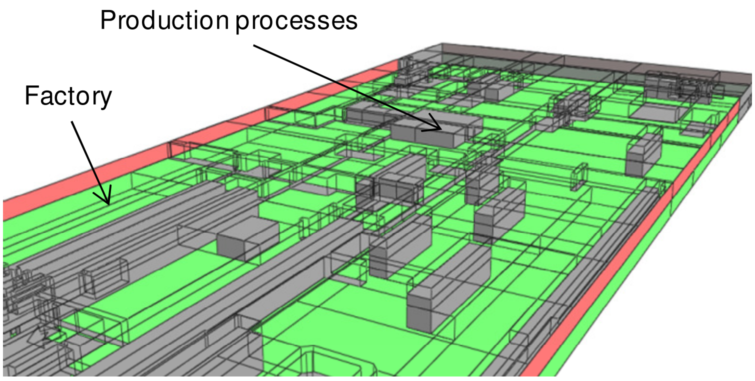


Figure 3-3 – IES VE, factory building and production processes

Further to the factory model, a dynamic model of a high temperature process was also created using IES VE, Figure 3-4. The process was created as a thermal zone. A simplified model of the production process was created based on construction properties and a time driven profile representative of the internal temperature of the process during operation. A thermal simulation was carried out. The simulation model reported an error. The temperature profile of the process exceeded the 100℃ upper limit of the modelling capabilities of the tool for modelling of air. This is not an issue in everyday building modelling as the tool is traditionally used for modelling of domestic and non-domestic environments.

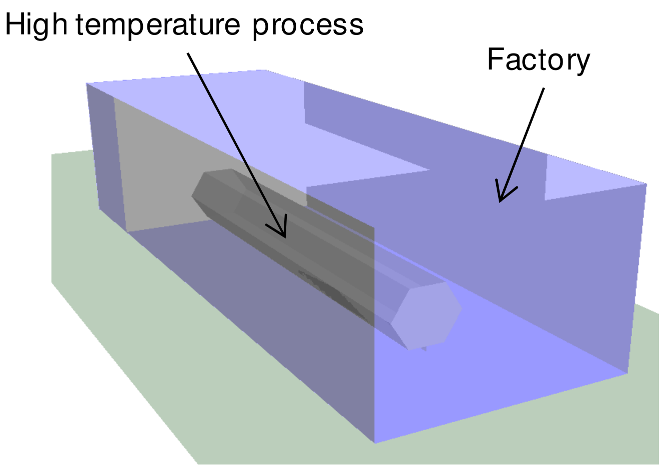


Figure 3-4 – IES VE, high temperature process

Other work was carried out using the discrete event simulation (DES) tool, Arena (Rockwell 2012) and the material analysis flow software, subSTance Analysis Flow (STAN) (STAN 2012).

These tools were selected based on their ability to model material flow. STAN performs material flow analysis through graphical modelling and balance equations. Discrete event simulation is of interest in that building modelling tools traditionally model energy flows deterministically, where as DES is more about stochastic flows (e.g. materials, people, services etc). Though the integration of a building modelling and DES software has been discussed (Hesselbach et al. 2008; Herrmann et al. 2011), there is inherent difficulties in coupling time-driven and event-driven approaches together (Clune et al. 2006). This was considered to be outside the scope of this work.

From the software exploratory work an existing building modelling tool designed and operated in the Mathworks Matlab and Simulink software environment was identified, section 5.1. The building modelling tool known as the International Building Physics Toolbox (IBPT) operates under the open source license for free software for Europe (FSFE 2012). The open source license is an important aspect of this research, because the development of an integrated approach to modelling factory energy flows requires access to a tools coding and structure. The open source license coupled with the block flow method of modelling in Simulink enables the research to extend the building modelling framework to include the simulation of manufacturing process systems and material flow. The IBPT is not currently validated against criteria for building modelling tools such as TM33 (CIBSE 2006c) and ASHRAE140 (ASHRAE 2008). To provide confidence in the algorithms and their implementation to model building physics the researcher software verified the IBPT against the commercially used and validated building modelling tool IES VE (IES 2012c) in comparable areas of building modelling, see section 5.3.

In order to use the toolbox to model factory energy flows, two significant changes have been made to the existing IBPT, as described in section 5.2. Firstly, mathematical and structural changes have been made in line with the framework set out in chapter 4. Secondly, further mathematical changes to the toolbox have been made, narrowing the difference in the modelling approaches used by IBPT and IES VE. There are still differences between the tools' approaches to modelling building physics (section 5.2), however changes made to the existing IBPT result in simulated outputs that are sufficiently similar to output from IES VE in comparable areas of building modelling. Changes to the existing IBPT have been made to create the 'Adapted IBPT', incorporating functions that are outside the scope and capabilities of current building modelling tools. They include the modelling of liquid based manufacturing process systems and material (product) flow. Areas of building modelling in the adapted IBPT that are comparable to IES VE have been verified in sections 5.4, 5.5 and 5.6. Case studies based on real manufacturing operations have been used to model liquid-based process systems and material flow, as discussed below and in chapter 6. Two of the case studies are based on modelling a large factory zone with internal manufacturing processes, and material (product) flow between the factory and manufacturing processes. It is feasible to extend these models to include a number of zones within the factory environment, defined by work spaces (i.e. different types of manufacturing processes) or environmental strategies (i.e. naturally or mechanically ventilated, heating or cooling). The flow of material between these sub-zones could also be included. This would require an extension to the mathematical and structural approach of the IBPT to include thermal energy flows between the zones and profiles that account for the flow of material from zone to zone.

Manufacturing covers a wide range of industrial practice. As a result, there is a range of typologies and taxonomies of manufacturing processes (DeGarmo et al. 2003; CO_2PE 2012), that are used in industry (ONS 2012). Due to time and resource constraints, the development of the adapted IBPT has primarily focused on the energy flows between thermal and electrical manufacturing processes, factory buildings, manufacturing plant and products. This focus is discussed in section 4.2. The toolbox is capable of being enhanced in future work, as discussed in sections 4.1 and 5.2.

Energy flows within a factory environment are identified and relationships explored through conceptual modelling and observations made from the factories of the THERM industrial partners (internal validity). The conceptual modelling (non simulation) framework forms the basis for the development of a software tool. The software tool has been verified where applicable against the commercially available and trusted building modelling tool IES VE to ensure reliability and repeatability.

3.6. *Description of the case studies*

It is important that case studies are selected on their ability to address the research question(s) (section 2.7) and focus of the work. Table 3-2 compares three industrial case studies derived from data obtained from the industrial partners of the THERM project against modelling criteria. The author assisted in the collection of data from the automotive and aerospace industrial partners of the THERM project. From the table, the modelling criterion shows that the cases studies are different from one another and offer different modelling perspectives. The three case studies; industrial drying tank, industrial treatments and air supply house, are based on a multiple (holistic) case study design (section 3.4.3) and are discussed in greater detail below. The case studies from the industrial partners of the THERM project have been chosen to generalise the work across sectors of the manufacturing industry besides only aerospace and automotive manufacturing (external validity).

Table 3-2 – Case study selection

	Criteria									
Case studies (section number, title)	Factory	Windows	Space heating	Weather file	Process only	One internal process	> 1 internal process	Air (i.e. gas) process	Liquid process	Material flow
6.2_Industrial drying tank	•	•	•	•		•		•		•
6.3_Industrial treatments process	•	•	•	•			•	•	•	•
6.4_Air supply house				•	•			•		

3.6.1. Industrial drying tank

3.6.1.1. Model description and analysis

The model of the industrial drying tank within the adapted IBPT includes the following elements: building (fabric and heating system), material flow and manufacturing process (drying tank) with supplementary plant (i.e. fan, heat exchanger and air re-circulation ductwork). The industrial drying tank, plant and material are part of a real industrial process used by one of the industrial partners of the THERM project. The case study combines empirical data with assumptions to create a model within the adapted IBPT, as described in section 6.2.3. Models of the supplementary plant have been created according to the physics of the systems involved, and are integral to the behaviour of the model, see Appendix B. For more information on the data see section 6.2.

The industrial drying tank case study has been chosen on the basis of its ability to address the main and subsidiary research question, section 2.7. The modelling of energy flows between the factory environment, industrial drying tank including plant, facility heating and material (product) flow in part provides answers to the main research question. By simulating energy flows that occur within a factory environment, energy efficiency measures at a facility and process level from the simulated scenarios are identified, and directed towards opportunities to reduce energy use and associated carbon emissions, section 3.5.1.

The modelling of the case study also provides, in part, answers to the subsidiary research question focused on the appropriate level of detail required to model factory energy flows. The simulated industrial drying tank is based largely on data obtained from equipment data sheets and operational performance data provided by the THERM industrial partner, section 6.2.3. This case study implements a detailed model of the drying tank and plant. From this, simulated results were derived in relation to the balance of energy flows in a factory environment, and identified savings through scenario modelling. The level of detail used in this case study furthers the understanding of the appropriate level of detail required in producing valuable outputs.

3.6.1.2. Validity

Simulated scenarios such as the variability in the operation of factory facility heating, drying tank and material (product) flow schedules, have been modelled within the adapted IBPT, section 6.2.5. For scenarios that don't include material (product) flow, the simulated results from the adapted IBPT have been software verified against IES VE simulated outputs, see section 5.3.5. For scenarios that include material (product) flow, into and out of the drying tank, the verification of the original model provides confidence that the model is performing correctly. Tool verification for the modelling of material (product) flow is also demonstrated by comparing simulated outputs against logged material temperature obtained from site, section 6.2.7. These validity checks provide confidence in the outputs of the case study, and ensure reliability and repeatability.

3.6.2. Industrial treatments process

3.6.2.1. Model description and analysis

The industrial treatments process is representative of one of the industrial THERM partners manufacturing process systems. The manufacturing process system is based on a treatments process, consisting of four treatment tanks (three water and one air based), building (fabric and heating system) and material (product) flow. For more information on the key data obtained from site and generalised, section 6.3.3.

The case study has been chosen on the basis of its ability to address the main and subsidiary research question, section 2.7. In a similar method applied to the drying tank case study (section 6.2), the treatments process has been modelled within the adapted IBPT and consists of, building (fabric and heating system), material (product) flow and manufacturing process system (four treatment tanks). The modelling of the treatments case study in part provides answers to the main research question, as the main difference between the drying tank and treatments process case studies is the inclusion of a liquid based treatments tank. The modelling of liquid based manufacturing process systems are outside the capabilities of current building modelling tools.

The simulated case study is based on operational performance data provided by the THERM industrial partners, section 6.3.3. This is a different approach to the level of detail used to model the drying tank case study. The treatment tanks are modelled on designed operational temperature data obtained from site and different tank mediums. No manufacturing plant has been modelled. The model simulates a demand side energy requirement for the tanks based on heat gains/losses to and from the tanks. Two scenarios have been modelled within the adapted IBPT focusing on high and low level infiltration rates to the factory, section 6.3.5. Simulated results indicate that total energy consumption (i.e. building and manufacturing process systems) is reduced by decreasing the infiltration rate of the factory, section 6.3.6. As expected, most of the savings are attributed to the heating system of the building. Unexpectedly, energy savings were identified in the heating of the four treatment tanks. From the initial set of results, focus changed to a micro level analysis, section 6.3.7. The inherent complexity of an integrated tool enables the user to explore in-depth the fundamental energy balance of a factory environment. This is achieved through investigating the components that contribute to convective gains/losses to the internal air temperature of the factory thermal zone. The level of detail used in this case study is another outlook on the appropriate level of detail required to model factory energy flows, this provides in part answers to the subsidiary research question.

3.6.2.2. Validity

Due to the nature and locality of the industrial treatments process observed at the industrial THERM partner's factory, the case study has been simplified, section 6.3.3. Therefore simulated outputs are not entirely comparable to site metered data. However, gas consumption data from the THERM industrial partner has been used to analyse the consumption pattern of the real life facility and systems gas usage against the simulated adapted IBPT results. The pattern analysis approach, discussed in section 6.3.6, provides confidence that the model is simulating factory energy flow behaviour in a similar way to that is occurring in real life. The tool verification section (5.3) comparing the adapted IBPT to IES VE and verified results in the drying tank case study, also provide confidence in using the adapted IBPT for the treatments case study.

3.6.3. Air supply house

3.6.3.1. Model description and analysis

The air supply house (ASH) process is made up of a combination of manufacturing plant designed to supply a large volume of air under controlled conditions (i.e. dry bulb temperature and relative humidity) and volumetric flow rate (i.e. laminar) to a desired location. The approach is modelled differently to the other case studies. The ASH model does not include the modelling of the factory building. The model concentrates on the manufacturing process aspect only, based on data obtained from the industrial partners of the THERM project. The Simulink environment to which the adapted IBPT is created in has been used in the build of the case study. The nodal network approach discussed in section 4.1, enables the process to be coupled with the factory building at a later date. Block flow models of each of the manufacturing plant (i.e. gas burner, biscuit humidifier, steam injection, closed loop cooling coil, closed loop steam re-heat and supply fan) constituting to the overall functionality of the ASH unit have been created within the Simulink environment. For more information on the key data of the case study, section 6.4.2.

The ASH case study has been chosen on the basis of its ability to address the main and subsidiary research question, section 2.7. This case study is different from the other studies as primarily the model does not include the factory building. Therefore, the case study seeks to provide different answers to the research question(s). The case study applies two approaches to modelling the ASH process based on site data. Firstly, a model based on site metered valve position data and manufacturing plant capacity ratings for each of the manufacturing plant has been created within Simulink. This approach is designed to analyse macro level data to further understand the energy consumption behaviour of the process under operational conditions, section 6.4.3. The second approach, also built in Simulink uses fundamental physics and air-based psychrometrics to model each of the manufacturing plant that make up the ASH process, section 6.4.4. This approach uses detailed performance data obtained from site to model the psychrometrics of the air condition throughout the process to further understand the performance of the ASH process when in operation. The modelling of the ASH process has required extensive resources and time. This is a valuable outcome in answering the subsidiary research question to understanding the appropriate level of detail required in factory modelling. The two approaches applied to the case study also provide important answers to the main research question, when modelling complex manufacturing process systems. Though the case study does not include the factory building or material flow, the case study does model demand side process energy consumption. The case study identifies opportunities to reduce energy use and associated carbon emissions.

3.6.3.2. Validity

The ASH process is a specialised manufacturing process system and is rigorously monitored to maintain quality. Recorded site data at intervals of approximately 10 seconds for a number of process variables, Table 6-20, have been used to validate the micro level approach to modelling, section 6.4.7. Supply side energy consumption data has been difficult to validate as the supply network of steam is supported and transported from a neighbouring building. The steam network is also connected to other process systems. Simulated results from the macro level approach (section 6.4.6) are compared against the simulated results of the micro level approach, section 6.4.8. The results show confidence in that the modelled results are in good agreement for most of the ASH plant, with exception of the steam injection plant. The steam injection plant is only operated for a short period of time, having a minimal effect on the outcome of the process energy consumption. Further work is required in this area.

4. Conceptual modelling

This chapter develops an integrated approach to representing energy flows within a factory environment through conceptual modelling. Section 4.1 develops a framework for representing the inputs and outputs of manufacturing process systems through a nodal system of interconnecting networks. The framework couples energy flows from the built environment, manufacturing process systems and material (i.e. product). Section 4.2 formalises the energy flow paths within a factory environment through mathematical expression. Energy flow paths to and from manufacturing process systems are discussed in the form of thermal and electrical processes and material flow. Section 4.2.3 integrates energy flows from within a built environment with those from manufacturing process systems and material, resulting in an integrated approach to representing energy flow paths within a factory environment.

4.1. *Framework approach for modelling processes*

4.1.1. Generic manufacturing process systems

Simulation models are complex, and the structure needs to be very carefully defined. A graphical representation begins to express a structure for detailing industrial processes and plant (Oates et al. 2011b). Figure 4-1, illustrates a generic graphical representation of energy and material flows into and out of a manufacturing process system, where required. The generic approach is applicable to representing manufacturing processes (oven, press etc), intermediary processes (conveyors, storage etc) and plant/equipment (fans, pumps, motors etc) at macro and micro levels of detail. The flows consist of material (product), and the main forms of energy used by the process. Depending on the modelling approach, thermal interaction between the process and environment may not be considered or included via the thermal input (shown entering into the top of the process) and as a output (shown exiting the process). The list of energy sources and energy carriers is not exhaustive, but the most common forms are included and assigned a colour i.e. product (green), water (blue), air (purple), gas (yellow), electricity (pale green), steam (red), thermal energy (orange) and mechanical energy (brown). For the purpose of this work, a substance or mass that enters and leaves a process, whose sole purpose is not to transfer energy, is deemed a material (product). Energy carriers such as water, steam and air, are intended to transfer thermal energy to desired heat sinks and sources. Gas and electricity are primary and secondary sources of energy. Mechanical energy is a result of a transformation of primary or secondary sourced energy. Thermal energy may be the result of a chemical reaction, transfer of heat flux energy from surfaces, etc. The physical boundary of the manufacturing process system is defined by the solid outer blue line.

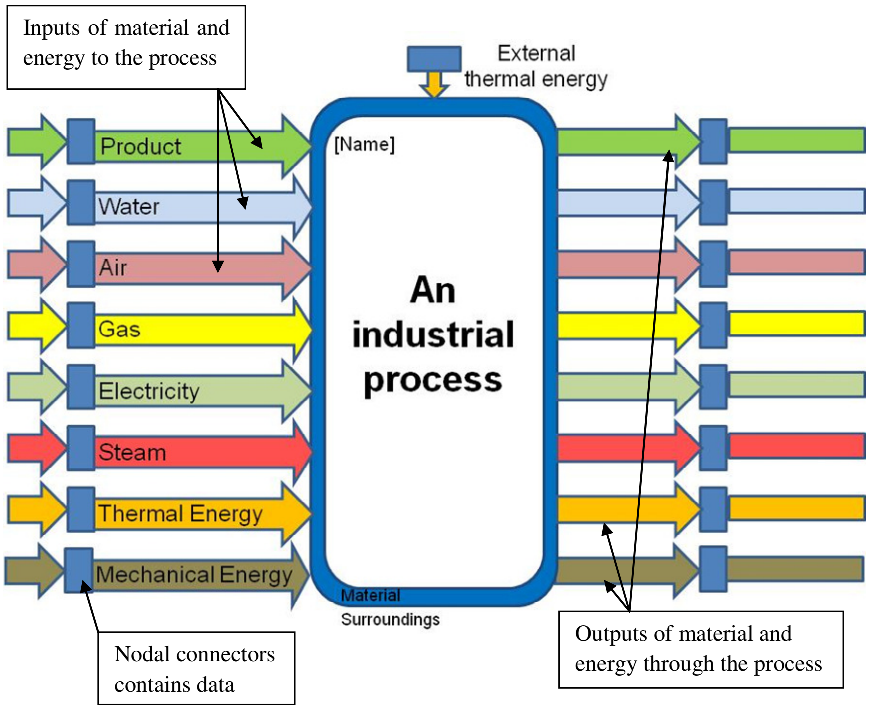


Figure 4-1 - Energy and material flows into and out of a process

An example of material flow from one manufacturing process to another, and further links, is shown in Figure 4-2. The input-output method of the graphical representation is not dissimilar to that of a Sankey diagram (Schmidt 2008). The visual difference between the two methods is that the thicknesses of the flow lines do not signify quantity as does in a Sankey diagram, they merely demonstrate flows of material (product) and energy through the process system. Data is collated at nodal points before and after each process for material (mass, density, specific heat capacity etc), energy source (source type, power rating, pressure etc) and energy carriers (pressure, temperature, volumetric flow rate etc) that are of interest. In Figure 4-2 the model records input states for the properties of material (e.g. mass, density, specific heat capacity etc). Data can be input as predefined set point values, or inherited values from another point within the model. Figure 4-2 illustrates the flow of material through a process and its recording of properties as outputs, identified as blue blocks.

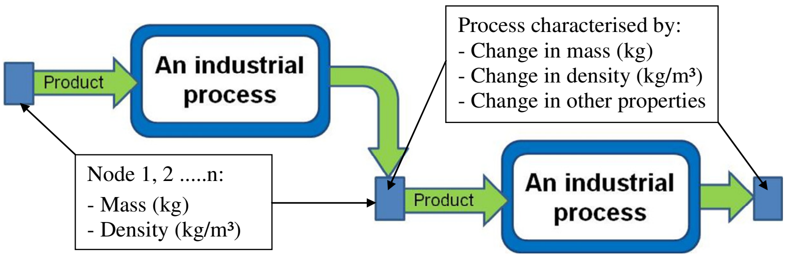


Figure 4-2 - Nodal network of material flow through a system

It is therefore possible to build up blocks of equipment and processes through connection and transferring of data dynamically from node to node through the conceptual model of a simple or complex system. The generic graphical representation of manufacturing processes as black-boxes enables the approach to be considered at either a macro or micro level, dependent upon the level of detail that is available. Along a production line of manufacturing processes a macro level approach may be required in relation to the amount of known data e.g. a production line or process(es) consumes “x” amount of energy and the properties of the material flowing through the processes changes by “y” density, “z” temperature etc. A more detailed model may consider interactions of supplementary/auxiliary equipment. This enables several micro level processes to be grouped together to form an enhanced conceptual model, in the form of ‘nested black-boxes’. This allows the approach to consider simple or complex manufacturing process systems as well as complete production lines.

4.1.2. Manufacturing plant

An electric motor is illustrated in Figure 4-3. Electrical energy is supplied to the motor as an input. The electrical energy is then transformed into energy outputs such as thermal energy, mechanical energy, sound etc. Thermal interaction between the motor and the surroundings will occur. In Figure 4-3 it is assumed that motor inefficiencies result in thermal energy outputs only.

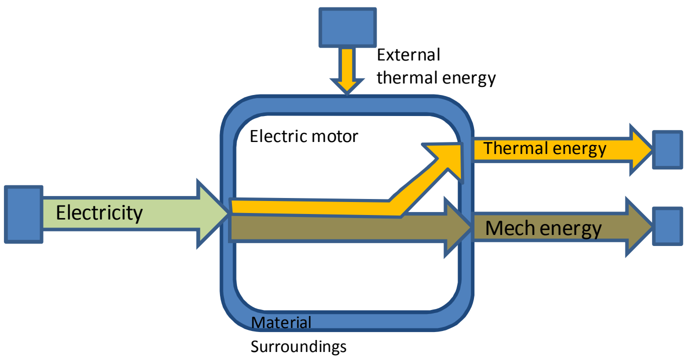


Figure 4-3 – Overview of an electric motor

It is from this representation of a widely used industrial piece of equipment that other forms of industrial equipment and plant can be represented at a macro and micro level of detail. Figure 4-4 illustrates a graphical representation of a fan typically used in industry. The fan is represented at a macro (general) level. The figure differs to the representation of an electric motor, as there are two main inputs illustrated in Figure 4-4. Details of the motor have been omitted at the macro level. Energy is supplied as an input to the fan (i.e. electricity). Air is also drawn into the fan. Properties of air at the input of the fan are known at the ‘blue’ nodal box as described in the nodal network diagram, Figure 4-2. During operation of the fan the properties of the air as an output (i.e. blue box) will change in relation to the input conditions e.g. increased temperature and pressure. Thermal interaction between the fan and the surroundings will also occur.

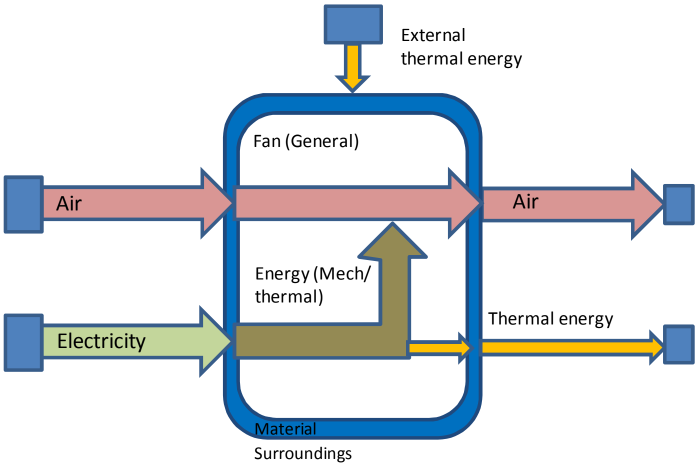
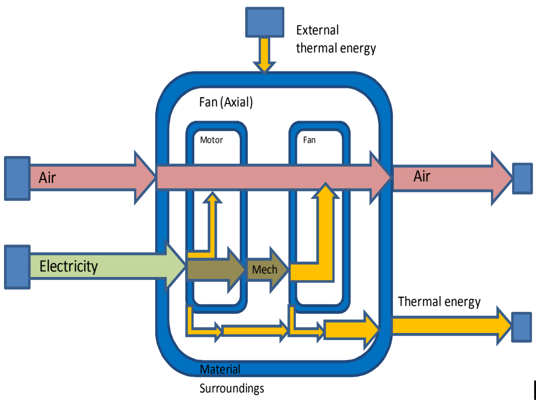


Figure 4-4 – Overview of a industrial (general) fan

Figure 4-5 shows a more detailed representation, where the motor model is nested within the fan model. Dependent upon the type of fan and whether the fan is in line with the passing air, axial or centrifugal, the amount of energy transferred to the air will vary. As illustrated in Figure 4-5a) and b), both fan types have a motor and a fan component. The axial fan Figure 4-5a), transfers energy from both the motor and fan to the passing air, due to respective inefficiency losses and pressure rise (adiabatic compression at the fan) (Wright et al. 1988). The centrifugal fan as shown in Figure 4-5b) is not in line with the passing air. In this case thermal energy is transferred to the air from the fan only and thermal energy from the motor is redirected to the motor casing and surrounding environment.

a) 

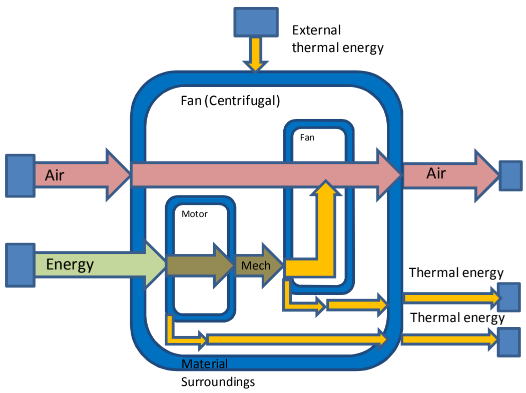
b) 

Figure 4-5 – Micro level graphical representation of an, a) axial fan and b) centrifugal fan

Similar macro and micro graphical representations are presented for a pump in Figure 4-6a) and b). The figure illustrates the passing of water instead of air, though the mechanics are similar, as both manufacturing process systems include a motor to transfer medium to its desired destination.

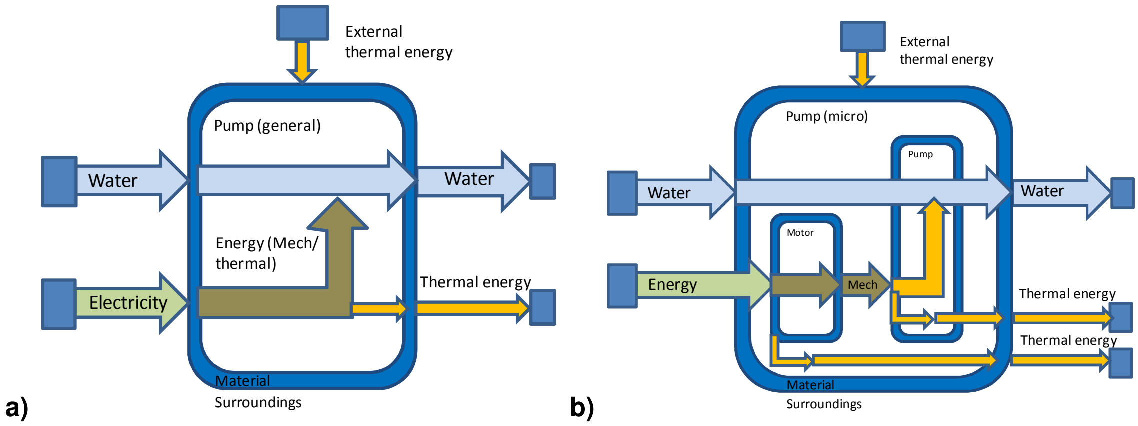


Figure 4-6 - Graphical representation of a pump, a) macro and b) micro

4.1.3. Manufacturing process

By combining several graphically represented components such as the motor and pump, larger and more complex manufacturing process systems can be formed and their energy flows and transformations can be further investigated. Figure 4-7 and Figure 4-8 are representations of traditional and computer numerical control (CNC) milling machines, both using a combination of motors, pumps, material (product) and energy transformations. Due to the additional numerical control components of the milling machine, Figure 4-8 includes more nested black boxes than the traditional milling machine shown in Figure 4-7.

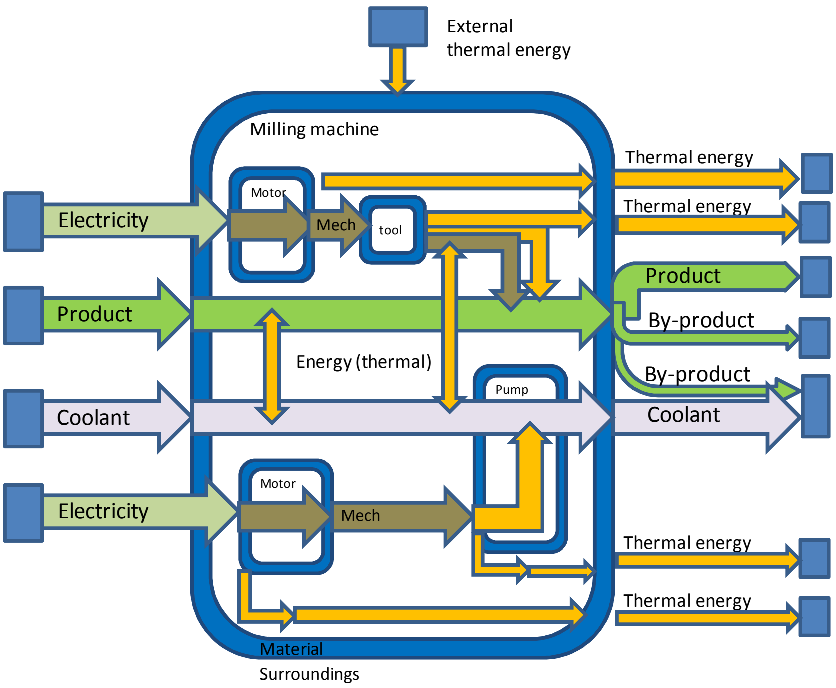


Figure 4-7 – Macro level representation of a milling machine

A simple conceptual model of a CNC milling machine at a macro level would state that the process consumes “x” amount of electricity during production. The product reduces in mass. Product and by-product (e.g. swarf, scrap) are outputs of the system – this is a ‘black box’ approach. Figure 4-8 is a micro representation of the CNC milling machine. Rather than just knowing the amount of electricity that is consumed during the process, more data may be available to understand which parts of the CNC machine are consuming a higher proportion of energy (i.e. motors, actuators, pumps etc) (Dahmus et al. 2004; Devoldere et al. 2007; Ciceri et al. 2010). Transformation of energy can be further investigated, such as how much energy from the cutting process is transferred to the cooling lubricant, tool piece, product, or surroundings.

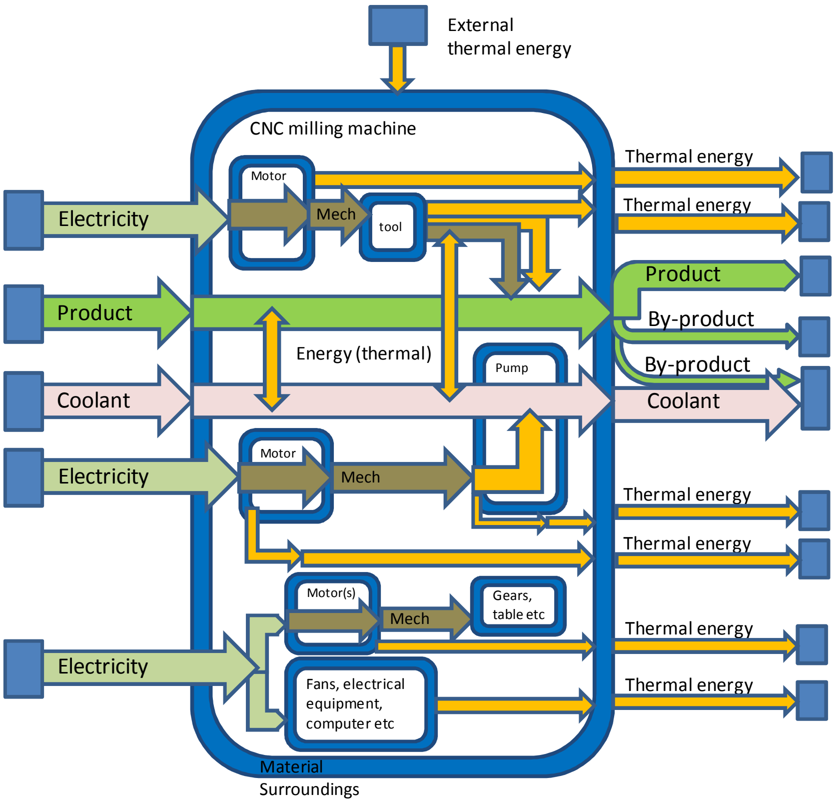


Figure 4-8 - Micro level representation of a CNC milling machine

Figure 4-9 is an example of a manufacturing process and its equipment. The block flow diagram connects graphical models of a drying tank, a fan and a heat exchanger (HX).

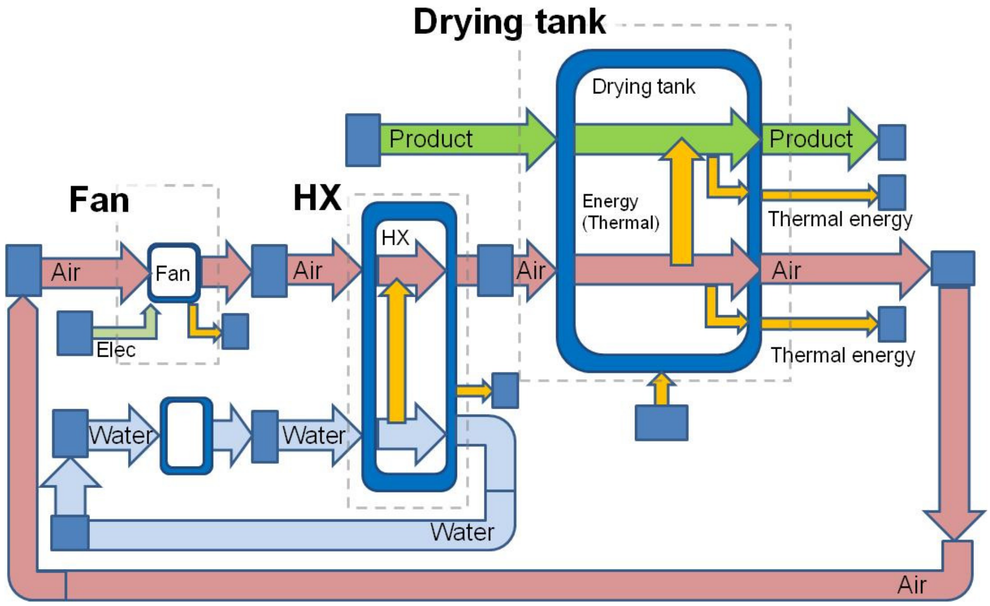


Figure 4-9 - Graphical representation of a drying tank and its subsequent equipment

Product (material to be dried) passes through the drying tank. Air is drawn through the fan. Thermal energy is transferred to the air from the fan and the heat exchanger before entering the drying tank. The product is dried, and the process is repeated. Latent heat transfer will occur during the transfer and drying of the material to its surroundings. A proportion of the air from the drying tank is re-circulated back into the incoming air stream. For clarity, the properties of the materials and energy have not been included within the figure. Energy carriers air and water are assigned properties such as temperature, volumetric flow rate, humidity ratio (air), enthalpy, mass etc. Similar properties are also assigned to material (product) flowing through the drying tank.

4.2. *Modelling approach*

Conceptual modelling is about moving from a problem situation, through model requirements to a definition of what is going to be modelled and how (Robinson 2006). Section 4.2.1 considers energy flow paths that occur within a typical built environment. Energy flow paths to and from manufacturing process systems are discussed in the form of, thermal and electrical process and material flow in section 4.2.2. Section 4.2.3 integrates energy flows from within a built environment with those from manufacturing process systems and material, resulting in an integrated approach to representing energy flow paths within a factory environment. An example of a process within a factory environment is shown in section 4.2.4.

4.2.1. Built environment

The energy flow paths in a typical built environment, such as office, residential etc are illustrated in Figure 4-10.

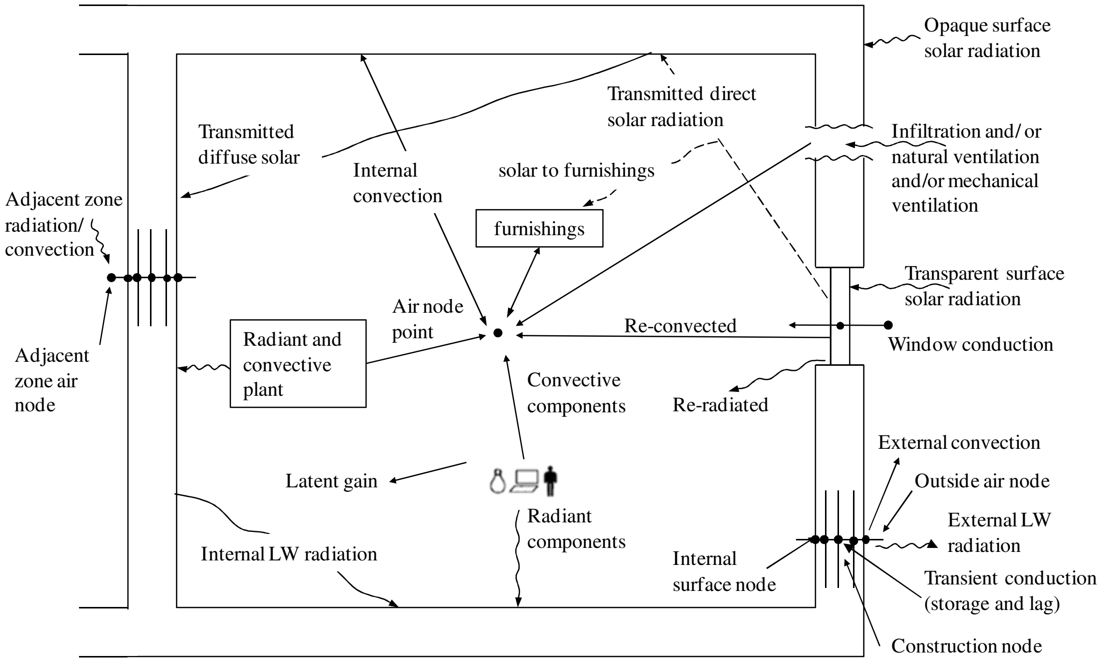


Figure 4-10 – Schematic of the built environment energy flow paths (adapted from (Clarke 2001))

Figure 4-10 illustrates a bulk air flow approach to modelling energy flow paths within a built environment, see section 2.3.2 for other methods. A bulk air flow model calculates the properties of air at a single air mass node per zone (e.g. temperature and humidity) (Wright et al. 2012). The air is considered to be fully mixed and is directly influenced by convective heat transfer. The equation for the heat balance of a single interior air mass node is shown below (Kalagasidis 2002):

$$\rho_{air} \cdot c_{p,air} \cdot V \frac{dT_{air,in}}{dt} = Q_{vent} + Q_{htg,c\lg} + Q_{conv,\text{int}} + Q_{conv,\text{int}\_surf\_zone}$$

Equation 4-1

Where, ρ_{air} is density of air (kg/m³), $c_{p,air}$ is specific heat capacity of air (J/kg.K), V is volume of air (m³), $T_{air,in}$ thermal zone dry bulb air temperature (K), t is time (s), Q_{vent} is ventilation convection (W), $Q_{htg,c\lg}$ is internal convective gains/losses from space heating and cooling plant (W), $Q_{conv,source}$ is internal convective gains (e.g. occupants, artificial lighting) (W) and $Q_{conv,\text{int}\_surf\_zone}$ is convective heat transfer from internal walls (W).

The equation is expanded to:

$$\rho_{air} \cdot c_{p,air} \cdot V \frac{dT_{air,in}}{dt} = \left[\rho_{air} c_{p,air} \cdot q_{air} \cdot \left(T_{air,out} - T_{air,in}\right)\right]_{vent} + \left[\rho_{air} c_{p,air} \cdot V_{zone} \cdot \left(\frac{T_{ctl,} - T_{air,in}}{dt}\right)\right]_{htg,c\lg}$$
$$+ \left[q_{occ} + q_{lights} + q_n\right]_{conv,\text{int}} + \left[\sum_i^n h_c \cdot A_i \cdot \left(T_{surface} - T_{air,in}\right)\right]_{conv,\text{int}\_surf\_zone}$$

Equation 4-2

Where, q_{air} is volumetric flow rate of air (m³/s), $T_{air,out}$ is outside dry bulb air temperature (K), V_{zone} volume of the zone (m^3), $T_{ctl,}$ temperature set-point of the heating or cooling control (K), $q_{occ,lights,...n}$ is internal convective gains (e.g. occupants, artificial lighting etc) (W), h_c is the surface convective heat transfer coefficient (W/m².K), A is internal surface area (m²) and $T_{surface}$ is internal surface temperature (K).

The four bracketed terms on the right hand side of Equation 4-2 are heat gains/losses for, intentional or unintentional ventilation, space heating or cooling, internal convective gains and internal wall surfaces of the thermal zone, respectively. Internal convective sources consist of internal gains such as people, lighting and equipment. Convective and radiant heat transfers occur at internal and external construction surfaces. Radiation heat transfers are in the form of short and long wave radiation exchanges between internal and external surfaces and from other sources. Mathematical expression for the area weighted average of the net rate of radiation per surface area of an internal construction (e.g. wall, floor, ceiling etc) in linearized form is shown below (Kalagasidis 2002):

$$\dot{Q}_{rad,\text{int},surface} = \left[\frac{Q_{rad,sourced} + \left[\sum_i^n h_{ri} \cdot A_i \cdot T_i\right]_{\text{int,surface}}}{\sum_i^n A_{\text{int},surface}}\right] - \left[h_r \cdot T\right]_{\text{int,surface}}$$

Equation 4-3

Where, $\dot{Q}_{rad,\text{int},surface}$ is the net radiation flux from a surface (W/m²), $Q_{rad,sourced}$ is the radiation from internal components (W), $\sum A_{\text{int},surface}$ is the sum of areas of total internal surfaces (m²), $T_{\text{int,surface}}$ is the temperature of internal surfaces of the thermal zone (K) and h_r is the long wave radiation heat transfer coefficients (W/m².K). Note h_r is only valid for moderate temperature differences. This is addressed in Equation 5-3 for increased temperature differences, as can be found in manufacturing environments.

The first bracket terms absorbed radiation from all internal construction surfaces and radiation from internal components (e.g. plant and internal gains) and through glazed constructions, over a defined surface area. The second bracketed term calculates re-radiated heat transfer from the surface. For area weighted average of the net rate of radiation per surface area for glazed constructions see Kalagasidis (2002). The net heat flux for an internal opaque surface is shown below (Kalagasidis 2002):

$$Q_{\text{int},opaque\_surface} = A_{\text{int},surface} \cdot \dot{Q}_{rad,\text{int},surface} + Q_{conv,\text{int}\_surf}$$

Equation 4-4

Where, $Q_{\text{int},opaque\_surface}$ is the net heat flux for an internal opaque (W) and Q_{conv,int_surf} is the convective heat transfer from the internal wall (W). The other terms are defined in Equation 4-1 to Equation 4-3.

For convective and radiant heat transfers at external surfaces, see Kalagasidis (2002) and Incropera, DeWitt et al. (2006). Heat transfer via conduction at boundary and internal walls influence construction surface temperatures. For a homogenous construction, one dimensional steady state heat transfer by conduction is expressed below (Incropera et al. 2006):

$$Q_x = -k\frac{dT}{dX}$$

Equation 4-5

Where, Q_x is the heat flux in the X direction (W/m²), $-k$ is the construction property thermal conductivity (W/m.K) and T is temperature (K) (Incropera et al. 2006; CIBSE 2006a). A transient approach to calculating heat transfer via conduction is commonly applied in building modelling tools. A finite difference approach is one method, where a material is segmented into nodes across the plane of the material. The effects of heat transfer through the material is calculated at each node (Incropera et al. 2006).

4.2.2. Production system

There are a range of typologies and taxonomies of manufacturing processes (DeGarmo et al. 2003; CO_2PE 2012) that are used in industry (ONS 2012). Robinson (2006), states that a conceptual model is a simplified representation of a real system. This research focuses on manufacturing processes in two forms, thermal and electrical, explained below. Energy transformations occurring at a material level discussed in section 2.4.3 (e.g. breaking of atomic bonds, chemical reaction) are currently outside the scope of this work with exception of thermal energy flows to and from a material (product).

4.2.2.1. Thermal manufacturing process

A thermal process can be considered as an extension of a thermal zone (e.g. a room), as defined in dynamic building modelling tools, Figure 4-10. Two thermal processes are considered, volumes containing gases (including air) and liquid. A manufacturing process system such as an oven, furnace etc can be considered to resemble a gas based thermal process. Whereas a liquid container represents a bath, tank, vat etc. The main difference between volumes containing gases (including air), and liquids arise due to different physical properties, specific heat capacity, density etc. Evaporation losses from open liquid surfaces and steam generation may occur. The transfer of moisture from manufacturing processes to the surrounding air is considered outside the scope of this work. Depending on the level of granularity of a model, a thermal process may include all of the energy interactions illustrated in Figure 4-10 and mathematically expressed in Equation 4-2 to Equation 4-5. Heat transfers within a thermal process are dependent upon the nature of the process. Figure 4-11 illustrates energy flows paths within a thermal process.

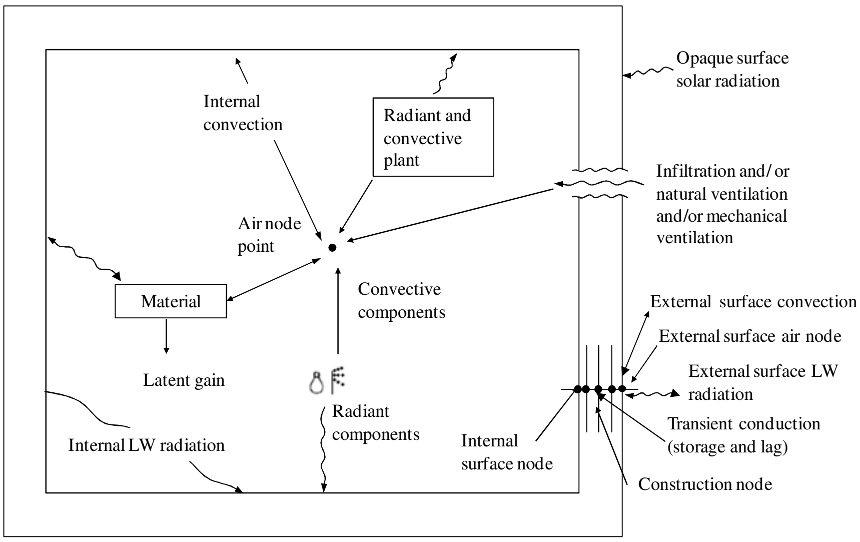


Figure 4-11 - Schematic of the internal energy flow paths within a thermal process

A thermal process may be located and operated in an enclosed environment such as a factory, or externally and directly affected by climatic weather conditions. For indoor thermal processes, heat transfers at the boundary surfaces are calculated using Equation 4-4. External thermal processes are similar to large thermal zones, where external surfaces are directly affected by dynamically changing weather conditions, Figure 4-10

4.2.2.2. Electrical manufacturing process

Energy flows from an electrical process are often in the form of radiation and convection heat transfers. For example, an electric motor will emit thermal energy to its surroundings. This is mainly as a result of inefficiencies of the motor, emitting radiation and transferring convective heat transfer from the outer surface of the motor casing. The total thermal energy from an electrical process to its surrounding environment can be written as:

$$Q_{th\_elec\_process} = Q_{rad,elec\_process} + Q_{conv,elec\_process}$$

Equation 4-6

Where, $Q_{th\_elec\_process}$ is the total thermal energy transfer from an electrical process to its surrounding environment (W), $Q_{rad,elec\_process}$ is the radiant proportion of heat transfer from an electrical process to its surrounding environment (W) and $Q_{conv,ele\_process}$ is the convective proportion of heat transfer from an electrical process to its surrounding environment (W).

4.2.2.3. Material (product)

Heat transfers from the flow of material (product) are considered. Materials that flow through manufacturing process systems, but are not considered as energy carriers may still contain significant amounts of thermal energy. The amount of energy absorbed or released is related to the materials temperature, geometry and construction properties e.g. emissivity, absorption, specific heat capacity, thermal mass etc. The thermal energy flow interactions to and from a product (materials) and its surrounding environment are illustrated in Figure 4-12.

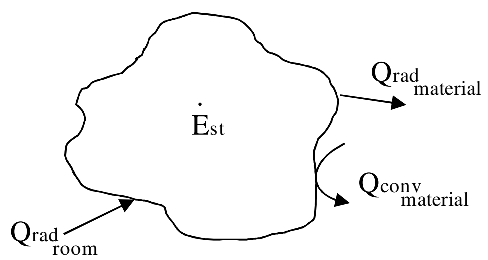


Figure 4-12 - Schematic of a material (product) energy flow paths

The lumped capacitance method has been used to express the mathematical approximation of a material (product) increasing and decreasing in temperature in relation to its stored energy, long wave radiation to and from its surrounding environment and convective heat transfer, below (Incropera et al. 2006):

$$[-(Q_{conv_{material}} + Q_{rad_{material}}) + Q_{rad_{room}}]A_s = \rho V c_p \frac{dT}{dt}$$

Equation 4-7

Where, $Q_{conv_{material}}$ is the net convective heat transfer of energy per surface area of the material to its surroundings (W/m^2), $Q_{rad_{material}}$ is the long wave radiative heat transfer of energy per surface area of the material to its surroundings (W/m^2), $Q_{rad_{room}}$ is the long wave radiative heat transfer per area from the thermal zone to the material (W/m^2), A_s is the surface area of the material (m^2), ρ is the density of the material (kg/m^3), V is the volume of the material (m^3), c_p is the specific heat capacity of the material (J/kg.K) and T is the homogenous temperature of the material in relation to time (K/s).

Equation 4-7 may be expressed as:

$$\int_{T_i}^{T} dT = T(t) - T_i = \frac{1}{\rho c_p L_c} \int_0^t \left((Q_{conv_{material}} + Q_{rad_{material}}) - Q_{rad_{room}} \right) dt$$

Equation 4-8

Where, L_c is the characteristic length ratio of a materials solid volume to surface area $L_c = \frac{V}{A_s}$ and $T(t)$ and T_i is the homogenous temperature of the material in relation to time (K/s) at the current and initial time states.

The convective and radiant heat transfer from the material (product) to its surrounding environment can be approximated in a similar way to a construction material as expressed in Equation 4-4.

4.2.3. Integrated factory approach

Figure 4-13 couples energy flow paths from within a built environment with those from manufacturing process systems and material, resulting in an integrated approach to representing energy flows within a factory environment.

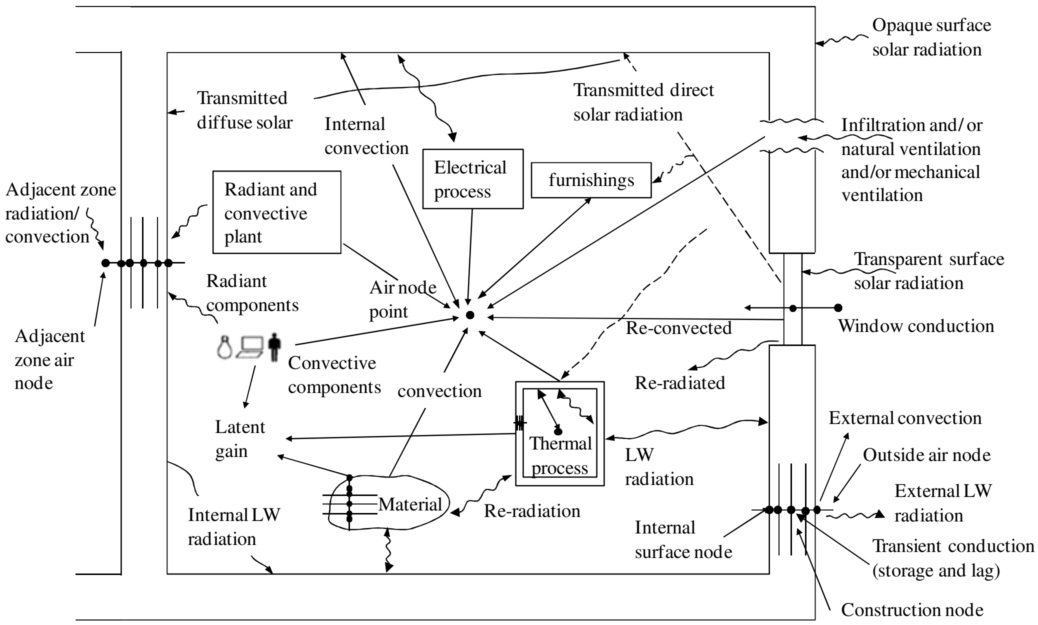


Figure 4-13 - Schematic of the overall energy flow paths of a factory environment

Extending Equation 4-1 the heat balance of a single interior air mass node per integrated factory zone is derived from the above work to:

$$\rho_{air} \cdot c_{p,air} \cdot V \frac{\partial T}{\partial t} = Q_{vent} + Q_{htg,c\lg} + Q_{conv,source} + Q_{conv,\mathrm{int}\_surf\_zone} + Q_{conv,surf\_th\_process} + Q_{conv,elec\_process} + Q_{conv\_material}$$

Equation 4-9

Where, $Q_{conv,surf\_th\_process}$ is the convective heat transfer from the boundary surface of a thermal process (W), $Q_{conv,ele\_process}$ is the convective proportion of heat transfer from an electrical process to its surrounding environment (W) and $Q_{conv\_material}$ is the convective heat transfer from the material (product) (W). The other terms are defined in Equation 4-1 to Equation 4-8. The three additional terms represent the convective heat transfer from thermal and electrical processes and material flow, respectively.

The area weighted average of the net rate of radiation per surface area for the internal surfaces of the integrated factory zone can be extended from Equation 4-3. The radiative component from the thermal and electrical processes and material flow can be coupled with the internal radiative gain component of the equation:

$$\dot{Q}_{rad,\text{int},surface} = \left[\frac{[Q_{rad}]_{\text{int}\_gains,process,material} + \left[\sum_i^n h_{ri} \cdot A_i \cdot T_i\right]_{\text{int,surface}}}{\sum_i^n A_{\text{int},surface}} \right] - [h_r \cdot T]_{\text{int,surface}}$$

Equation 4-10

Where, $[Q_{rad}]_{\text{int}\_gain,process,material}$ is the radiation from internal components, thermal and electrical processes and material flow (W). The other terms are defined in Equation 4-3.

4.2.4. Process within the factory environment

Figure 4-14 expands the graphical representation of the drying tank model shown in Figure 4-9 by linking the manufacturing process to its surrounding environment (i.e. factory building). The interactions of energy flows from the building fabric (convection and radiation), material flow, inefficiencies of the fan and generated heat flux from the fabric construction (wall) of the drying tank are coupled together. Radiation and convection energy flows are represented in Figure 4-14 as faded directional orange arrows. The arrows are faded to enhance clarity of the figure.

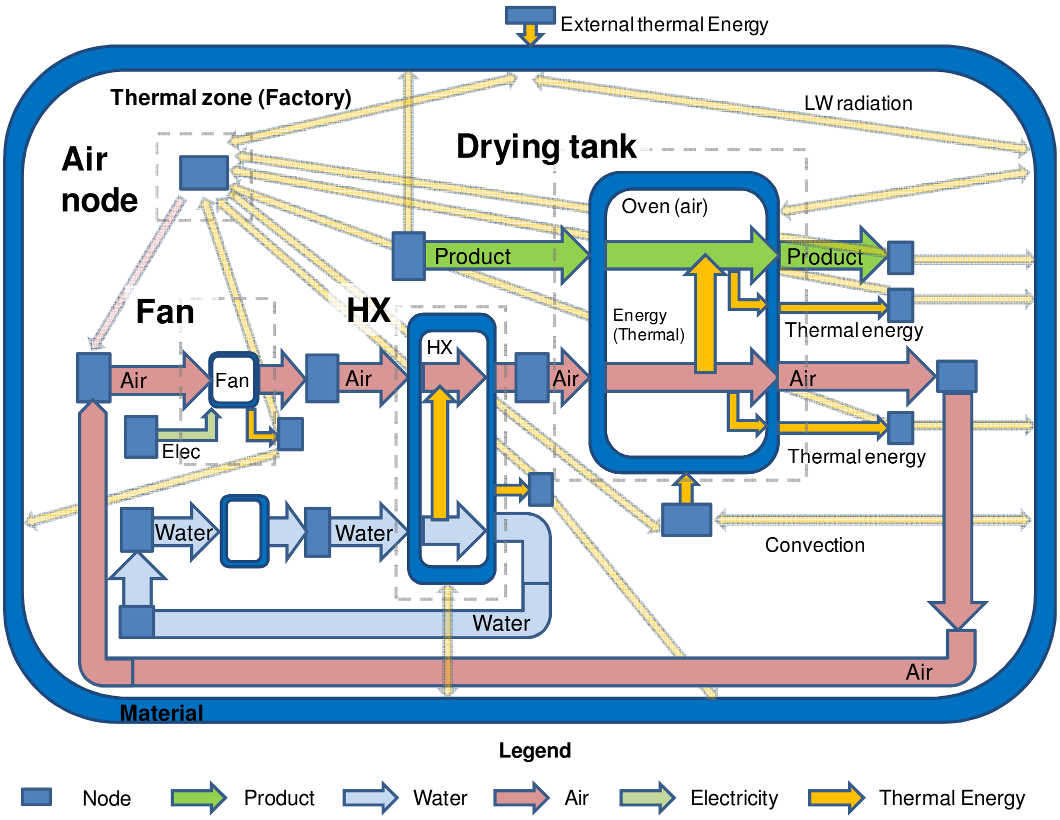


Figure 4-14 – Graphical representation of a drying tank and its subsequent equipment coupled to its location (factory environment) (Oates et al. 2011b)

5. Model design

This chapter outlines the development of an integrated software tool in line with the research methods, chapter 3. The integrated software tool builds on the conceptual modelling framework, chapter 4. Section 5.1 identifies an existing building modelling tool, the International Building Physics Toolbox (IBPT). Section 5.2 extends the framework of the existing toolbox to include the modelling of factory energy flows between the built environment, manufacturing process systems and material flow within the adapted IBPT. In section 5.3, software verification is used to compare the existing and adapted IBPT against the commercially validated building modelling tool, Integrated Environmental Solutions Virtual Environment (IES VE), in comparable areas of building physics.

5.1. *Existing building modelling tool*

5.1.1. International Building Physics Toolbox (IBPT)

The International Building Physics Toolbox (IBPT) is a building modelling tool (IBPT 2012) developed in the Matlab/Simulink environment and operates under the open source license for free software for Europe (FSFE 2012). The IBPT is a collaborative approach by the Department of Civil Engineering at the Technical University of Denmark and the Department of Building physics, at the Chalmers University of Technology in Sweden. The building physics toolbox unique library of software packages relates to the basic building components, e.g. layered wall structures with material data, boundary and surface conditions, ventilated space, windows, heat sources, HVAC components, etc (Rode et al. 2002). The initial collaborative approach concentrated on the heat transfer within a building only and produced a software called H-Tool. The project further developed the toolbox into a library of building blocks capable of modelling heat, air and moisture within a building, named HAM-Tool. For the purpose of this research, the author has used the H-Tool version due to its reduced complexity and simulation time. The H-Tool and HAM-Tool are structured on the same input and output data array structure, therefore work initiated in this research should be compatible with the HAM-Toolbox if required in the future. The toolbox is clearly documented, well structured and in a software package that requires little knowledge of computer programming. References made throughout this work to the IBPT are to be considered as the H-Tool version of the IBPT building modelling tools.

5.1.2. IBPT structure

The IBPT is capable of modelling a single thermal zone. The IBPT is based around five library blocks (Kalagasidis 2002):

- constructions (e.g. walls and windows)
- zones (e.g. single thermal zone)
- systems (e.g. HVAC systems)
- helpers (e.g. handling of weather data)
- gains (e.g. internal heat gains)

The IBPT dynamically transfers data around the block flow model within the Simulink environment. Data is transferred via a set of seven data arrays: surface weather data, construction, system, geometry, zone, radiation and gain (Kalagasidis 2002). The physics of the model are formulised at subsystem level within the library blocks, and then processed to the high level structured array and passed to the next phase in the flow. Due to the nature of the block flow environment in Simulink, the user is able to follow the flow of data through the model. Figure 5-1 is an example of data being transferred via data arrays, between the construction and zone library blocks.

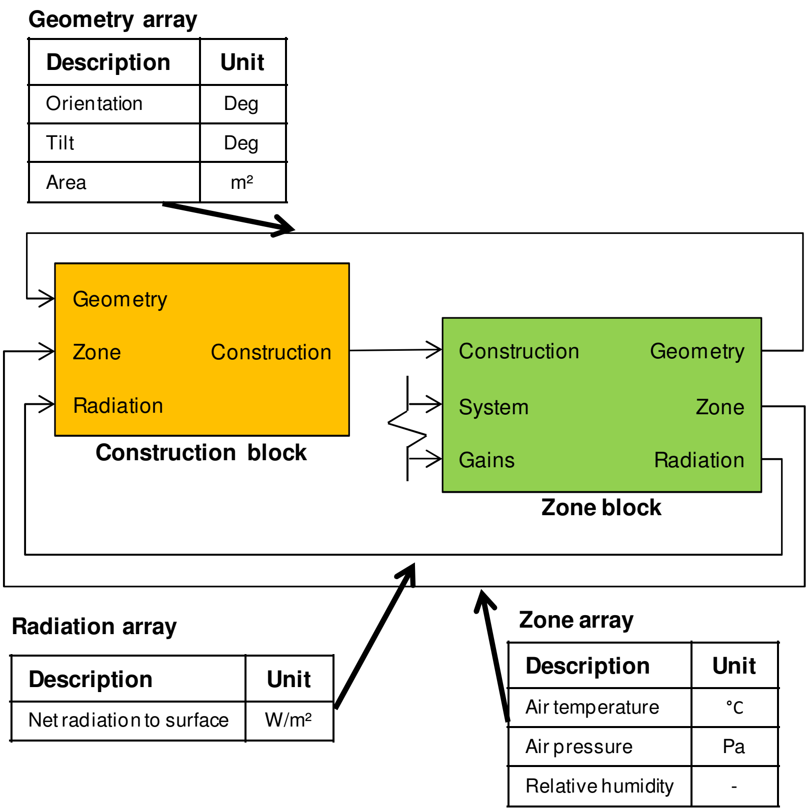


Figure 5-1 – IBPT transfer of data between library blocks

Figure 5-2 illustrates a single thermal zone modelled within the Matlab/Simulink environment using the IBPT library blocks. The construction box (orange) is shown on the left side of the figure. Construction blocks consist of wall, floor, roof and glazing construction elements. Construction properties are used to calculate the energy balance of the construction elements.

The zone block (green box) within the figure brings together the seven data arrays. The bulk air flow model calculates the properties of air at a single air mass node per zone (i.e. dry bulb air temperature, relative humidity and pressure) within the green zone block. System and gains blocks are shown in blue. The weather file block does not directly connect to the other library blocks. Data is transferred via signal routers to the appropriate positions within the model (e.g. external dry bulb air temperature data is sent via a signal router to the external surface of the construction elements).

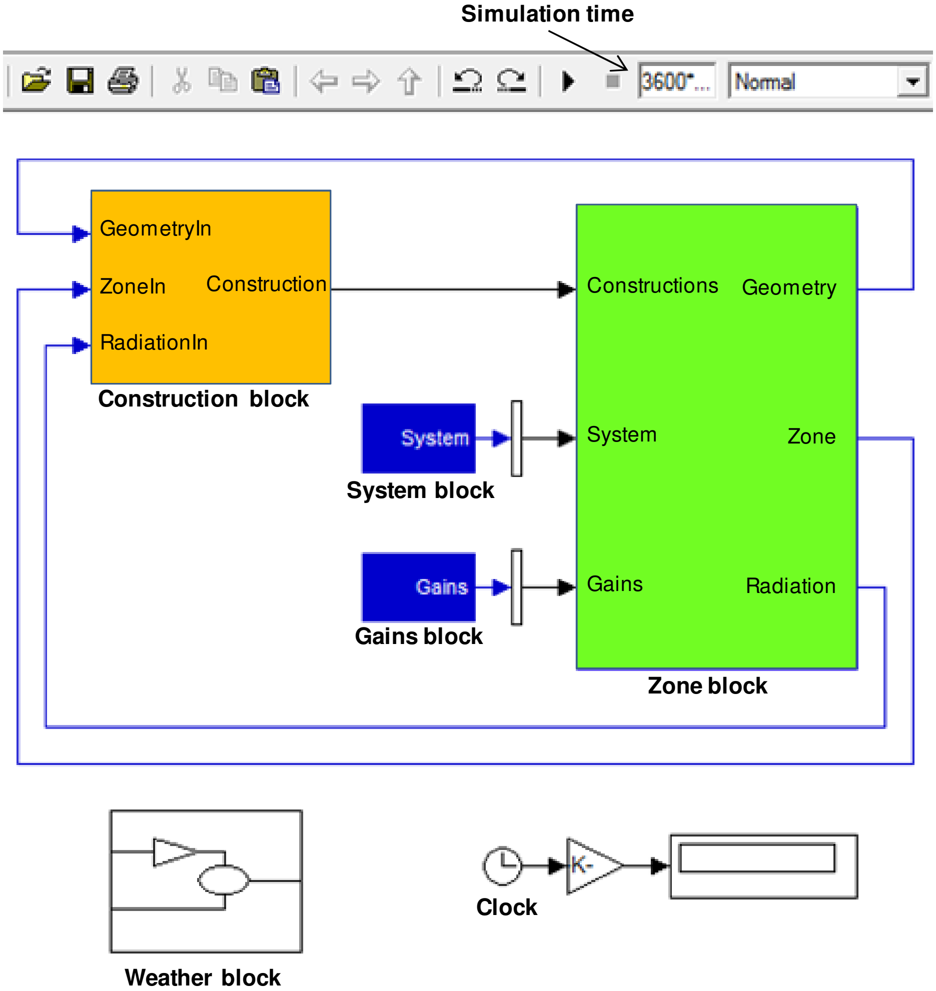


Figure 5-2 – IBPT structure and graphical user interface

Further information on the mathematical framework and block flow structure used by the IBPT can be found in the H-Tools IBPT Block Documentation report (Kalagasidis 2002).

5.2. *Adapted IBPT tool*

The IBPT is capable of modelling energy flow paths within a single thermal zone. In order for the IBPT to model energy flows within a factory environment as illustrated in Figure 4-13, the existing IBPT has been modified to include the modelling of: internal thermal zones, manufacturing process systems (thermal and electrical) and material flow. Changes to the existing IBPT have been made to create the ‘Adapted IBPT’, incorporating functions that are outside the scope and capabilities of current building modelling tools. These changes have been recorded in a user manual, Appendix C (material provided on a CD). A brief summary of the main changes to the existing IBPT are discussed below.

5.2.1. Extension of the thermal model

The adaptation of the toolbox to model internal thermal zones within a larger surrounding thermal zone (i.e. zone inside a zone approach), enables the toolbox to be used to model volumetric thermal manufacturing processes (e.g. furnace, drying tanks, treatment baths) that reside inside a factory building. Long wave radiation between boundary surfaces of the factory, manufacturing processes and material are included. Convective heat transfers from these surfaces to the central air node are also included. Modifications to the structured data array of the existing IBPT is an important aspect of the work, ensuring transferability, compatibility and communication between the original Simulink blocks and future developed blocks. These changes have been recorded in Appendix C (i.e. material provided on a CD).

5.2.2. Exterior surface convective heat transfer coefficient

Simulation accuracy has been improved by modifying the way that the exterior surface convective heat transfer coefficient are used within the IBPT model to calculate the convective heat gains/losses at the exterior surface of a building construction element. Originally the toolbox required a constant input value of 3W/m^{2}K. The adapted toolbox has been revised to the same formulation as used by IES VE. The exterior surface convective heat transfer coefficient is linked to external wind speed, based on the McAdams empirical equation (IES 2012b):

$$\mathrm{h_c} = 5.6 + 4.0\mathrm{v} \qquad (\mathrm{v} < 4.88)$$

Equation 5-1

$$\mathrm{h_c} = 7.2\mathrm{v}^{0.78} \qquad (\mathrm{v} \geq 4.88)$$

Equation 5-2

Where, h_c is the exterior surface convective heat transfer coefficient (W/m^2.K) and v is the wind speed (m/s).

5.2.3. Internal long wave radiation heat transfer coefficient

The existing IBPT distributes internal long wave radiation via average area weighting to all internal surfaces. This is just one method, IES VE uses view factors (IES, 2011b), which are considered more accurate, but require complex mathematical algorithms and increased simulation time (depending on programming language). The IBPT internal long wave radiation heat transfer coefficients are based on a constant value of 5W/m²K. This constant assumes all materials within a thermal zone are of similar construction and properties. Due to the variability of construction materials used within manufacturing industry, an algorithm approach has been used, similar to that used for the external construction surface node (Kalagasidis 2002). It is assumed that the sum of absorbed and transmitted radiation (the latter only for short wave radiation through the glazing) per unit of surface area is equal for each surface. As each surface also emits radiation, the net rate of radiation per surface area of an internal construction (e.g. wall, floor, ceiling etc) is shown below:

$$\dot{Q}_{rad,\text{int},surface} = \left[\frac{\left[Q_{rad}\right]_{\text{int\_}gains,process,material} + \left[\sum_i^n A_i \cdot \varepsilon\sigma \cdot T_i^4\right]_{\text{int,surface}}}{\sum_i^n A_{\text{int},surface}} \right] - \left[\varepsilon\sigma \cdot T^4\right]_{\text{int,surface}}$$

Equation 5-3

Where, T is the temperature of internal surface of the thermal zone (K^4), ε is surface emissivity (dimensionless) and σ is the Stefan-Boltzmann constant ($5.67.10^{-8}$ $W/m^2.K^4$). The other terms are defined in Equation 4-10. The first bracket terms absorbed radiation from all internal construction surfaces and radiation from internal components (e.g. plant and internal gains) and through glazed constructions, over a defined surface area. The second bracketed term calculates re-radiated heat transfer from the surface. For net rate of radiant heat transfers at external surfaces, see Kalagasidis (2002) and Incropera, DeWitt et al. (2006). See Appendix C (i.e. material provided on a CD) for the mathematical framework and block flow structure used by the adapted IBPT.

5.2.4. Material (product) flow

The modelling of material is based on the lumped capacitance method, section 4.2.2. This approach approximates a material increasing and decreasing in temperature in relation to its stored energy, long wave radiation to and from its surrounding environment and convective heat transfer. At present, material is modelled within the adapted IBPT using a deterministic time variant profile. The mathematical framework and block flow structure used by the adapted IBPT can be found in the Appendix C (i.e. material provided on a CD).

5.2.5. Manufacturing process systems

Manufacturing processes are considered in two forms, thermal and electrical. Thermal processes are modelled as an extension of a thermal zone, either as standalone or internal process. Thermal processes can be modelled as gas (including air) or liquid, the main differences arise due to different physical properties such as, specific heat capacity, density etc.

At present thermal energy transferred from an electrical process to its surroundings are modelled in the form of convective and radiant heat transfers, section 4.2.2. This approach does not however account for modelling in detail of surface temperatures and reciprocal heat transfers to and from the surrounding environment, as is in the case when modelling thermal processes. Material level energy transformations discussed in section 2.4.3 are currently considered outside the scope of this work with exception to thermal energy flows to and from a material. The block flow environment of Simulink enables a user to extend the framework of the thermal and electrical processes to include modelling of manufacturing plant at both macro and micro levels. Examples are given in the case studies in chapter 6.

5.3. *Tool verification*

Due to the novel approach of the research it is difficult to validate a new simulation tool as in the adaption of the IBPT to model an integrated approach that combines building, manufacturing process systems and material energy flows. Some fundamental changes to the adapted IBPT are within the modelling capabilities of existing building modelling tools (i.e. the modelling of thermal zones within a larger thermal zone). This section compares results simulated within the existing IBPT and the adapted IBPT against the commercially used and validated (IES 2012c) building modelling tool, IES VE, version 6.4. A selection of scenarios have been chosen and simulated, testing the accuracy of the tools in response to external climatic conditions that are both controlled and weather driven, see Table 5-2. Controlled means that the dry bulb temperature of the air that surrounds the factory is controlled via a time variant profile. Long wave and short wave solar radiation is excluded in the controlled models. This approach tests the thermal response of the model against changes in surrounding air temperature only. A weather driven scenario includes both air temperature and solar radiative effects. Capabilities that are currently outside the scope of existing building modelling tools (i.e. modelling of liquid tanks and material flow), and modelled using the adapted IBPT are validated against simulated case studies, chapter 6. The approach of this work has taken the IBPT, a standard building modelling tool and adapted it to include modelling of manufacturing process systems and material. The development of the adapted IBPT is therefore reliant upon the accuracy and validity of the original IBPT. The following sections cover software verification between:

- Section 5.4 - original IBPT vs. IES VE (large factory zone only)
- Section 5.5 – adapted IBPT vs. IES VE (one internal thermal zone)
- Section 5.6 – adapted IBPT vs. IES VE (six internal thermal zones)

5.3.1. Simulation inputs

The following section outlines data and information input into the simulated modelled scenarios discussed in sections 5.4, 5.5 and 5.6.

5.3.2. Weather

The London Heathrow weather file 96-97 extracted from the IES VE software has been used for all of the scenarios modelled within the tool verification section.

5.3.3. Dimensions

Each scenario includes a factory building, dimensions (H/L/W) 19m, 120m and 51m. Some models include windows at a percentage ratio of 10% per vertical walled surface area. The length of the building is oriented along the North axis, Figure 5-3.

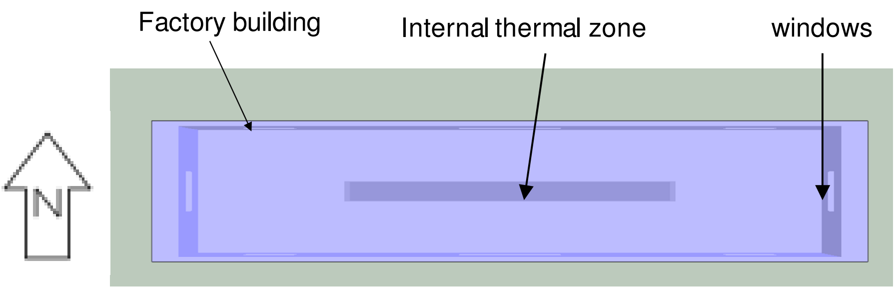


Figure 5-3 – Orientation plan of the factory building

The volume of the factory building is 116280m³, including internal thermal zones. Some modelled scenarios consist of a factory building and a number of internal zones. Each internal zone is (H/L/W) 5m, 35m and 2m. The internal zones reside inside the building, 2m above ground level with the length of the zone running across the width of the building. See Figure A-5, Figure A-12 and Figure 5-21 for examples.

5.3.4. Construction properties

Properties of construction used within the building modelling tools are shown in Table 5-1.

Table 5-1 – Construction properties

Material properties	
- Concrete	- Density 2400kg/m³, - Thermal conductivity 1.5W/m.K, - Heat capacity 800J/kg.K, - Absorptivity 0.65 - Emissivity 0.9.
- Steel	- Density 7800kg/m³, - Thermal conductivity 50W/m.K, - Heat capacity 480J/kg.K, - Absorptivity 0.7 - Emissivity 0.9.
- Glass	- Density 2500kg/m³, - Thermal conductivity 0.7W/m.K, - Heat capacity 840J/kg.K, - Emissivity 0.9

5.3.5. Modelled scenarios

Table 5-2 outlines the criteria that the modelled scenarios discussed in Sections 5.4, 5.5 and 5.6 are simulated against in the existing and adapted IBPT and IES VE.

Table 5-2 – Tool verification modelled scenarios

	Criteria * modelled as mean air temperature								
Modelled scenarios (section number, brief title)	Factory	Factory construction > 1 material	Windows	Factory floor adiabatic *	Profile driven external weather	Weather file	One internal thermal zone	> 1 internal thermal zone	Space heating
5.4 IBPT (single thermal zone)									
5.4.1 Controlled – one material	•				•				
5.4.2 Controlled – mixed material	•	•			•				
A.1 Dynamic – mixed material, mean ground temperature	•	•		*		•			
5.4.3 Dynamic – mixed material, adiabatic ground	•	•		•		•			
A.2 Dynamic – mixed material, ground adiabatic, windows	•	•	•	•		•			
5.4.4 Dynamic – mixed material, ground adiabatic, windows and heating	•	•	•	•		•			•
5.5 Adapted IBPT (Zone inside a zone)									
A.3 Controlled – one material	•				•		•		
A.4 Controlled, mixed material	•	•			•		•		
A.5 Dynamic – mixed material, ground adiabatic, windows	•	•	•	•		•	•		
5.5.1 Dynamic – mixed material, ground adiabatic, windows, heating	•	•	•	•		•	•		•
5.6 Adapted IBPT (several zones inside a zone)									
5.6.1 Dynamic – mixed material, ground adiabatic, windows	•	•	•	•		•		•	
5.6.2 Dynamic – mixed material, ground adiabatic, windows, heating	•	•	•	•		•		•	•

5.4. *IBPT (single thermal zone)*

Below are a selection of scenarios simulated in the IBPT and IES VE. Results from both building modelling approaches are compared, verifying the accuracy and capability of the original IBPT against the validated IES VE software to model first principle mathematical heat transfer equations occurring within and around a building (IES 2012b; IES 2012c). A brief explanation of each scenario can be found under each heading. IBPT models and Excel results can be found in Appendix D (material provided on a CD). A selection of scenarios can also be found in Appendix A - Tool verification:

- Appendix A.1 - Single zone (dynamic - mixed material, mean ground temperature)
- Appendix A.2 - Single zone (dynamic - mixed material, ground adiabatic and windows)

5.4.1. Single zone (controlled – one material)

The following scenario is based on a single thermal zone model. The thermal zone is considered to resemble that of a large factory building. This scenario is designed to test the thermal dynamic response of the construction properties under predefined conditions. The following environmental conditions outside of the boundary of the factory building are controlled i.e. profile driven dry bulb air temperature and omission of solar radiation. The thermal response of the building is based on air temperature differentials. To achieve this, different modelling techniques have been applied to both the existing IBPT and IES VE. Within the IBPT (Figure 5-4b), direct solar radiation to the surface of the factory building from the weather file has been blocked and set to zero. External dry bulb air temperature has been overridden by a deterministic profile i.e. 18℃ Monday to Friday (9am - 5pm), 12℃ during all other times. The simulation does not include a preconditioning period. Depending on the construction of the factory building (light and heavy weight) this may result in the factory air temperature oscillating until the models settle down. The factory building has no internal gains. External surface convection coefficients are set at 3 W/m².K, in line with the IES VE modelled approach. Figure 5-4a, illustrates a controlled environment approach within IES VE. The factory building is encapsulated in a surrounding air tight thermal zone. The properties of the external surface of the zone have been changed to an adiabatic construction, blocking solar radiation exchange between the weather file and the external surface of the factory building. The outer zone is also driven by the same air temperature profile as used in the IBPT model. IES VE models the factory building as an internal zone, though in reality this is not the case. IES VE models internal surface convection coefficients in line with CIBSE fixed values of 3W/m².K for simple heat loss and gain calculations (IES 2012b). The same value is used within the IBPT model. Both simulation models are shown in Figure 5-4 and consist of one material construction for all surfaces (i.e. walls, roof and ground).

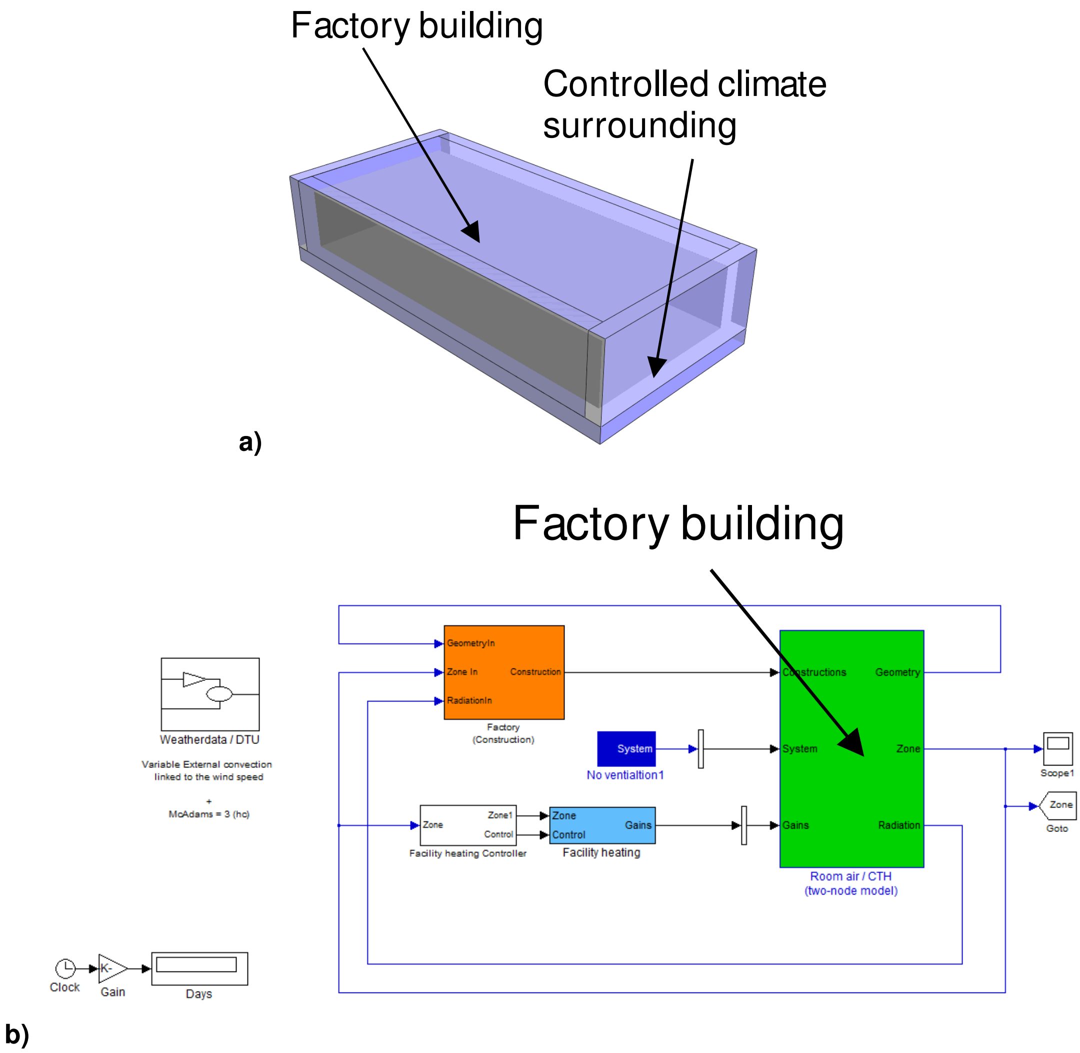


Figure 5-4 – Factory building with climate controlled surrounding zone, a) IES VE, b) IBPT

5.4.1.1. Results

Results from the simulation runs using IBPT and IES VE are shown in Figure 5-5 and Figure 5-6 for a factory building constructed from 0.2m thick concrete and 0.01m thick steel respectively for the month of 31 days. Construction properties used can be found in Table 5-1. The two models highlight the significant differences between light and heavy weight construction materials. A root mean square error (RMSE) for the IBPT has been calculated against IES VE results of 0.37°C and 1.58°C, for models using 0.2m thick concrete and 0.01m thick steel respectively.

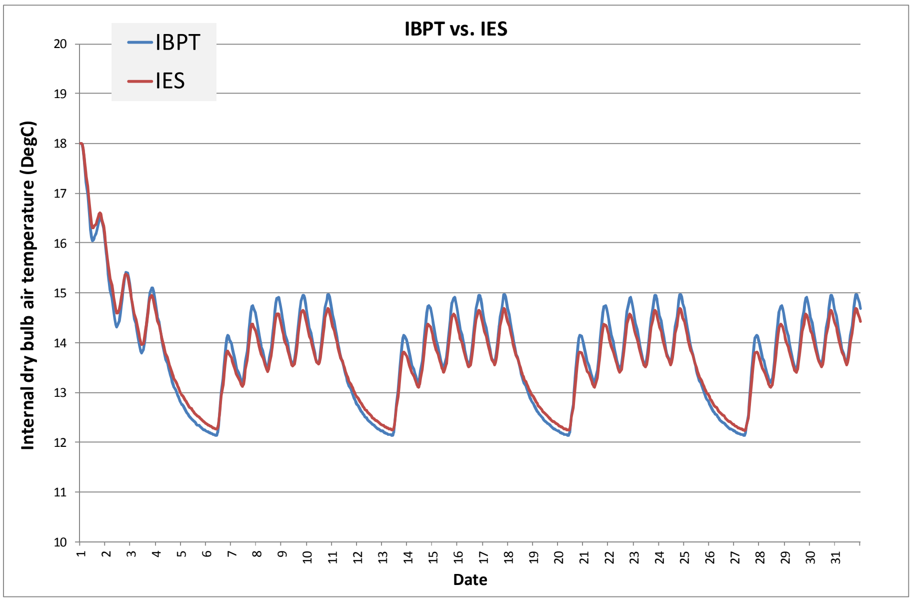


Figure 5-5 – Factory air temperature - IBPT vs. IES VE – 0.2m thick concrete (31 days)

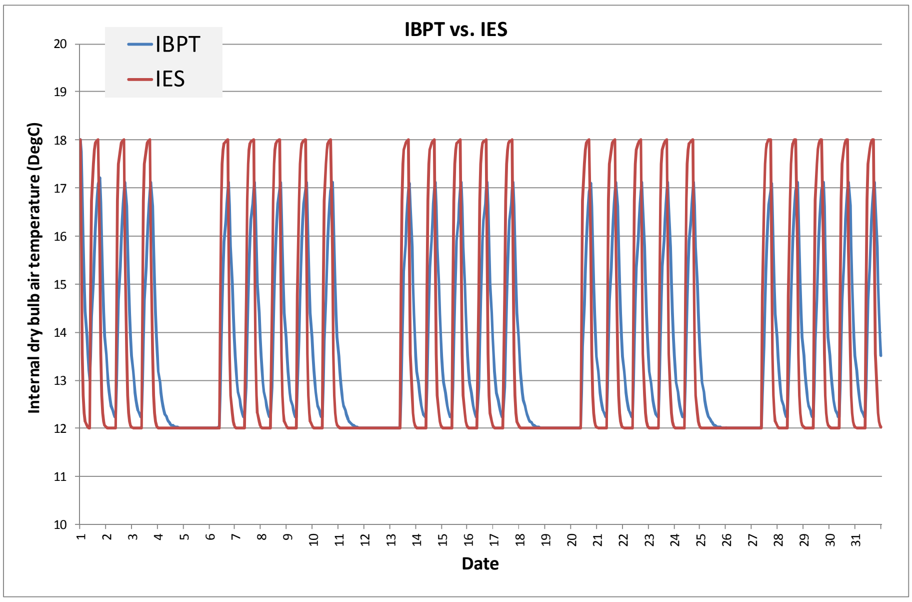


Figure 5-6 – Factory air temperature - IBPT vs. IES VE – 0.01m thick steel (31 days)

5.4.1.2. Summary

The building constructed from 0.2m thick concrete illustrates good correlation between the two modelling approaches after the initial settling down period, Figure 5-5. As discussed there is a settling down period for the factory air temperature as a result of there being no allowance for a preconditioning period, usually 10 days. In Figure 5-6 (i.e. 0.01m thick steel building) the short cyclic time step of the profile driven external climate does not seem to be responding as closely in the IBPT modelled approach. Different mathematical approaches are used by the tools. IES VE is based on a hop scotch method, a combination of the finite difference explicit and implicit time-stepping method. Whereas the IBPT uses the explicit finite difference method only (Kalagasidis 2002). Therefore the combined approach used by IES VE enables the tool to model the surface temperature and internal energy balance of construction materials more accurately, responding to quicker time step changes. Another factor may be the predetermined value of 5W/m².K used for long wave radiation coefficient within the existing IBPT. Long wave coefficients are not preset within the IES VE tool and are calculated on changes in material surface temperature and surrounding dry bulb air temperature.

5.4.2. Single zone (controlled – mixed material)

A factory building constructed from a combination of materials has been modelled. The factory building is constructed from 0.2m thick concrete for all vertical wall elements and ground floor. The roof is modelled as 0.01m thick steel. The factory building is encapsulated by a surrounding climate controlled zone, as in Figure 5-4, and is controlled by the same temperature driven profile as explained in section 5.4.1. There are no internal heat gains to the building.

5.4.2.1. Results

Results from both IBPT and IES VE for the month of 31 days are shown in Figure 5-7. The IBPT model has a RMSE of 0.40°C against the IES VE result.

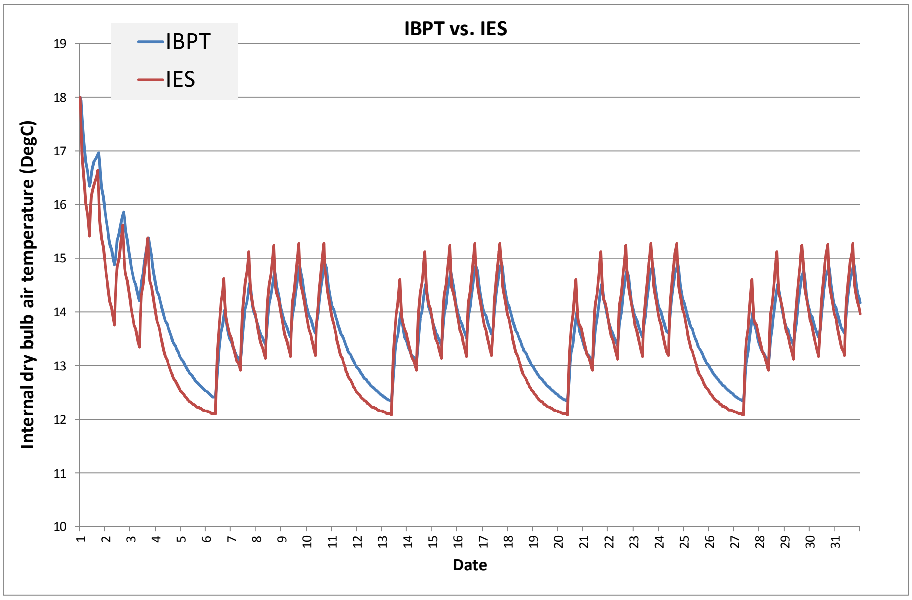


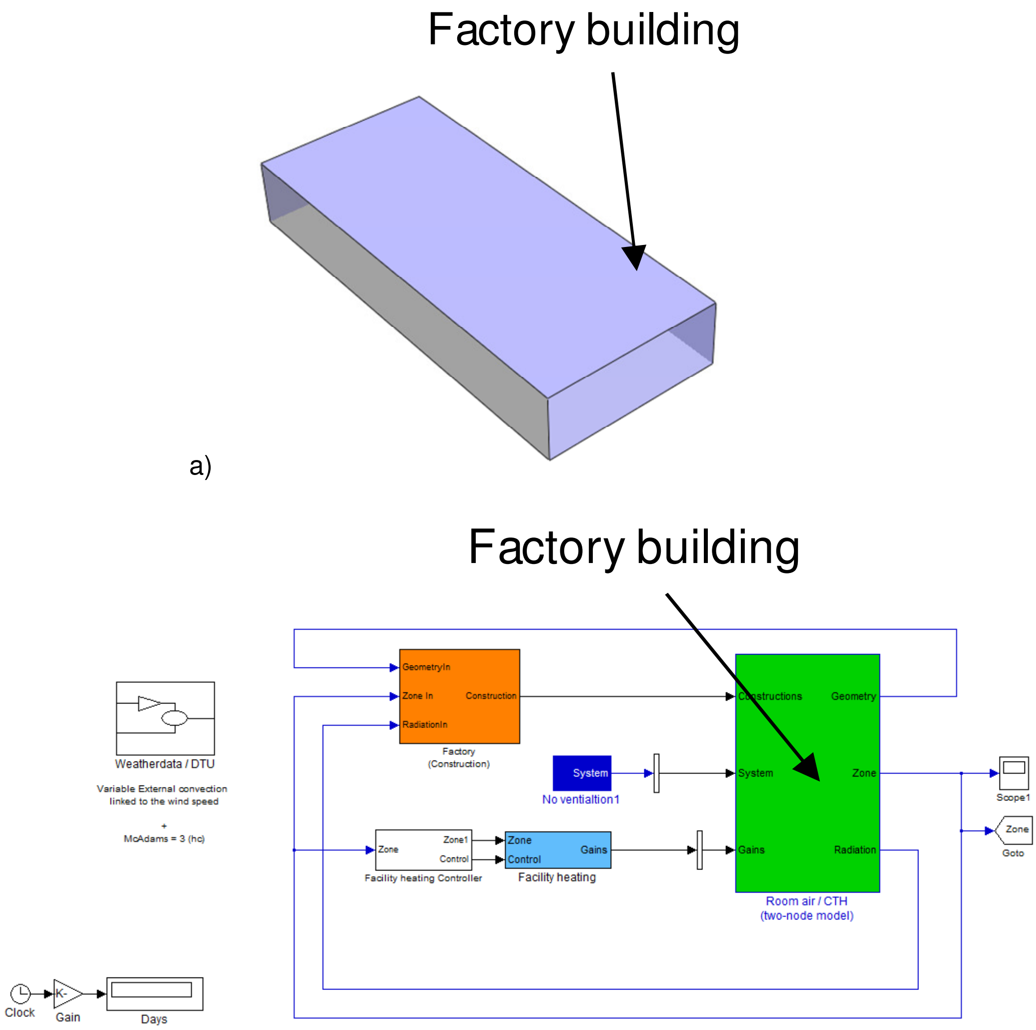
Figure 5-7 - Factory air temperature - IBPT vs. IES VE – mixed construction, 0.01m thick steel roof, all other surfaces 0.2m thick concrete (31 days)

5.4.2.2. Summary

The mixed material scenario combines both light and heavy weight constructions. The combination of the light and heavy weight constructions demonstrates a good correlation in results (Figure 5-7), averaging out the differences in the modelled approaches of the two tools used, as discussed in section 5.4.1.

5.4.3. Single zone (dynamic - mixed material, adiabatic ground)

The following scenarios are considered dynamic, driven by weather input files and do not require an outer controlled environmental zone, Figure 5-8. This model includes solar radiation and wind speed affects upon the outer surface of the building. There are no supplementary internal gains inside of the building. The IBPT has been modified to calculate a variable external surface convective heat transfer coefficient that is linked to the external wind speed from the attached weather file, section 5.2.2.



b)

Figure 5-8 - Factory building only, a) IES VE and b) IBPT

The below scenario is the same as described in Appendix *A.1 - Single zone (dynamic - mixed material, mean ground temperature)*, with the exception that the ground floor construction has been modelled as an adiabatic construction. An adiabatic construction assumes that there is no heat transfer through the material (e.g. from the soil to the internal factory environment and vice versa). The surface temperature of the ground floor material is assumed to be the same of that of the internal air temperature of the factory.

5.4.3.1. Results

Factory building dry bulb air temperature results for January and July are shown in Figure 5-9 and Figure 5-10 respectively. The IBPT model has a RMSE of 0.84°C against IES VE result.

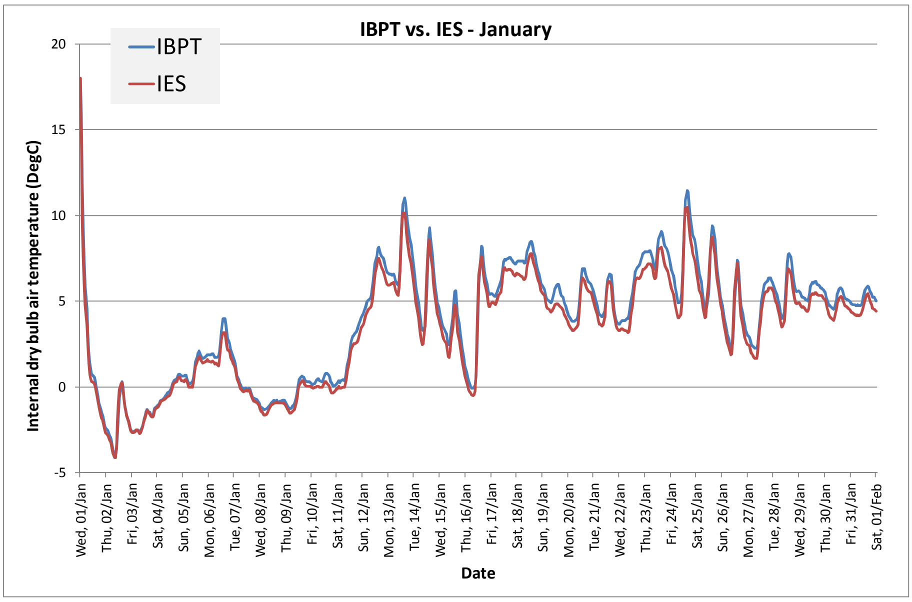


Figure 5-9 - Factory air temperature - IBPT vs. IES VE – mixed construction and adiabatic ground material (January)

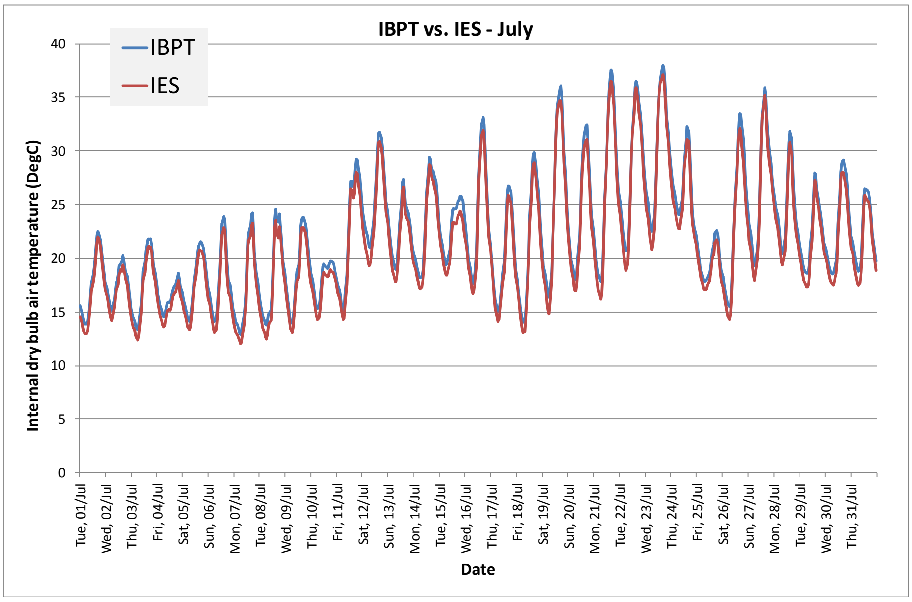


Figure 5-10 - Factory air temperature - IBPT vs. IES VE – mixed construction and adiabatic ground material (July)

5.4.3.2. Summary

From results graphed in Figure 5-9 and Figure 5-10 the adiabatic scenario produces closer matching results than the mean soil temperature scenario in Appendix *A.1 - Single zone (dynamic - mixed material, mean ground temperature)*. Future models are to be modelled on the basis that the ground floor construction is adiabatic.

5.4.4. Single zone (dynamic - mixed material, ground adiabatic, windows and heating)

The below scenario is the same approach as discussed in Appendix *A.2 - Single zone (dynamic - mixed material, ground adiabatic and windows)* with the exception that the factory building is space heated. The factory zone is heated to the following profile, from 9am till 5pm to a minimum of 18℃, Monday to Friday. At all other times the building is heated to a minimum of 12℃. The radiant fraction for the heating system is set at 0.2 (i.e. 20% radiant, 80% convective).

5.4.4.1. Results

The factory building dry bulb air temperature results for January are shown in Figure 5-11 based on a 20% radiant heating system. The graph shows good correlation and this is repeated throughout the year. The IBPT model has a RMSE of 1.06°C against IES VE result.

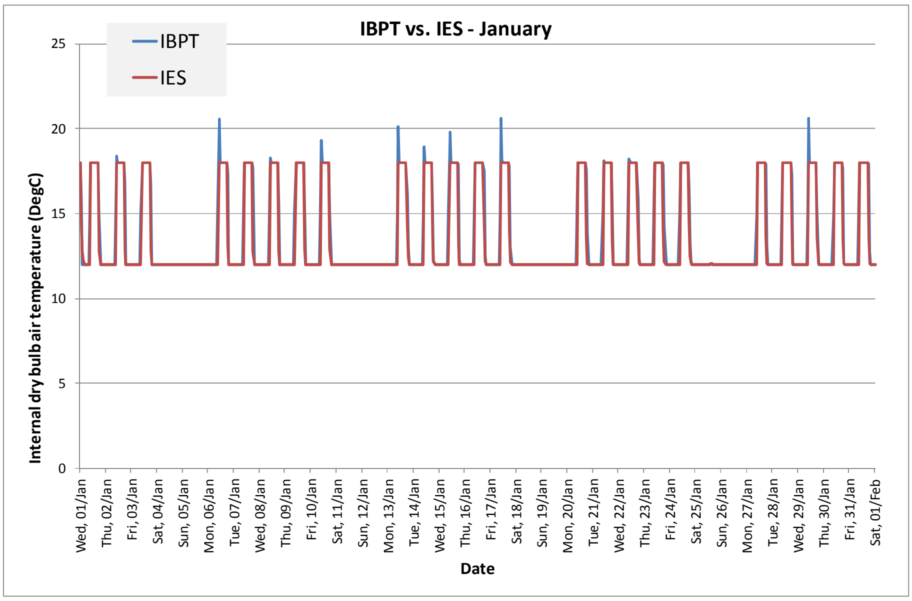


Figure 5-11 - Factory air temperature - IBPT vs. IES VE – mixed construction, adiabatic ground material, 10% percent windows and heating (January)

Figure 5-12 indicates that there is a difference between the two models when comparing the heating load requirement of the factory building. The IBPT is under estimating the demand side heating requirement for the building. Over an annual heating load, the percentage error between the two models is 26.81%, IBPT (920.08 MWh/yr) and IES VE (1257. 07 MWh/yr).

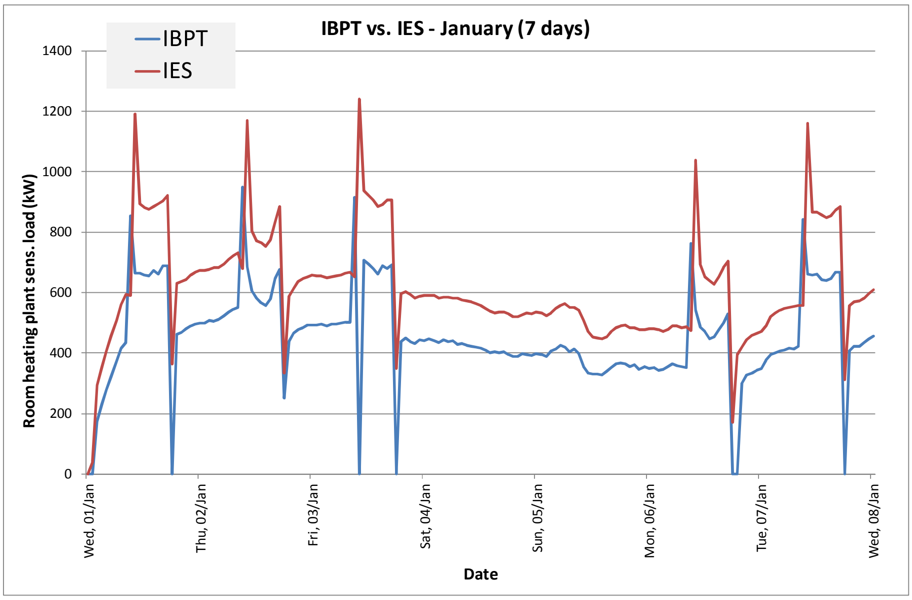


Figure 5-12 - Factory heating load - IBPT vs. IES VE – 1st to 8th January - 0.2 radiant htg

The author believes that this disparity lies with the way that the two modelling tools simulate fabric heat transfer, section 5.4.1. The results of the model are still performing within tolerable limits for the internal factory air temperature, however the heating load requirements of the factory are not. This is apparent in Figure 5-13, when increasing the radiant portion of the space heating from 20% to 40%.

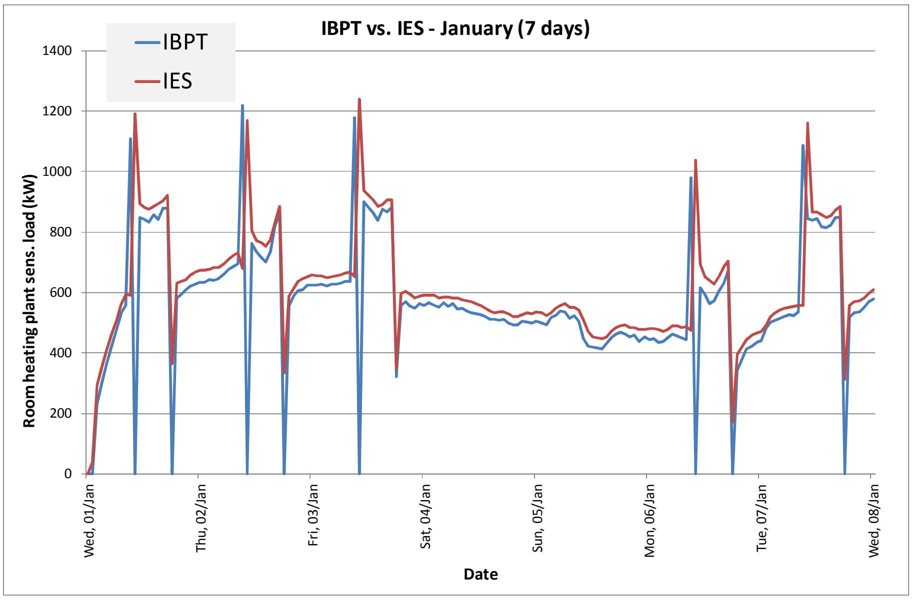


Figure 5-13 - Factory heating load - IBPT vs. IES VE – 1st to 8th January - 0.4 radiant htg

To ensure that the factory zone maintains air temperatures that match the heating profile, the convective part of the heating system still requires the necessary energy input as modelled in the scenario with 20% long wave radiation proportion from the heating system. This in turn increases the amount of radiant heat to the factory zone, increasing the energy demand of the overall system, Figure 5-13. The results of the internal air temperature remain in good correlation with the IBPT model RMSE being 1.07°C against IES VE result. The annual heating load percentage error between the two modelled approaches decreases to 7.42%, IBPT (1163.85 MWh/yr) and IES VE (1257. 07 MWh/yr). The results for IES VE are still based on a radiant heat proportion of 0.2.

5.4.4.2. Summary

The addition of space heating has highlighted an area of disparity between the two modelling approaches. The author believes that this difference lies with the way that the two building modelling tools simulate fabric heat transfer; further highlighted when increasing the radiant proportion of the space heating from 20% to 40%.

5.4.5. Summary

The future work of this research is based on the accuracy and validity of the existing IBPT to model building energy flow paths. This section has progressed through a number of scenarios from a controlled climatic environment to models that are responsive to external weather conditions, as well as modelling of different construction materials and the inclusion of space heating, Table 5-2. The inherent differences between the two modelling approaches such as the different mathematical and modelling techniques highlight the fact that there will be a margin of error between the results of the simulations. Great effort has gone into minimising this margin by modelling scenarios in the two building modelling tools as closely and as accurately as possible through use of similar inputs, constants, variables, weather file and understanding where differences lie between the two approaches (i.e. modelling of the ground floor as an adiabatic surface).

Results from Appendix *A.2 - Single zone (dynamic - mixed material, ground adiabatic and windows)*, modelling a factory building which is respondent to an external weather file, mixed materials, adiabatic ground floor and windows of 10% area to vertical surfaces, demonstrated that the IBPT is in good correlation between the two approaches. However, scenario 5.4.4 with the addition of space heating has highlighted that there is an area of disparity between the two modelling approaches. The author believes this is as a result of the different ways that the two building modelling tools simulate fabric heat transfer, section 5.4.1. The author has discussed the modelling differences with the Technical Director of IES. There could be many reasons for the differences; some of the reasons are listed below.

- Different finite difference modelling approach (IES VE Hop-scotch method vs. IBPT explicit method), as discussed in section 5.4.1. This could lead to sizeable differences between the simulated results.
- Apache, the calculation engine of IES VE, apportions a fraction of radiative output to the central air node of a zone (the air emissivity phenomenon). This is deemed to have a small effect on the results. Also on reflection this would have a negative effect (i.e. effectively making Apache's heater a bit less radiant) on the outcome making the differences greater.
- Under clear sky conditions the sky temperature (as modelled by Apache) can be a few degrees lower than the external air temperature. Great effort has gone into modelling similar weather conditions to that of IES VE. The results of the scenarios without space heating show good correlations.
- Assumptions about external wind-driven convection, wind speed data, and how it's interpreted (i.e. variation with height, effect of wind direction and surface orientation). IBPT accounts for wind speed correlations but does not account for direction, however results of the scenarios without space heating show good correlation.

With exception to the scenario modelled in section 5.4.1 (including space heating), the accuracy and the ability of the IBPT to model comparable building energy flow paths when compared with IES VE, makes the tool suitable for future use by the research. Future scenarios shall explore this issue further. Though one solution could be to increase the radiant heating fraction of the heating system within the IBPT from 20% to 40%, where required.

5.5. *Adapted IBPT (zone inside a zone)*

The following section discusses results from the adapted IBPT tool, advancing the fundamentals of the existing IBPT into a tool that is capable of modelling a thermal zone inside a thermal zone, Figure 5-14a). Changes to the existing IBPT are discussed in detail in section 5.2. A brief summary of the changes are listed below:

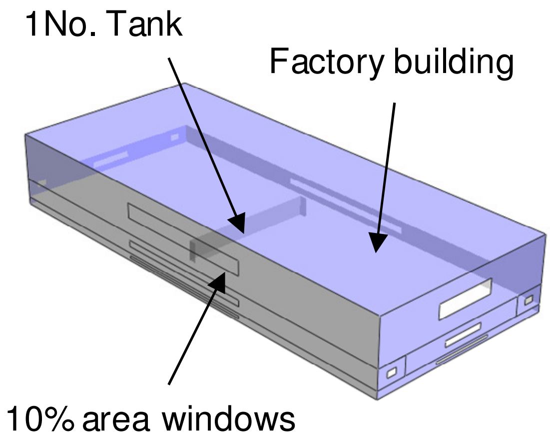
- Revision to the structure of the IBPT to model internal thermal zones.
- Exterior surface convective heat transfer coefficient is linked to external wind speeds based on the McAdams empirical equation.
- Internal long wave radiation coefficients are calculated on dynamic changes in material construction surface temperatures and thermal zone dry bulb air temperature.

These changes are in line with the simulation approach of IES VE. The following scenarios compare results from the simulations runs in the adapted IBPT against the commercially used and validated building modelling tool IES VE. A brief explanation of each scenario can be found under each heading. Adapted IBPT models and Excel results can be found in Appendix D (material provided on a CD). A selection of scenarios can be found in Appendix A - Tool verification:

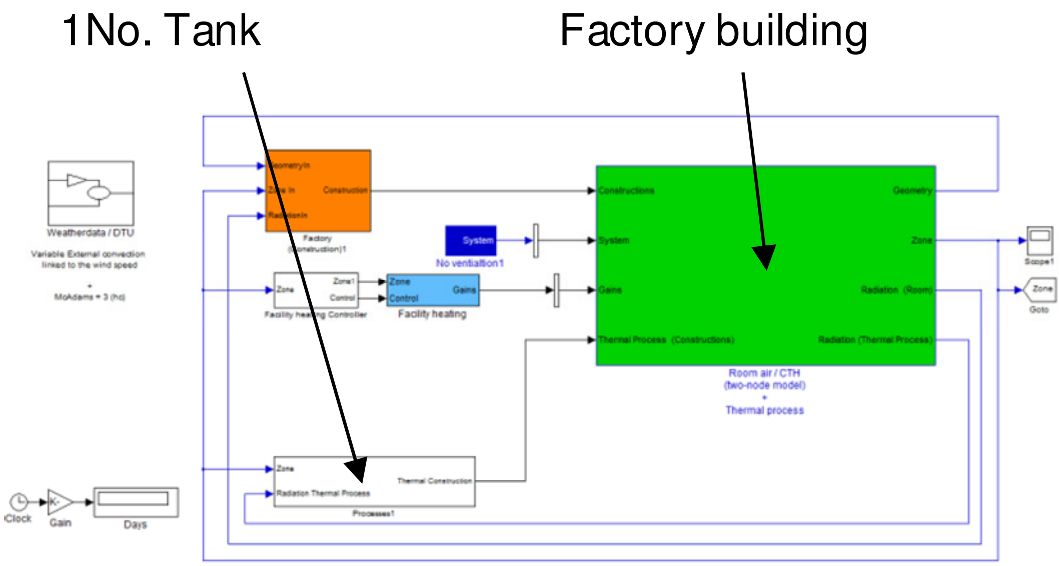
- A.3 – Single internal zone (controlled – one material)
- A.4 - Single internal zone (controlled – mixed material)
- A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows)

5.5.1. Single internal zone (dynamic - mixed material, ground adiabatic, windows and heating)

The below scenario uses the same approach as discussed in Appendix *A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows*, with the exception of space heating to the factory building, Figure 5-14. The factory zone is heated to the following profile, from 9am until 5pm, to a minimum of 18℃ Monday to Friday. At all other times the factory building is heated to a minimum of 12℃. The radiant fraction for the heating system is set at 0.2 (i.e. 20% radiant, 80% convective).



a)



b)

Figure 5-14 - Factory building and 1No. internal zone, a) IES VE and b) IBPT

5.5.1.1. Results

The factory building dry bulb air temperature results for January are shown in Figure 5-15. As highlighted in section 5.4.4, the internal air temperature of the factory shows good correlation.

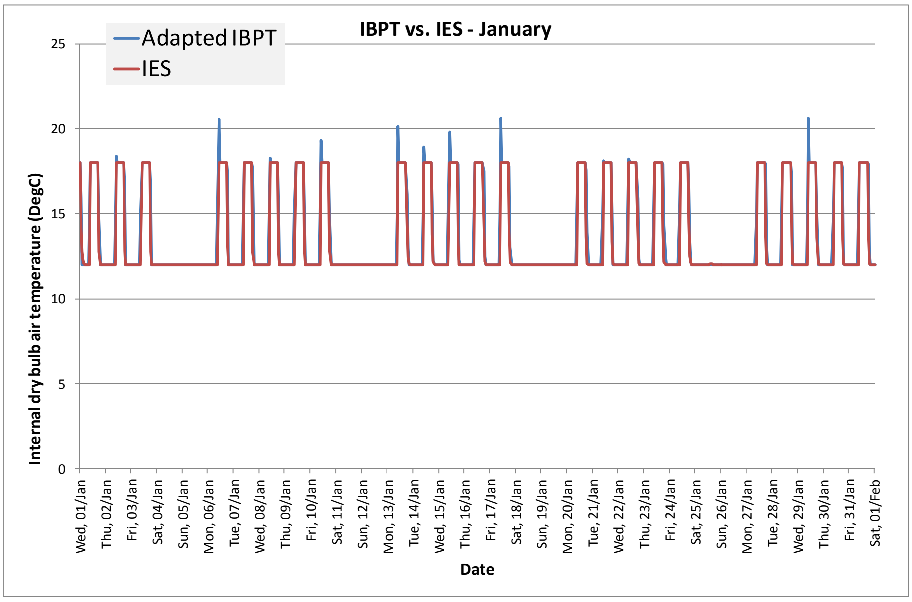


Figure 5-15 - Factory air temperature Adapted IBPT vs. IES VE – mixed construction, adiabatic ground material, windows and factory heating (January) - 0.2 radiant htg

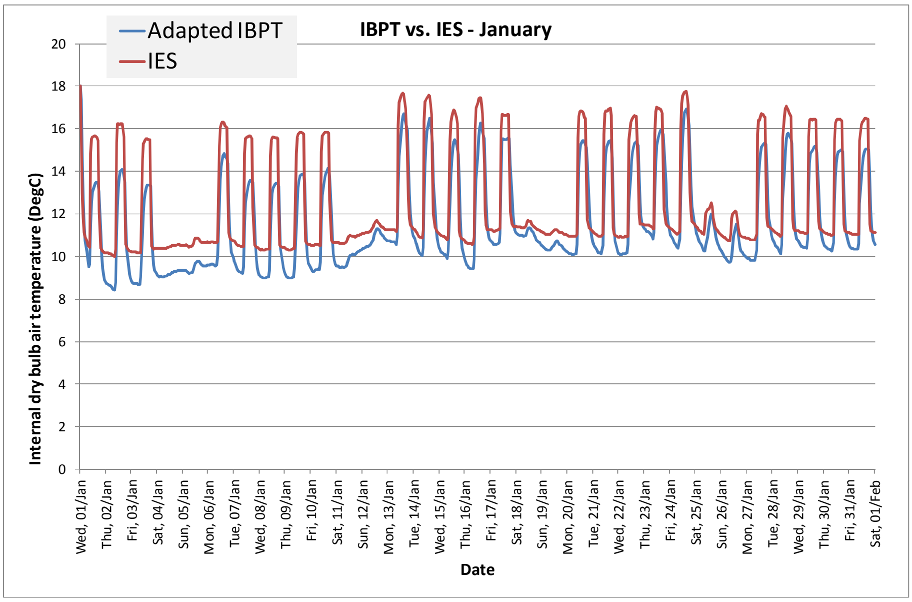


Figure 5-16 - 1No. internal zone air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January) - 0.2 radiant htg

The IBPT is under estimating the demand side heating requirement for the building, Figure 5-17. Over an annual heating load, the percentage error between the two models is 32.54%, IBPT

(933.66 MWh/yr) and IES VE (1384.04 MWh/yr). The under performance of the heating system results in insufficient long wave radiant heat transfer between the factory and surfaces of the internal zone, resulting in a difference between the air temperature of internal zone from the two modelling approaches, Figure 5-16. The author believes that this disparity lies with the different way that the two modelling tools simulate fabric heat transfer, section 5.4.1.

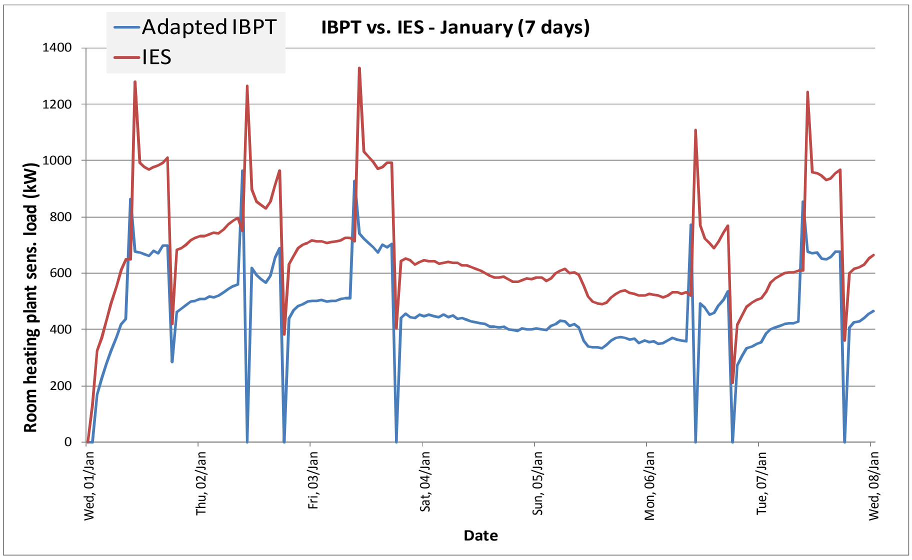


Figure 5-17 - Factory heating load - Adapted IBPT vs. IES VE – 1st to 8th January - 0.2 radiant htg

As demonstrated in section 5.4.4, by increasing the radiant proportion of the heating system from 20% to 40% the annual heating load percentage error between the two model approaches decreases, in this case to 15.46%, IBPT (1170.11 MWh/yr) and IES VE (1384.04 MWh/yr), Figure 5-18. The results for IES VE are based on a radiant heat proportion of 0.2.

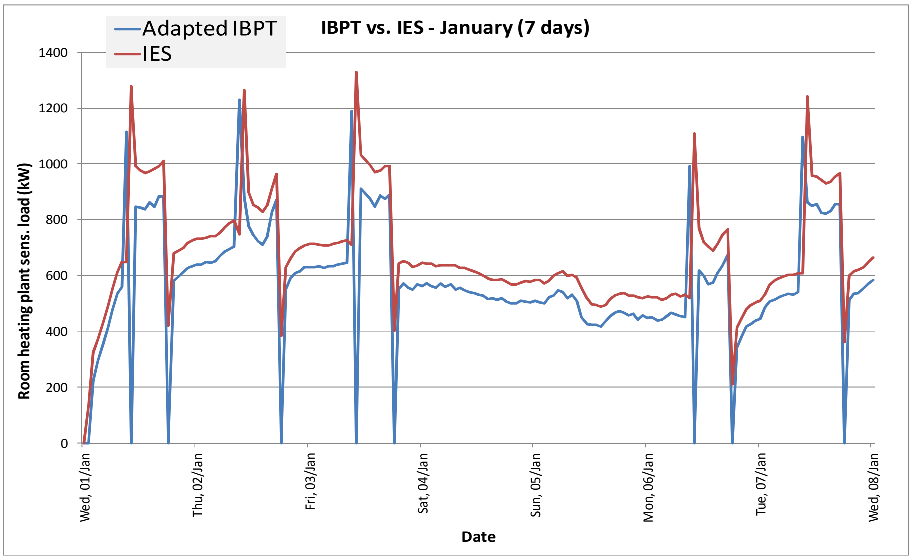


Figure 5-18 - Factory heating load - Adapted IBPT vs. IES VE – 1st to 8th January - 0.4 radiant htg

By changing the radiant fraction of the heating system the results of the internal air temperature of the internal zone show good correlation, Figure 5-19. The IBPT model has a RMSE of 1.08°C and 0.98°C against IES VE result for the factory building and the internal zone.

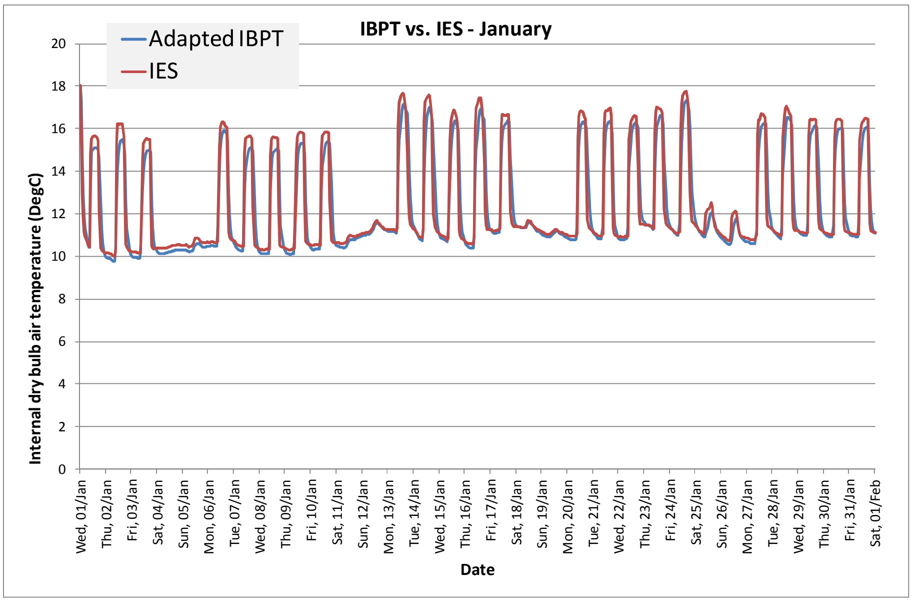


Figure 5-19 - 1No. internal zone air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January) - 0.4 radiant htg

5.5.1.2. Summary

The author believes that these results highlight an area of disparity between the two modelling approaches, section 5.4.4. An increase in the heating systems radiant proportion retains accuracy within the adapted IBPT results when compared with IES VE for both the factory environment and the internal zone.

5.5.2. Summary

From results shown above, the adaption of the existing IBPT to model an internal thermal zone inside a larger thermal zone, has not had an effect upon the results when compared against similar simulated scenarios in section 5.3.5. The results from the adapted tool also indicate that the internal air temperature of the untreated internal zone (i.e. tank) is reacting to its surroundings (i.e. factory building), and displaying similar results to the factory air temperature, as would be expected. The inclusion of space heating to the factory building has identified a difference between the two modelled results. The author believes this difference lies with the way that the two modelling tools simulate heat transfer across fabric constructions, sections 5.4.1 and section 5.4.4.

5.6. *Adapted IBPT (several zones inside a zone)*

The following scenarios are based on a large thermal zone (factory building) and six internal thermal zones (6No. air based tanks), Figure 5-20. The following scenarios test the validity and accuracy of the adapted IBPT against results simulated in the building modelling tool, IES VE.

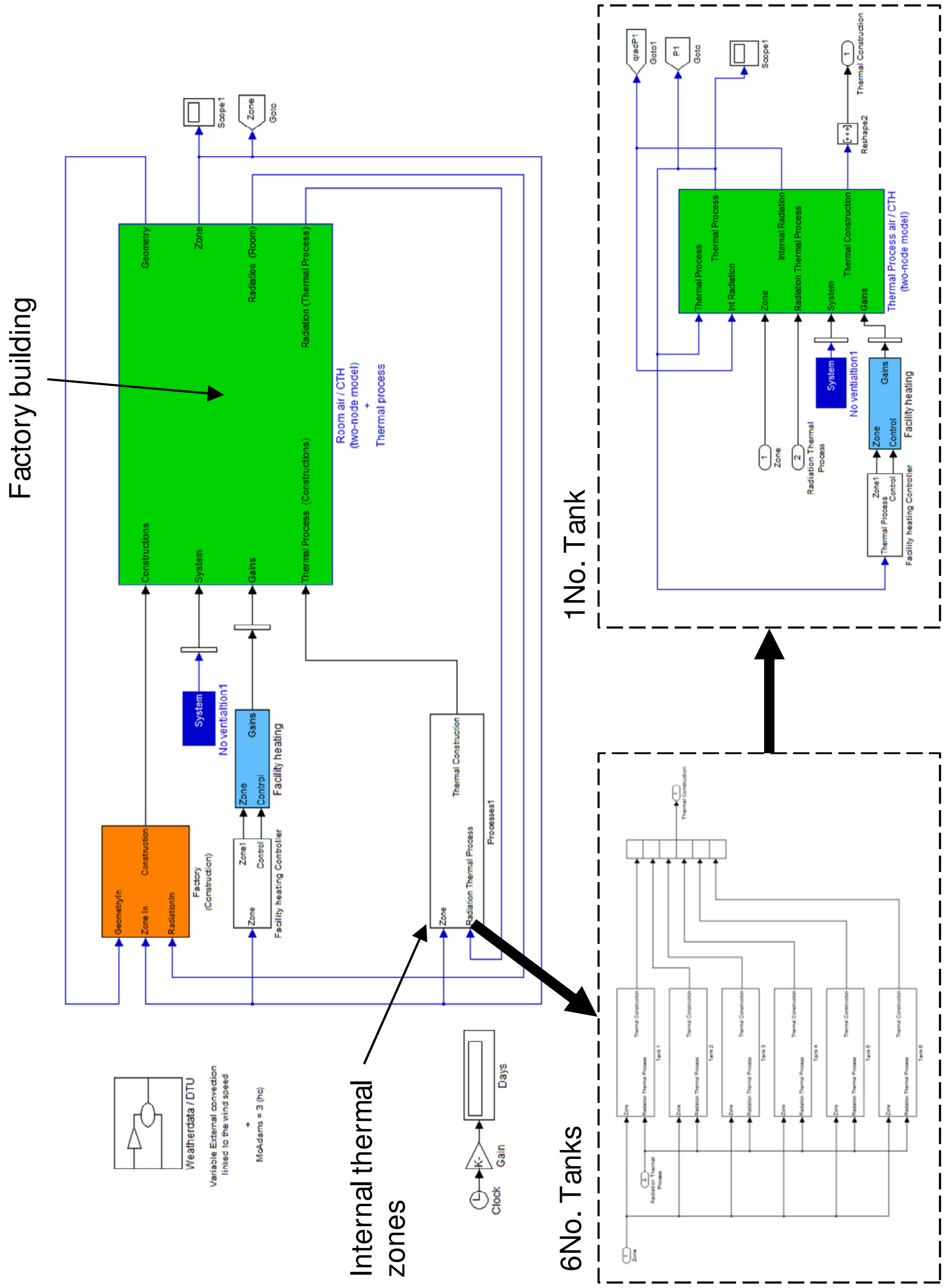


Figure 5-20 – Adapted IBPT six internal zoned model

The difficulty of modelling an internal zone inside a larger zone within the IBPT occurs with the understanding and modification of the structure and flow of data within the existing IBPT. This section considers a factory building with a number of internal thermal zones. The increase in internal thermal zones from one (section 5.3.5) to six will test and ensure that any revisions to the structure of the toolbox have been applied correctly. Most importantly the model will also determine whether there are differences between results in relation to the way that the two modelling tools simulate long wave radiation (i.e. IBPT area weighed average and IES VE view factors), section 5.2.2. Adapted IBPT models and Excel results can be found in Appendix D (i.e. material provided on a CD).

5.6.1. Six internal zones (dynamic – mixed material, adiabatic ground and windows)

The below scenario uses the same approach as discussed in Appendix *A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows*, with the exception of modelling five additional internal thermal zones (i.e. six in total) inside a larger zone (factory building).

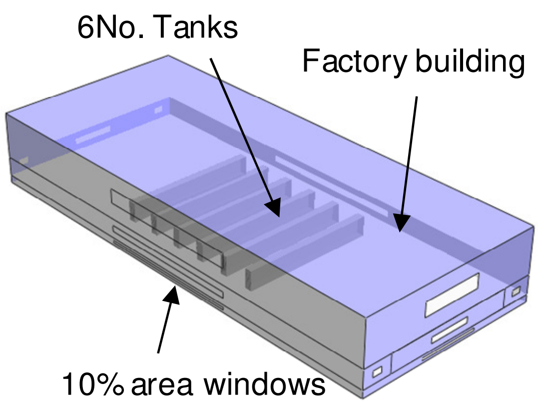


Figure 5-21 - Factory building with windows and 6No. internal tank, in IES VE

Figure 5-20 and Figure 5-21 are models created in the adapted IBPT and IES VE respectively. The models are weather file driven. The factory building is of mixed materials, adiabatic ground floor construction and windows of 10% area to all vertical surfaces. The six internal thermal zones are constructed from 0.01m thick steel. The factory building and internal thermal zones have no internal gains.

5.6.1.1. Results

Dry bulb air temperature results for January are shown in Figure 5-22 for the factory building and internal thermal zone tank 1, Figure 5-23.

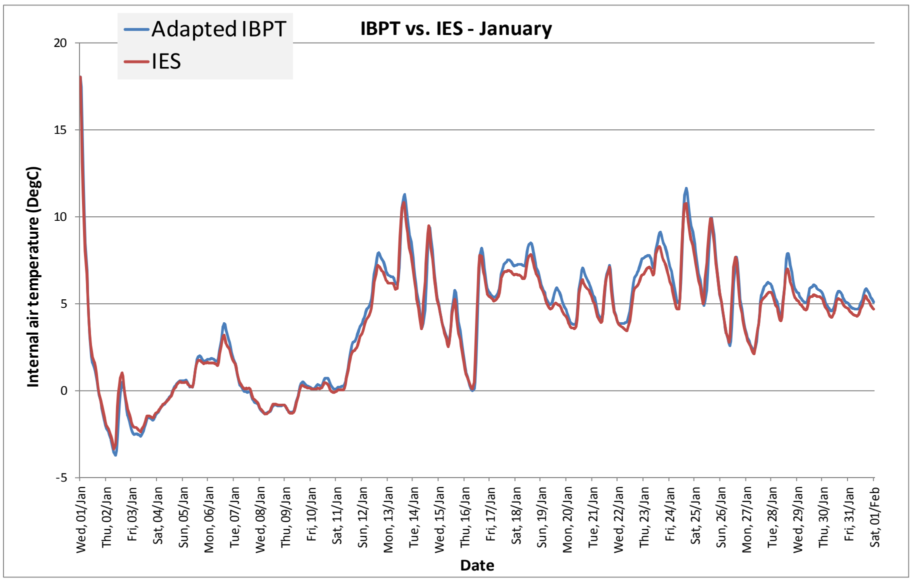


Figure 5-22 - Factory air temperature - Adapted IBPT vs. IES VE– mixed construction, adiabatic ground material and windows (January)

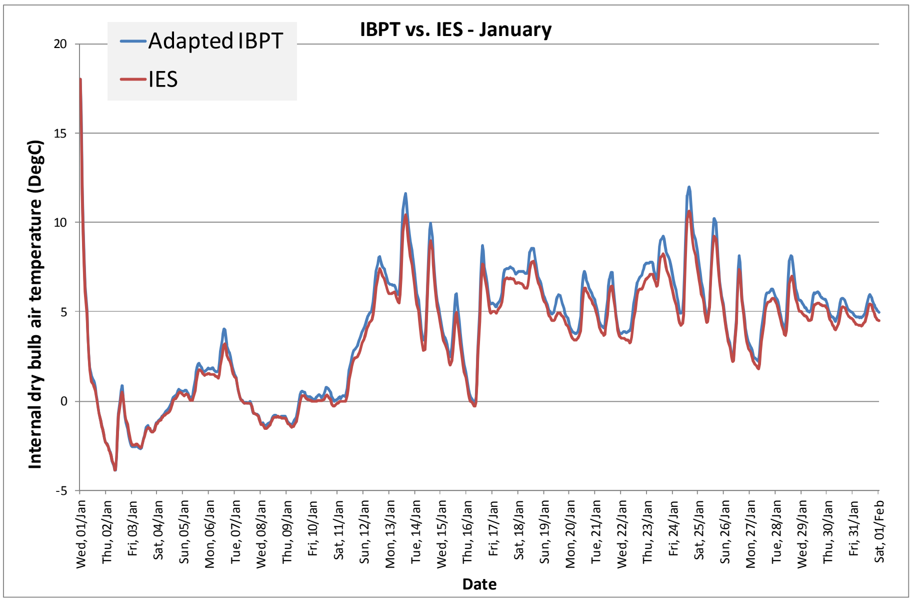


Figure 5-23 – Tank 1 of 6 air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January)

Figure 5-24 graphs the internal air temperatures of the six tanks modelled in both the adapted IBPT and IES VE. Note how the dry bulb air temperature of the 6No. internal thermal zones vary when simulated in IES VE.

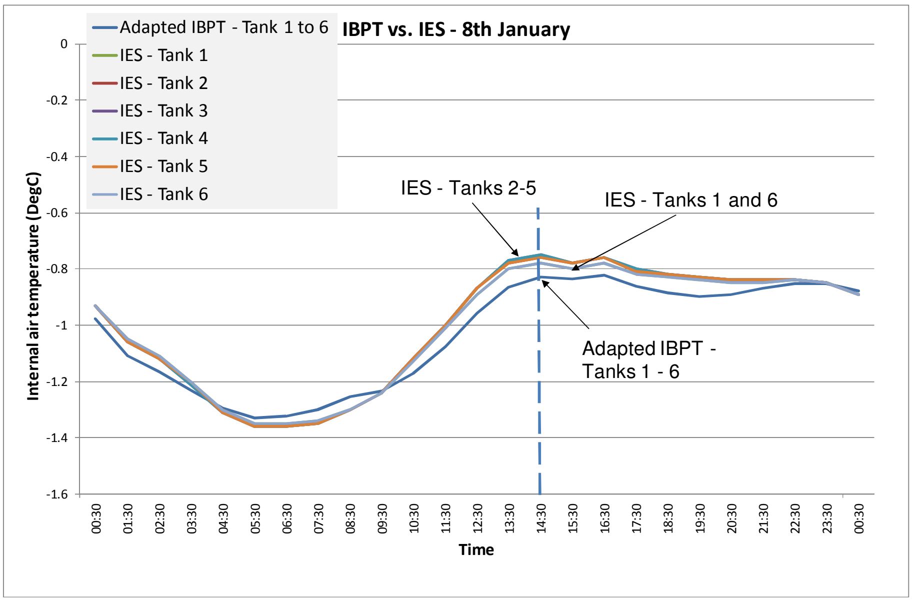


Figure 5-24 – Tank 1 of 6 air temperature - Adapted IBPT vs. IES VE– 0.01m thick steel (8th January)

This is due to the way that the tool calculates long wave radiation between surfaces (i.e. view factors). From Figure 5-24 it can be seen that the outer tanks (1 and 6) are similar in temperature (approximately -0.89℃) in IES VE, indicated by the vertical hashed line. The inner tanks (2 to 5) are warmer in temperature than the outer tanks, approximately -0.87. The difference is due to their locality and the reciprocation of long wave radiation with neighbouring surfaces and solar radiation. The outer tanks (1 and 6) reciprocate long wave radiation transfer, in this case to and from the high thermal mass concrete construction, as well as with neighbouring steel tanks (2 and 5). The inner tanks (2 to 5) reciprocate long wave radiation between each other, as well to surfaces that are insight of the outer perimeters of the factory building. The surface temperatures of the steel tanks are warmer than the high thermal mass concrete outer walls of the factory. In turn, long wave radiation exchanged between the inner tanks is greater than the outer tanks resulting in a marginally higher air temperature of the inner tanks (2 to 5). The tanks are also subject to solar radiation through windows. Solar radiation through window areas may have a greater affect on the transfer of long wave radiation to the tanks than between surfaces, though this would require further in-depth analysis.

5.6.1.2. Summary

As expected the results show good correlation and are in comparison to results demonstrated in Appendix *A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows*) for one internal thermal zone.

5.6.2. Six internal zones (dynamic – mixed material, adiabatic ground, windows and heating)

The below scenario uses the same approach as discussed in section 5.6.1, with the exception of space heating to the factory building. The factory zone is heated to the following profile, from 9am till 5pm, to a minimum of 18℃ Monday to Friday. At all other times the building is heated to a minimum of 12℃. The radiant fraction for the heating system is set at 0.2 (i.e. 20% radiant, 80% convective).

5.6.2.1. Results

The factory building dry bulb air temperature results for January are shown in Figure 5-25. As highlighted in Sections 5.4.4 and 5.5.1, the internal air temperature of the factory show good correlation.

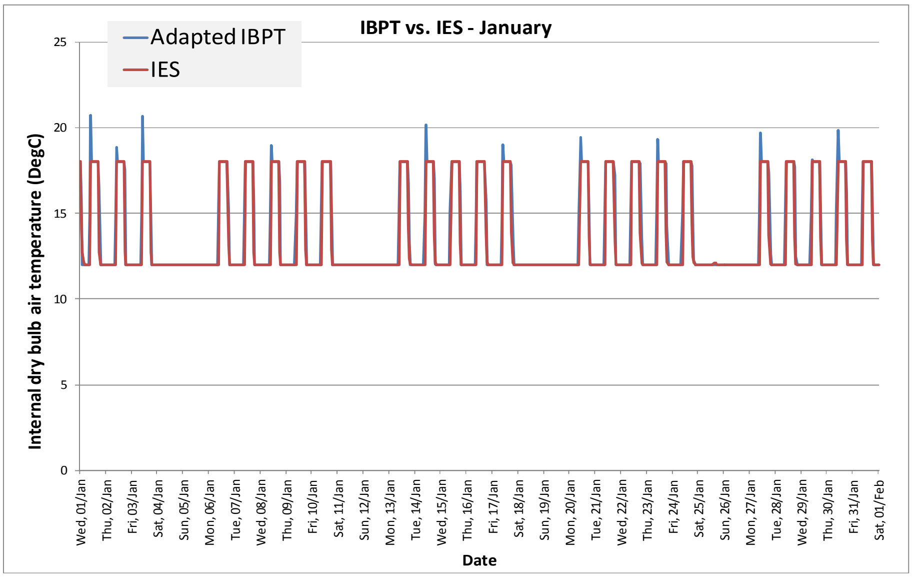


Figure 5-25 - Factory air temperature - Adapted IBPT vs. IES VE – mixed construction, adiabatic ground material, windows and factory heating (January) - 0.2 radiant htg

The IBPT is under estimating the demand side heating requirement for the building, Figure 5-27. Over an annual heating load, the percentage error between the two models is 30.04%, IBPT (970.38 MWh/yr) and IES VE (1387.13 MWh/yr). Insufficient long wave radiant heat transfer to the 6No. internal thermal zones results in a difference in dry bulb air temperature of the zones between modelled approaches, Figure 5-26.

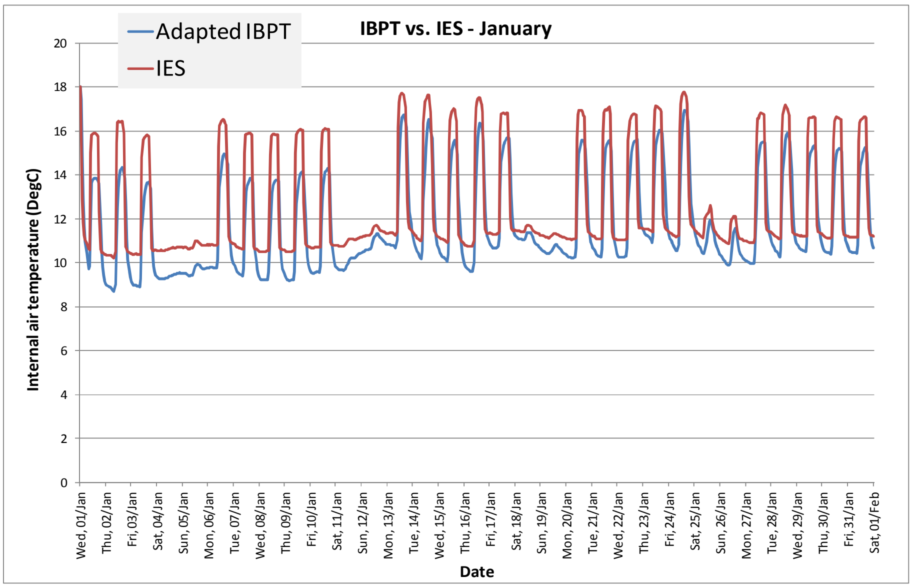


Figure 5-26 - Tank 1 of 6 air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January) - 0.2 radiant htg

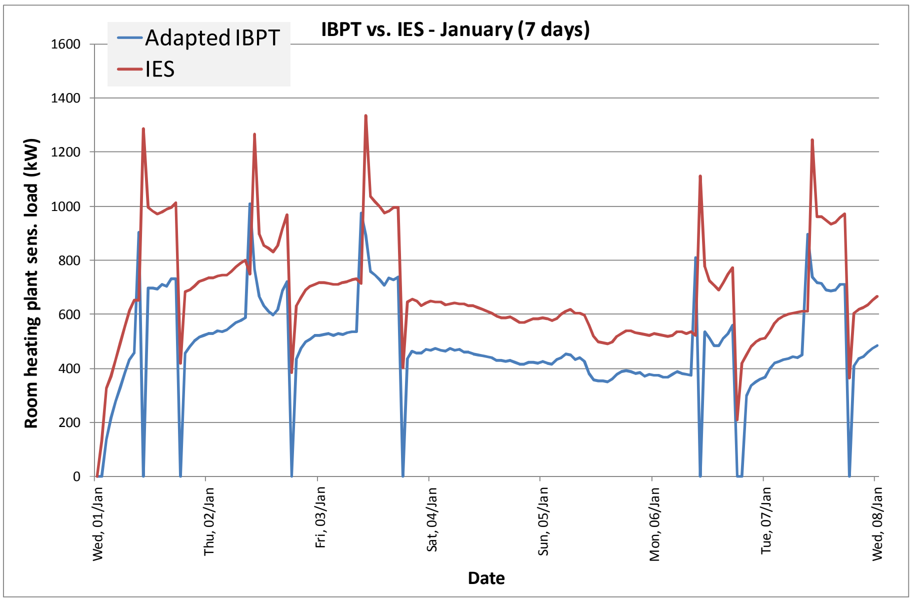


Figure 5-27 - Factory heating load - Adapted IBPT vs. IES VE – 1st to 8th January - 0.2 radiant htg

As demonstrated in section 5.4.4 and 5.5.1, by increasing the radiant proportion of the heating system from 20% to 40% the annual heating load percentage error between the two model approaches decreases, in this case to 13.53%, IBPT (1199.42 MWh/yr) and IES VE (1387.13 MWh/yr), Figure 5-28. The results for IES VE are based on a radiant heat proportion of 0.2.

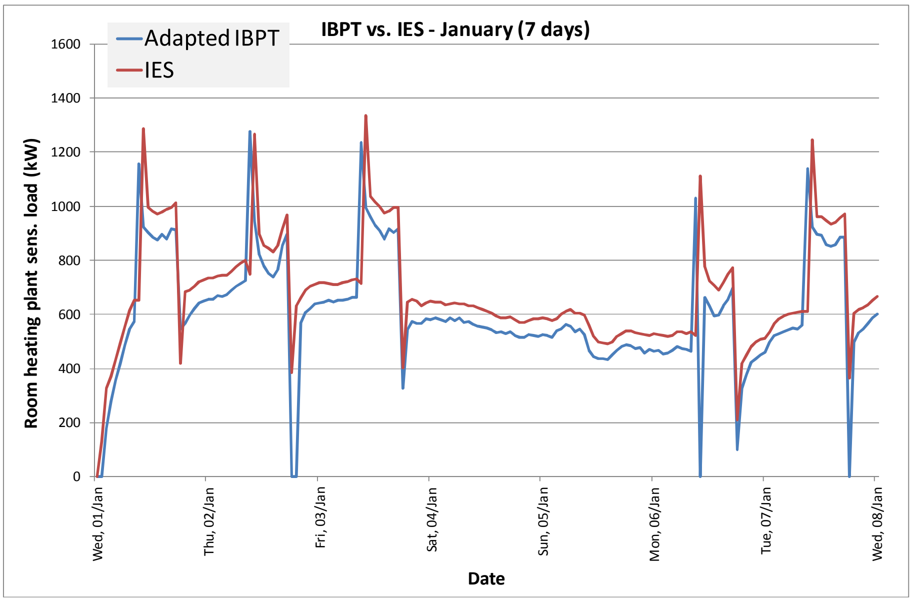


Figure 5-28 - Factory heating load - Adapted IBPT vs. IES VE – 1st to 8th January - 0.4 radiant htg

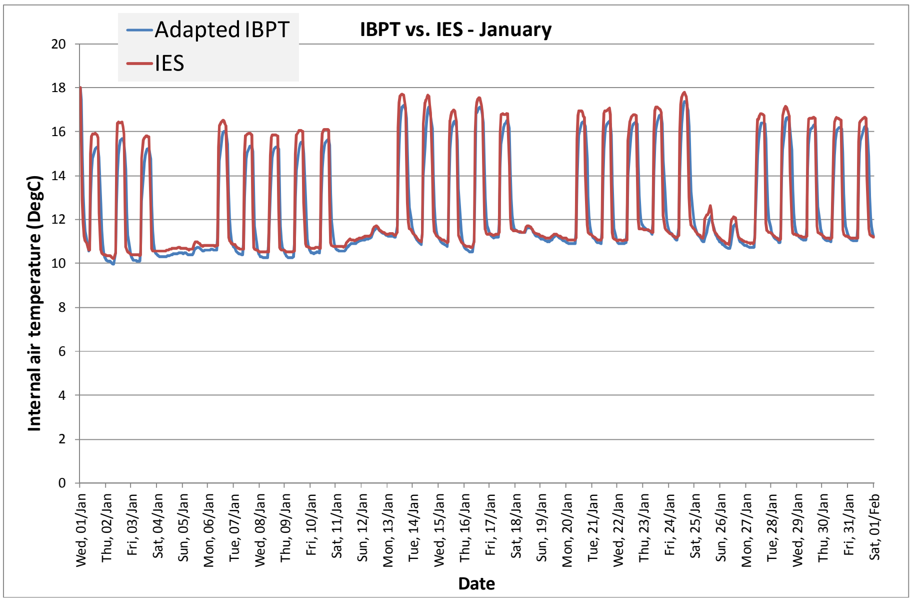


Figure 5-29 - Tank 1 of 6 air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January) - 0.4 radiant htg

5.6.2.2. Summary

An increase in the radiant proportion of the space heating to the factory building improves the correlation between the two modelling tools, Figure 5-28 and Figure 5-29

5.6.3. Summary

Results for both the factory building and six internal zones closely match that of a similar scenario shown in Figure 5-19, for one internal zone. This is as expected, as the only difference between the two scenarios is the inclusion of a further five internal zones, that thermally react to and with their ambient surrounding. Due to the difference in modelling approaches (i.e. view factors verses area weighted average), the results for the internal air temperature of the six tanks vary in relation to their positioning within the IES VE model, Figure 5-24. This is expected as the internal temperatures of the internal zones in the adapted IBPT are the same across all of the six tanks modelled, due to the modelling approach. A similar result outcome has been demonstrated for the heating load requirement for a building with one internal thermal zone versus a building with six thermal internal zones, section 5.5.1. The results also identify that the two different modelling approaches to simulating long wave radiant heat transfer have significant effects on the heating load requirement for the factory building.

5.7. *Modelling boundaries*

Below are list of modelling boundary identified during the development and software verification of the adapted IBPT to model both building physics and manufacturing process systems within one integrated tool.

- The IBPT uses the explicit finite difference method only. The IES software uses a combination of the finite difference explicit and implicit time-stepping method (i.e. hopscotch method) (IES, 2011b). Discussed further in Section 5.4.1
- The IBPT distributes internal long wave radiation via an average area weighting to all internal surfaces based on a constant internal long wave radiation heat transfer coefficient of 5W/m²K. IES distributes internal long wave radiation based on view factors (IES, 2011b), with are considered more accurate, but require complex mathematical algorithms and longer simulation time (depending on programming language). Changes made in the adapted IBPT calculate internal surface long wave radiation on a variable coefficient dependant on material properties and surface temperatures, see Section 5.2.3.
- Further to Section 5.3 and Chapter 6 the following boundary conditions have arisen:
    - Adapted IBPT verified against IES VE in Section 5.3. Ground floor modelled as adiabatic in both tool approaches, improving accuracy of the comparable results, see Section 5.3
        - Ground floor modelled as an adiabatic construction. Surface temperature based on the surrounding air temperature.
    - At present the adapted IBPT is limited to modelling the number of construction elements to 12 per large zone.

- Thermal process
    - Single interior air mass node per thermal zone limited to 100℃ based on linear mathematical equations for modelling air.
- Electrical process
    - Long wave radiation and convective heat transfer to surroundings only. Heat transfers are not reciprocal to and from surroundings
    - Surface temperatures are not modelled
- Moisture transfer
    - Evaporation losses (e.g. from liquid surfaces, steam processes etc) are not modelled, as the adapted IBPT is based on a heat transfer model only
- Product flow (material)
    - At present, material flow is driven by time variant deterministic profiles

6. Case studies

6.1. *Approach*

This chapter follows the research methods outlined in chapter 3. Data obtained from the industrial partners of the THERM project has been used to simulate case studies based on a multiple (holistic) case study design, Figure 3-1. This approach utilises the work presented from conceptual modelling (chapter 4) and model design including tool verification (chapter 5), to the modelling of case studies based on industrial derived data. Below is a brief overview of the case studies:

- **Industrial drying tank, section 6.2.**
    - Building (fabric and heating system), drying tank and supplementary equipment and material (product) flow.
- **Treatment tanks, section 6.3.**
    - Building (fabric and heating system), four treatment tanks and material (product) flow.
- **Air supply house (ASH), section 6.4.**
    - Individual plant components of the air supply house manufacturing process (i.e. burner, humidification, steam injection, cooling, re-heat), air based model only.

Table 3-2 compares the industrial based case studies against modelling criteria. The industrial drying tank (section 6.2) and treatment tanks (section 6.3) case studies have been modelled using the adapted IBPT. Further to the tool verification section 5.3, case studies have been designed to test the capabilities of the adapted IBPT to simulate building physics conditions that have been extended to include manufacturing process systems and material flow. The industrial drying tank case study models a gas (i.e. air) based process, manufacturing plant and material flow. The treatments case study includes the modelling of a liquid based process and material flow. The air supply house (section 6.4) has been modelled using the block flow method of the Simulink software, also used within the adapted IBPT. Case study models and Excel results can be found in Appendix D (material provided on a CD).

6.2. Industrial drying tank

6.2.1. Method

The industrial drying tank case study applies a fundamental approach to modelling a factory environment which includes an industrial drying tank, manufacturing plant (i.e. fan, heat exchanger and air re-circulation) and material flow. The drying tank is modelled as an internal thermal zone within the factory zone (a zone inside a zone), Figure 6-1. The case study includes the flow of material between the drying tank and factory. Table 6-1, an extract from Table 3-2, outlines the modelling criteria of the case study.

Table 6-1 – Industrial drying tank modelling criteria

	Criteria									
Case study (section number, title)	Factory	Windows	Space heating	Weather file	Process only	One internal process	> 1 internal process	Air (i.e. gas) process	Liquid process	Material flow
6.2_Industrial drying tank	•	•	•	•		•		•		•

6.2.2. Graphical representation

Figure 6-1, shown in Figure 4-14 and repeated again for clarity, is a graphical representation of the energy flow paths that exist between the built environment (factory building), manufacturing process system (drying tank), manufacturing plant (fan, HX and circulation ductwork) and material flow.

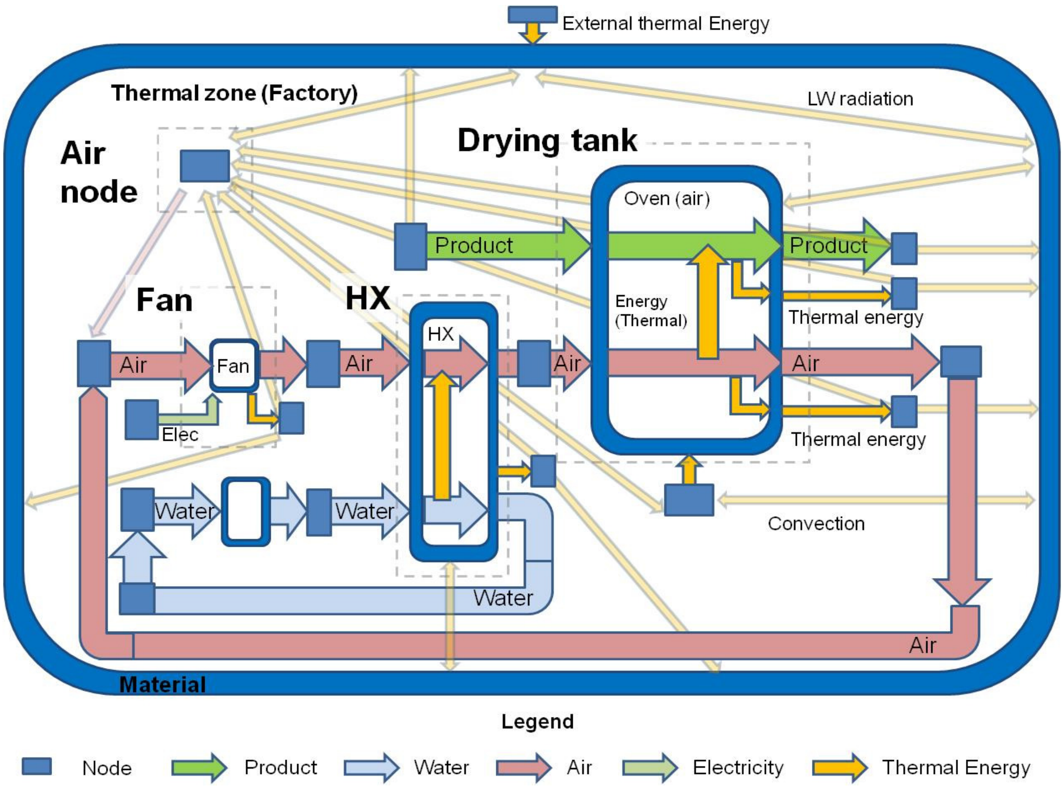


Figure 6-1 – Graphical representation of a drying tank and manufacturing plant, defined by its location (thermal zone) (Oates et al. 2011b)

6.2.3. Key data

The industrial drying tank, plant and material are representative of a real industrial process obtained from the THERM industrial partners. The environmental heating strategy for the factory environment is based on design conditions from the industrial partners. The dimensions of the building are not representative of actual on-site conditions housing the industrial process. The building is simplified and modelled as a control boundary around the process. The decision to simplify the model was based on a lack of data available from site in regards to the factory air temperature, external weather data and internal gains from neighbouring manufacturing process and lighting. The control boundary is a fixed condition within the scenarios modelled to ensure consistency, section 6.2.5. Tabulated data in Table 6-2, Table 6-3 and Table 6-4, list properties that have been used within the simulation models discussed below.

Table 6-2 – Factory simulation data

Factory	
- North/South elevations	- 0.2m concrete - Surface area = 500m² - Glazing - Surface area = 50m²
- East /West elevations	- 0.2m concrete - Surface area = 100m² - Glazing - Surface area = 10m²
- Ground - Roof	- Adiabatic - Surface area = 500m² - 0.01m steel - Surface area = 500m² - Volume = 5000m²
- Environmental conditions	- Heating - See profiles

Table 6-3 – Simulated material properties

Material properties	
- Concrete	- Density 2400kg/m³, - Thermal conductivity 1.5W/m.K, - Heat capacity 800J/kg.K, - Absorptivity 0.65 - Emissivity 0.9.
- Steel	- Density 7800kg/m³, - Thermal conductivity 50W/m.K, - Heat capacity 480J/kg.K, - Absorptivity 0.7 - Emissivity 0.9.
- Glass	- Density 2500kg/m³, - Thermal conductivity 0.7W/m.K, - Heat capacity 840J/kg.K, - Emissivity 0.9

Table 6-4 – Drying tank and supplementary equipment simulated data

Drying tank and equipment	
Drying tank - Outer walls - Environmental conditions	 - 0.01m steel - Surface area = 207.5m² - 2m off ground - Volume = 93.75m² - Heating - Temperature = 40°C - See profiles
Equipment - Fan (air not in-line) - Heat exchanger - Recirculation of processed air	 - Power Rating = 18kW - Efficiency = 90% - Flow rate = 6.3m³/s - Rating = 200kW - Flow rate = 5.3m³/s
Material (product) - Surface area	 - Steel - Surface area = 74m²

6.2.4. Simulation

Two models of the industrial tank case study have been created. Figure 6-2 and Figure 6-3 are extracts of these simulation models within IES VE and the adapted IBPT, respectively. The IES VE model is designed to verify the results of the adapted IBPT model in comparable areas of building modelling, such as a zone inside a zone and non-material flow. The adapted IBPT model goes onto modelling material flow between the drying tank and factory. Modelled scenarios are discussed in detail in section 6.2.5.

Figure 6-2, are extracts taken from the IES VE software. The simulation model comprises of a number of thermal zones. The reason for this is that IES VE cannot model a zone inside a zone, commonly known as the doughnut affect. As in the example of the drying tank, the internal zone (i.e. drying tank) is modelled as one thermal zone. The factory building comprises of a number of thermal zones positioned around the drying tank and are connected together to give the impression that the factory building is one thermal zone. This is clearly demonstrated in Figure 6-2 by the positioning of windows at the centre of each vertical wall per zone. The windows make up 10% of the outer surface of each zone, which in turn makes up 10% of each vertical elevation.

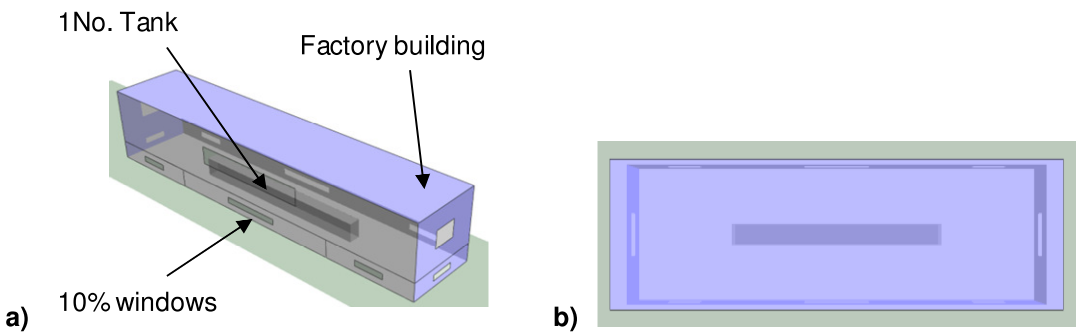


Figure 6-2 – IES model graphics – Factory and drying tank, a) Axonometric, and b) plan

Figure 6-3 are extracts from the adapted IBPT model. The figure shows the key areas of the model i.e. factory building (green large box), factory construction (orange box) and facility heating (light blue box). Other key areas are shown in dashed outlined boxes, bottom left, 1 No tank with supplementary equipment and bottom right, material (product).

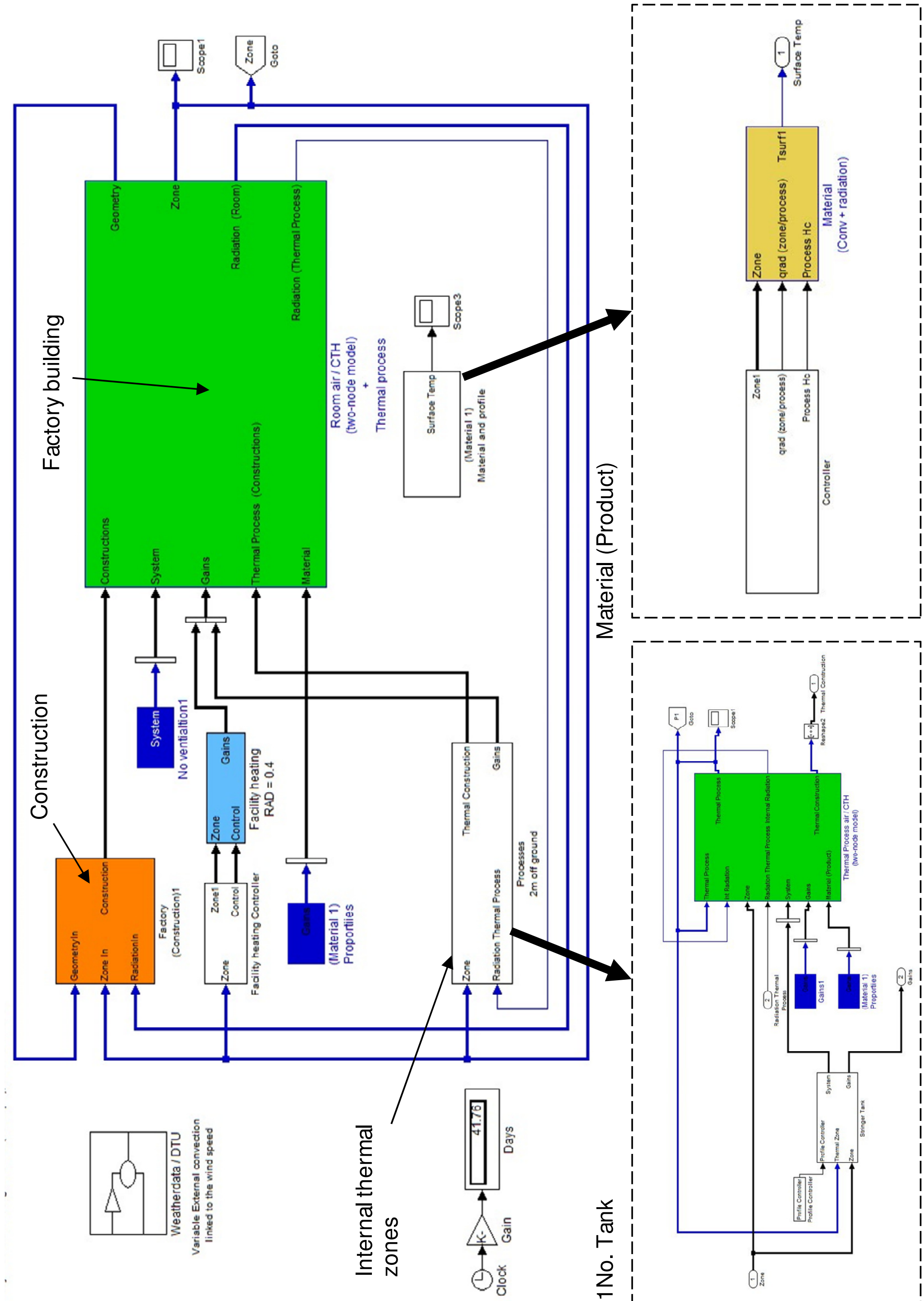


Figure 6-3 – Adapted IBPT illustration – Factory (environment, construction and manufacturing process system and material)

6.2.5. Scenarios

6.2.5.1. Adapted IBPT

Block flow models have been created for a fan, HX, mixing box and air splitter within the adapted IBPT, Figure 6-3. See Appendix B – Drying tank for first principle mathematical equations. Air at a volumetric flow rate of 6.3m^3/s from the surrounding thermal zone (i.e. factory building) is drawn into a large 18.5kW industrial fan, efficiency 90%. The motor is not in line with the incoming air of the fan. Thermal losses (1.85kW) from the motor of the fan are directed to the surrounding thermal zone. The air flows over a 200kW water to air heat exchanger, increasing the temperature of the air to the design temperature of the closed drying tank, 40°C. Air from the drying tank is re-circulated at a rate of 5.3m^3/s, mixing with the incoming air stream of the fan. Ductwork losses have not been included. The convective heat transfer coefficients for internal surfaces are set at 3W/m².K for natural or free convection. During the operation of the drying tank, the flow of air is considered forced. Values for forced convective heat transfer coefficients vary between 10 and 200W/m²K (EngineeringToolbox 2012). Due to the high velocity of the air, the upper value has been modelled. Dependent upon the scenario, batched material moving from the factory, into the process and back out into the surrounding zone is also included within the model. Material is constructed from a sheet of steel. Time variant profiles within the adapted IBPT drive the operational controls for the heating system (facility), drying tank (process) and the scheduled flow of material into and out of the drying tank process. These profiles are driven from industrial partner data. Weekly profiles are described in Table 6-5 and Table 6-6. The model uses the London Heathrow weather file 96-97 extracted from the IES software, as used in tool verification section 5.3. The use of a London weather file is not detrimental to the results as the building dimensions are not based on site conditions and historical heating demand from site is not available.

6.2.5.2. IES VE

The IES model is based on similar data inputs used in the adapted IBPT, Figure 6-2. The difference between the two modelled approaches is the implementation of the drying tank plant, i.e. fan, HX, mixing box and air splitter. The thermal efficiency losses within IES VE from the fan to the surrounding zone have been input as a heat gain to the environment via a modulating profile that matches the operational usage of the closed drying tank. The internal temperature of the drying tank is maintained at a constant 40°C, via an absolute profile. The fan and temperature profiles are based on the operational usage profiles of the drying tank. Changes to the operational profile of the drying tank will result in manual alterations to the fan and temperature profiles. It is possible to represent a simple model of the drying tank within the IES VE with some degree of accuracy. However, the model assumes that the HX is capable of matching the heating load duty required to raise the incoming air into the drying tank to a constant 40°C. This may not always be the case. Also, thermal energy losses from the fan to the factory environment are independent from the operational profile of the drying tank. In the event of future models including an extensive network of varying complexity of processes, this could lead to an increased risk of errors within the model. The flow of material within the IES VE model is not included, as IES VE is not capable of modelling decaying heat fluxes from flowing material in and out of manufacturing process systems at this moment in time.

6.2.5.3. Modelled scenarios

The environmental design conditions used in scenarios 1-4 for the factory environment and drying tank are shown in Table 6-5. Scenarios 1-4 are to be modelled in both the adapted IBPT and IES VE (v6.4). Results are to be compared and verified. Scenarios 1-4 do not include the flow of material to and from the drying tank.

Table 6-5 – Simulated scenarios 1-4, not including material flow

	Building (Factory)						Drying tank					
	Monday - Monday		Monday - Friday		Saturday - Sunday		Monday - Monday		Monday - Friday		Saturday - Sunday	
Scenarios	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm
1 (°C)	18						40					
2 (°C)	12	18						40				
3 (°C)	12			18						40		
4 (°C)	12			18			40					

Table 6-6 – Simulated scenarios 5-7, including material flow

	Building (Factory)						Drying tank						Material			
	Mon - Mon		Mon - Fri		Sat - Sun		Mon - Mon		Mon - Fri				Mon - Mon		Mon - Fri	
Scenarios	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	24 hrs	9am – 5pm	9am – 3pm	Scenarios (0 = factory, 1 = tank)	24 hrs	10am – 2pm	24 hrs	10am – 2pm
5 (°C)	12			18	12		40					(0-1)	0			1
6 (°C)	12			18	12		0			40		(0-1)	0			1
7 (°C)	12			18	12		0				40	(0-1)	0			1

Scenarios 5-7 include the flow of material, in and out of the drying tank, Table 6-6. For scenarios 5-7, the flow of material is considered to be located in the drying tank during the hours 10am till 2pm (Monday to Friday), and at all other times located in the surrounding room. Scenarios 5-7 are modelled using the adapted IBPT only.

6.2.6. Results – facility and process energy consumption

6.2.6.1. Scenarios 1-4

Scenarios 1-4 are based on an annual simulation period. Further to observations made in section 5.3, results for the facility heating system set at 20% and 40% radiant proportion within the adapted IBPT are shown in Table 6-7 and Table 6-8 respectively. Under the first column and each scenario heading, the thermal zone (factory) and drying tank environmental conditions are stated in brackets. The facility energy consumption results from the adapted IBPT model are within 12% of the results modelled within IES VE. The RMSE results are based on the internal air temperature of the factory. Process energy results are not available from IES VE as a simplified approach to modelling the drying tank within IES VE was used instead of a complex HVAC network model.

Table 6-7 - Facility heating energy consumption results (IES and adapted IBPT), radiant heating of 20% (Both IES and adapted IBPT)

	Facility heating			
- Thermal zone - Drying tank	IES (MWh/yr)	adapted IBPT (MWh/yr)	diff (%)	RMSE (°C)
Scenario 1 (constant 18) (constant 40)	229.20	201.98	11.88	0.80
Scenario 2 (Mon-Mon, 9-5) (Mon-Mon, 9-5)	148.70	135.35	8.98	0.80
Scenario 3 (Mon-Fri, 9-5) (Mon-Fri, 9-5)	137.98	126.00	8.68	0.80
Scenario 4 (Mon-Fri, 9-5) (constant 40)	108.59	97.97	9.78	1.14

Table 6-8 - Facility heating energy consumption results (IES and adapted IBPT), radiant heating of 20% (IES) and 40% (IBPT)

	40% radiant htg			
- Thermal zone - Drying tank	IES (MWh/yr)	adapted IBPT (MWh/yr)	diff (%)	RMSE (°C)
Scenario 1 (constant 18) (constant 40)	229.20	248.93	8.61	0.8
Scenario 2 (Mon-Mon, 9-5) (Mon-Mon, 9-5)	148.70	166.56	12.01	0.78
Scenario 3 (Mon-Fri, 9-5) (Mon-Fri, 9-5)	137.98	154.58	12.03	0.72
Scenario 4 (Mon-Fri, 9-5) (constant 40)	108.59	120.60	11.06	1.13

6.2.6.2. Scenarios 5-7

Scenarios 5-7 are based on an annual simulation period. The results in Table 6-7 and Table 6-8 do not include heat fluxes to the factory surroundings from material flowing in and out of the drying tank. Table 6-9 results are based on simulation model outcomes from the adapted IBPT, including material flow. Under the first column and each scenario heading, the thermal zone (factory) and drying tank environmental conditions are stated in brackets. The table includes both facility and process energy consumption results from the adapted IBPT model..

Table 6-9 - Process/Facility energy consumption (adapted IBPT) including material

		Radiant heating 40%	
- Thermal zone - Drying tank	Process energy (MWh/yr)	Facility energy (MWh/yr)	Total (MWh/yr)
Scenario 5 (Mon – Fri, 9-5) (constant 40)	193.75	117.29	311.04
Scenario 6 (Mon – Fri, 9-5) (Mon – Fri, 9-5)	43.17	151.85	195.02
Scenario 7 (Mon – Fri, 9-5) (Mon – Fri, 9-3)	34.71	154.14	188.85

Scenario 7 is the same as scenario 6 except for the change in the operational hours of the drying tank, 9am till 3pm. The change implies a conservation measure to minimise energy consumption of the drying tank by one hour before and after the material is scheduled to enter and leave the drying tank. The change results in a decrease in the overall energy consumption of the factory model by 3.16%, Table 6-10.

Table 6-10 - Process/Facility energy consumption results (adapted IBPT)

		Radiant heating 40%	
- Thermal zone - Drying tank	Process energy (MWh/yr)	Facility energy (MWh/yr)	Total (MWh/yr)
Scenario 5 (Mon – Fri, 9-5) (constant 40)	193.75	117.29	311.04
Scenario 6 (Mon – Fri, 9-5) (Mon – Fri, 9-5)	43.17	151.85	195.02
Scenario 7 (Mon – Fri, 9-5) (Mon – Fri, 9-3)	34.71	154.14	188.85
diff (MWh/yr)	8.46	-2.29	6.17
		diff (%)	3.16%

6.2.7. Discussion

6.2.7.1. Scenario 1 – 4 (IES VE vs. adapted IBPT, non-material flow)

Results from the simulations runs in the adapted IBPT and IES VE model show good agreement and verify the work undertaken within the adapted IBPT to model an integrated factory environment, Table 6-7 and Table 6-8. Results in Table 6-7 and Table 6-8 show how changes to the heating profile of the factory environment and changes to the operational usage of the drying tank begin to have an effect on the energy consumption of the facility heating system. From Table 6-7 and Table 6-8, Scenarios 3 and 4 are comparable examples highlighting this effect. Scenario 3, models a drying tank process that is in constant operation. In scenario 4, the drying tank process is in operation, 9am until 5pm, Monday to Friday. Results for the heating system with a radiant proportion of 40% indicate that the energy required to heat the factory environment has risen from 120.60MWh/yr to 154.58MWh/yr, for scenario 4 and 3 respectively. This is a 21.98% annual increase in the energy consumed by the heating system. These results are unsurprising, as a loss of thermal energy from the drying tank would require an input of energy from elsewhere, especially in circumstances when tight building temperature controls are being implemented.

6.2.7.2. Scenario 5 – 7 (adapted IBPT only, including material flow)

The heat flux from material flowing into and out of the drying tank, makes a difference to the facility energy consumption. These differences can be seen when comparing results for the 40% radiant proportion heating system from Table 6-8 with Table 6-9, scenario's 3 and 6

(2.7MWh/yr, 1.8% difference) and scenarios 4 and 5 (3.3MWh/yr, 2.7% difference). This is as a result of the material acting as a heater battery to the factory environment after leaving the drying tank. This reduces the load on the facility heating system.

Energy consumption at a process level differs by 150.6MWh/yr (i.e. 43.2 from 193.8MWh/yr) when comparing a constantly operated drying tank to one that is operated during shift hours (i.e. scenario 5 vs. 6), Table 6-9. Table 6-10 indicates a further 8.46MWh/yr process energy saving through reduction of the operational hours of the drying tank (i.e. scenario 6 vs. 7). These energy savings are at a manufacturing process level, and do not reflect the energy balance of the factory environment. When comparing the overall energy balance of the factory system for scenario 6 vs. 7 (Table 6-9), the process energy reduces by 19.6% (i.e. 34.7 from 43.2MWh/yr), but the facility energy increases by 1.5% (i.e. 151.9 to 154.1MWh/yr). This results in an overall (factory) energy balance saving of 3.2% as the facility energy is dominant.

By combining building physics and manufacturing process simulations the effects of energy conservation measures on the overall energy balance of the factory environment can be investigated. The results from the simulations shown in Table 6-7, Table 6-8, Table 6-9 and Table 6-10, highlight that the energy flows in a factory environment are complex. Use of this new simulation approach identifies that the change in operational hours of the process/facility systems can have an effect on the final energy consumption of the overall factory system, and not just at process level. Through use of an integrated simulation tool, energy managers can assess energy used at both facility and process level with a view to using energy in a more sustainable manner.

6.2.8. Further material modelling

This section discusses the modelling of material within the adapted IBPT. The modelling of material flow within a building physics tool is novel. The below, is based on the modelling of material flow using the above model inputs (i.e. factory building and tank – dimensions, construction and material properties), with exception to changes to the drying tank operation and material flow profiles. Profiles for tank operation and material flow have been obtained from logged data from the industrial partners of the THERM project, shown in Figure 6-4. Figure 6-4 illustrates one day of logged data. The blue area is the amount of time the drying tank is in operational mode (i.e. heated up to 40℃). The green area is the additional time the material resides inside in the tank after the tank has been turned off. The temperature of the material (i.e. red line) has been logged and recorded up to the moment the material is removed from the industrial process.

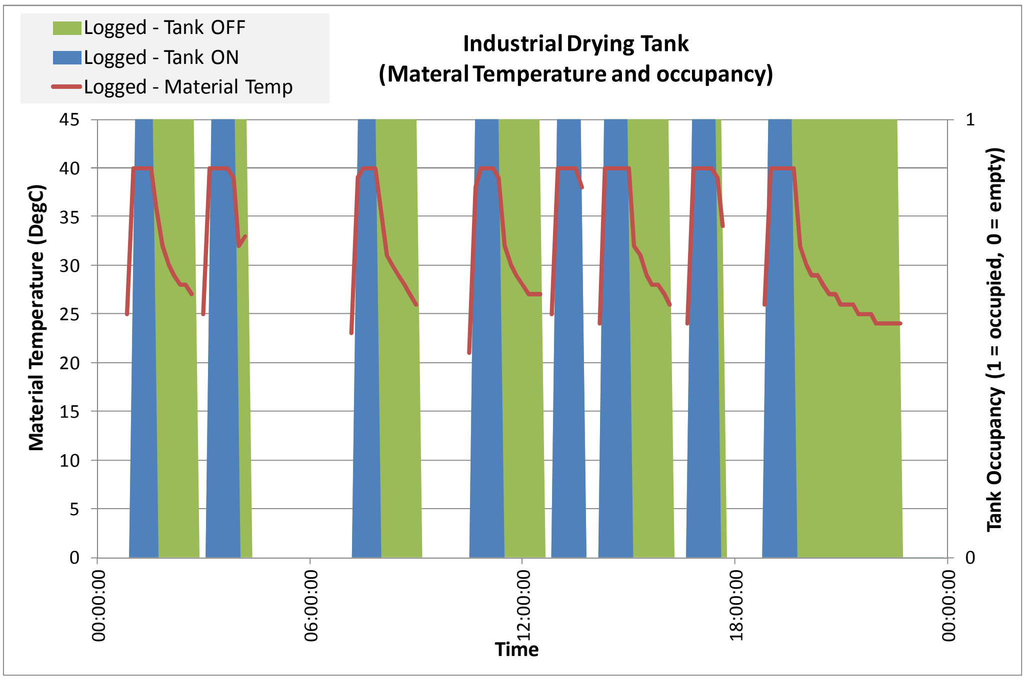


Figure 6-4 – Industrial logged data – Material temperature and occupancy

The tank operation and material flow profiles have been input into the adapted IBPT model and simulated over a year. Due to the period of assessment and the focus of the study at the time of the industrial logged data (i.e. historical study prior to research), no data was collected on the air temperature of the factory. By simulating the daily profiles over an annual period, estimations can be made on the environmental condition of the factory at that time. The logged data is from the period of November. The environmental strategy of the industrial partner states that in the heating season the temperature of the factory shall not fall under 18℃ during working hours. The environmental strategy coupled with the locality of the manufacturing process system on-site, explains why in Figure 6-4, the material temperature begins to decay sharply, and settles around 23℃. Figure 6-5 illustrates a best fit of the simulated results compared against the on-site logged data. Note, one material has been used in the simulation exercise, this can be seen in the figure. The figure extends the profile over two days to demonstrate the variability in the results.

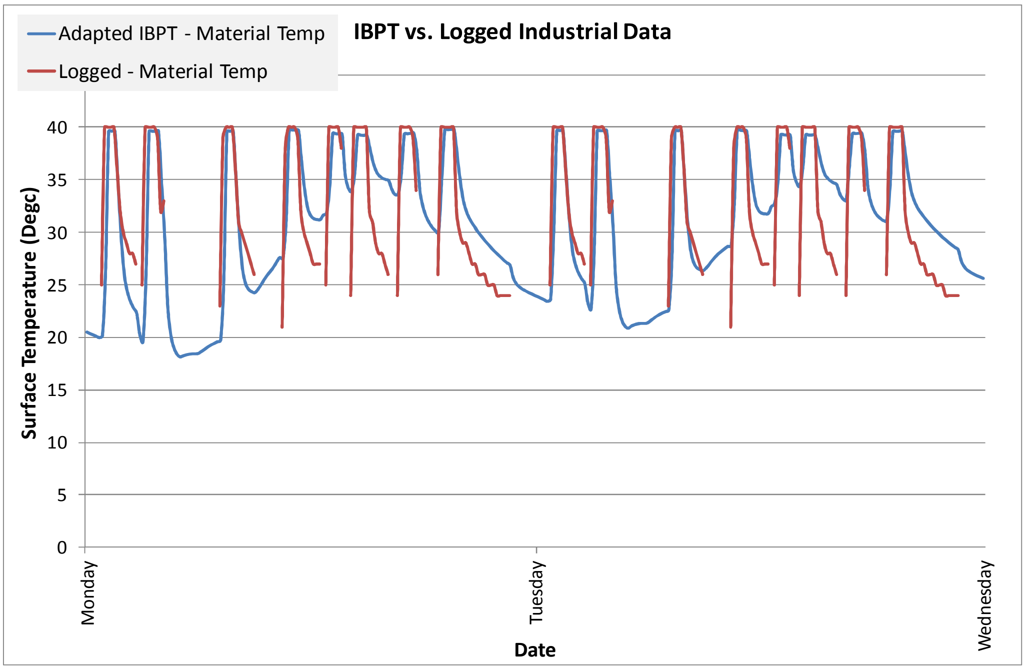


Figure 6-5 – Material surface temperature – adapted IBPT vs. logged industrial data

6.2.9. Discussion

6.2.9.1. Material

From Figure 6-5, it is shown that the simulated behaviour of the material is similarly matched to that of logged data from the industrial partners. The best fit occurs during the early hours of the day. This may be due to the lessening effects of variables that influence the internal air temperature of a factory building e.g. solar gains, internal gains, manufacturing process system gains. The increasing and decreasing of the simulated material temperature in a similar pattern to the logged data demonstrates good correlation. This provides confidence in the future use of the lumped capacitance method (section 4.2.2) to model material flow within the adapted IBPT.

6.3. Industrial treatments process

6.3.1. Method

This case study is based on an industrial treatments process representative of a thirteen tank process from data obtained from the industrial partners. Nine of the thirteen tanks operate at ambient temperature, and are not included within the case study. Three out of the four modelled closed tanks are temperature controlled (see Table 6-15) contain aqueous chemical solutions and have been simplified to water. The fourth tank is air based. All four are heated. The tanks are housed in a large factory building. Batched material is transferred from tank to tank following a sequence of dwelling and immersion, devised from an industrial recipe for cleaning material. The case study has been modelled within the adapted IBPT. The model includes internal thermal zones within the factory zone (a zone inside a zone), with three out of the four internal zones being filled with water. This is outside the capabilities of current building modelling tools. The case study also includes the flow of material between the treatment tanks and factory. The facility space heating (factory) and the heating of tank mediums (process) are based on a demand side energy approach only. Therefore no modelling of manufacturing plant has been included (e.g. boilers, heat exchanges, pipe networks etc). Table 6-11, an extract from Table 3-2, outlines the modelling criteria of the case study.

Table 6-11 – Industrial treatments process modelling criteria

	Criteria									
Case study (section number, title)	Factory	Windows	Space heating	Weather file	Process only	One internal process	> 1 internal process	Air (i.e. gas) process	Liquid process	Material flow
6.3_Industrial treatments process	•	•	•	•			•	•	•	•

6.3.2. Graphical representation

Figure 6-6 is a graphical representation of the energy flow paths that exist between the factory environment, the four treatment tanks and material flow.

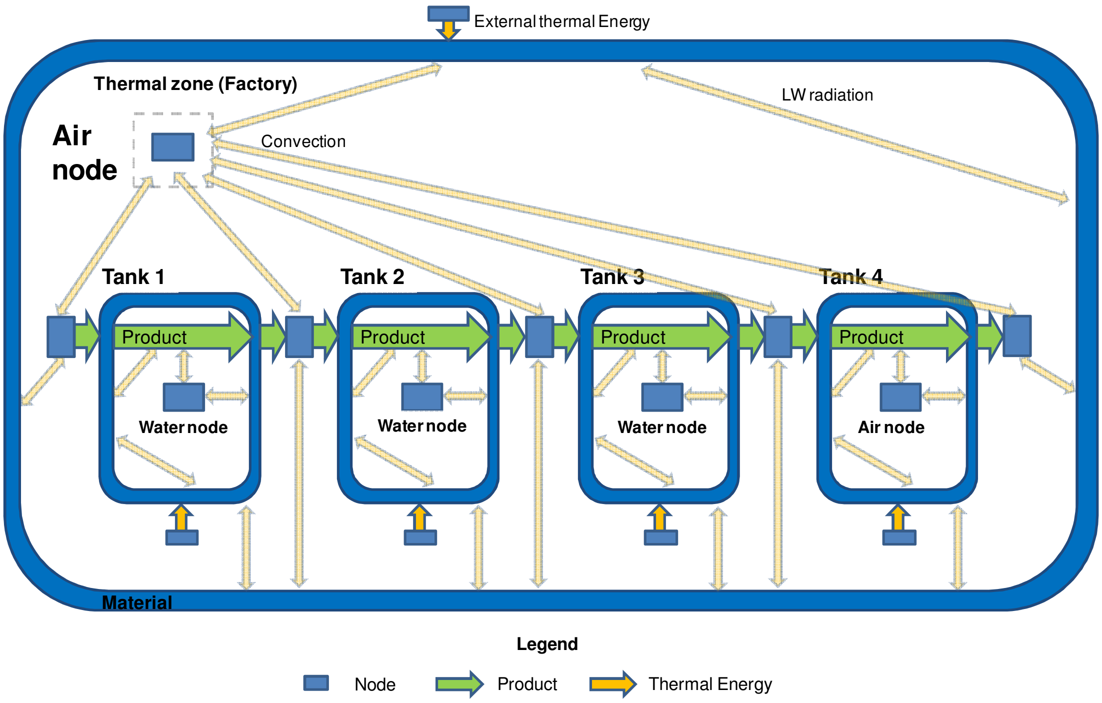


Figure 6-6 - Graphical representation of a four process tanks defined by zonal location)

6.3.3. Key data

The treatments process is representative of a real life industrial process obtained from the industrial partners of the THERM project. The environmental heating strategy for the factory environment is based on design conditions from the industrial partners. The building and treatment tanks are also representative of on-site dimensions, with the exception of adjoining thermal zones, windows and door areas to the factory building. The building has been simplified and modelled as a control boundary around the treatment tanks. The control boundary is a fixed condition within the scenarios modelled. Tabulated data in Table 6-12, Table 6-13 and Table 6-14, list properties that have been used within the adapted IBPT model.

Table 6-12 – Factory simulation data

Factory	
- North/South elevations	- 0.2m concrete - Surface area = 1000m² - Glazing - Surface area = 100m²
- East /West elevations	- 0.2m concrete - Surface area = 2400m² - Glazing - Surface area = 240m²
- Ground - Roof	- Adiabatic - Surface area = 6000m² - 0.01m steel - Surface area = 6000m² - Glazing - Surface area = 600m² - Volume = 120000m²
- Environmental conditions	- Heating season - See scenarios - Infiltration - See scenarios

Table 6-13 – Simulated material and medium properties

Material properties	
- Concrete	- Density 2400kg/m³, - Thermal conductivity 1.5W/m.K, - Heat capacity 800J/kg.K, - Absorptivity 0.65 - Emissivity 0.9.
- Steel	- Density 7800kg/m³, - Thermal conductivity 50W/m.K, - Heat capacity 480J/kg.K, - Absorptivity 0.7 - Emissivity 0.9
- Glass	- Density 2500kg/m³, - Thermal conductivity 0.7W/m.K, - Heat capacity 840J/kg.K, - Emissivity 0.9
- Water	- Density 1000kg/m³, - Heat capacity 4200J/kg.K

Table 6-14 – Treatment tanks and supplementary equipment simulated data

Treatment tanks and equipment	
Treatment Tank 1 - Construction - Environmental conditions	 - 0.01m steel - Surface area = 510m² - Volume = 350m³ - Medium = water - 2m off ground - Heating - Temperature = 50°C - Constant
Treatment Tank 2 - Construction - Environmental conditions	 - Same as Tank 1 - Heating - Temperature = 40°C - Constant
Treatment Tank 3 - Construction - Environmental conditions	 - Same as Tank 1 - Heating - Temperature = 35°C - Constant
Treatment Tank 4 - Construction - Environmental conditions	 - 0.01m steel - Surface area = 510m² - Volume = 350m³ - Medium = air - 2m off ground - Heating - Temperature = 35°C - Constant
Material (product) - Surface area	 - Steel - Surface area = 74m²

6.3.4. Simulation

Figure 6-7 is an extract of the treatments case study modelled within the adapted IBPT. The figure shows the key areas of the model i.e. factory building (green large box), factory construction (orange box), facility heating (light blue box) and infiltration (magenta box). Other key areas are shown in the dashed outlined boxes, bottom left, 4 No treatment tanks including sub-system representation of 1No. typical treatment tank and bottom right, material (product).

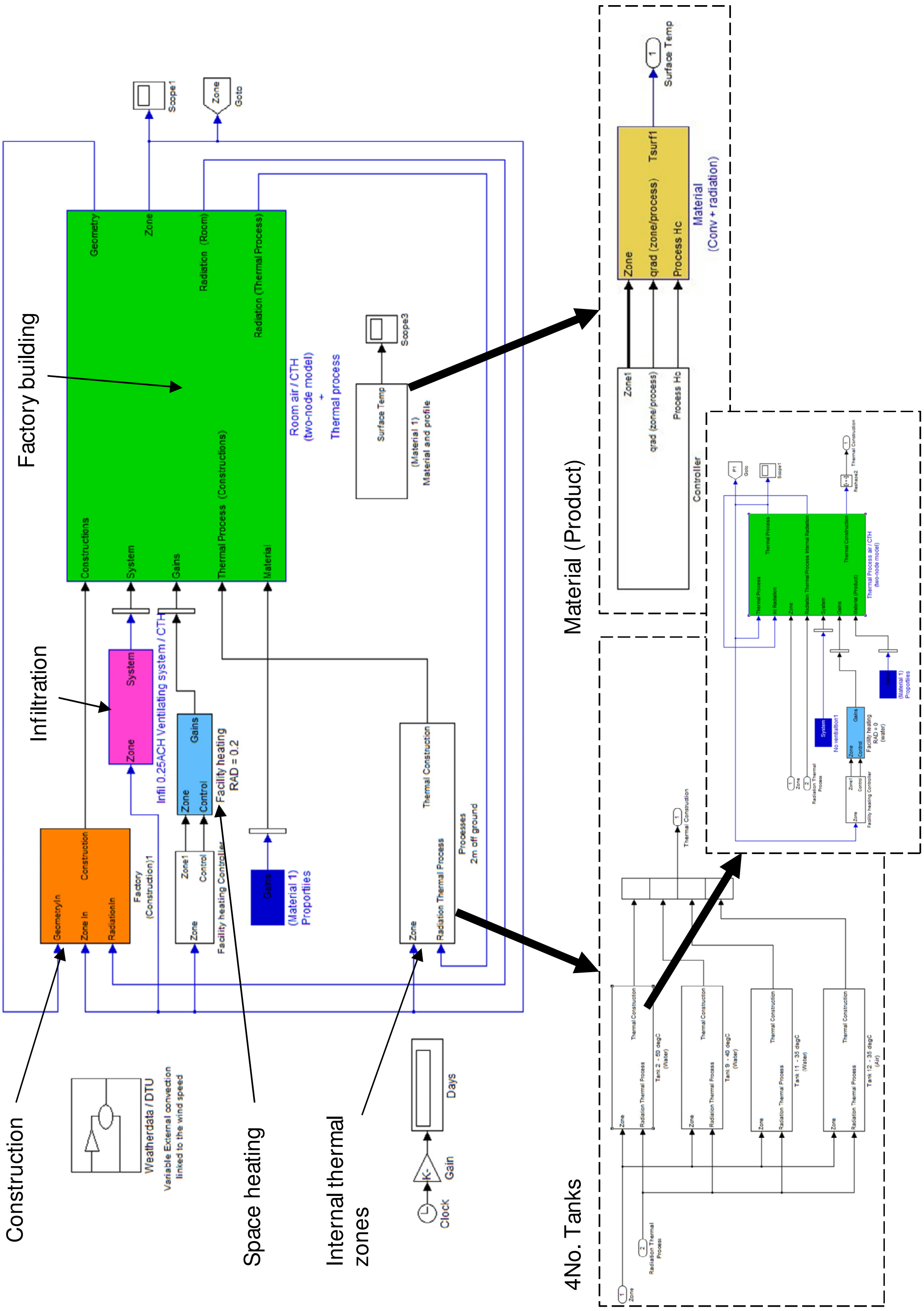


Figure 6-7 – Adapted IBPT illustration – Factory (environment, construction and four No. treatment tanks and material)

6.3.5. Scenarios

Table 6-15 details two scenarios that have been modelled within the adapted IBPT.

Table 6-15 – Simulated scenarios 1 and 2 including material flow)

	Building (Factory) (Radiant heating % = 0.2)					Process (Radiant heating % = 0.2)				Material
	Space heating (°C) * (1^{st} Oct – 28^{th} Feb)				ACH	Process heating (°C)				Profile
	Monday - Monday		Monday - Friday		Zone	Tank 1	Tank 2	Tank 3	Tank 4	
Scenarios	24 hrs	9am – 5pm	24 hrs	9am – 5pm*	24 hrs	24 hrs	24 hrs	24 hrs	24 hrs	
1	12			18	1.00	50	40	35	35	See profile
2	12			18	0.25	50	40	35	35	

The difference between the two modelled scenarios is the rate of infiltration to the factory building. Infiltration represents air leakage due to cracks and openings such as windows, doors and adjoining thermal zones. Typical infiltration rates for factories and warehouses lie between 0.25-2.5 air changes per hour (ACH) (BSRIA 2003). Building infiltration rates of 1ACH and 0.25ACH are modelled in scenarios 1 and 2. These equate to volumetric flow rates of $33m^3/s$ and $8m^3/s$, respectively. From Table 6-15 the infiltration rates are assumed constant all year round, representing air leakage due to cracks and openings such as windows, doors and adjoining thermal zones. The convective heat transfer coefficients for internal surfaces are set at $3W/m^2.K$ for natural or free convection within the IBPT. During the operation of the water and air based processes an allowance for forced convection of $500W/m^2.K$ and $200W/m^2.K$ has been modelled respectively to represent pumps, fans and motors that are designed to agitate the mediums (EngineeringToolbox 2012). Profiles within the adapted IBPT drive the operational controls for the heating system (facility), treatment tanks 1-4 (process) and the scheduled flow of material, Table 6-14. Material flowing from the factory, into the treatment tanks and back out into the surrounding zone is also included within the model. Figure 6-8, illustrates a material schedule based on six recipes (R1... to R6) to the treatment process obtained from an industrial partner of the THERM project. For each material recipe there is a maximum and minimum time band that the material can reside inside a tank. For example, R1 requires a minimum treatment time of 600seconds, and up to a maximum of 2400secsonds, for tank 1. This is shown in the figure by the floating vertical bands.

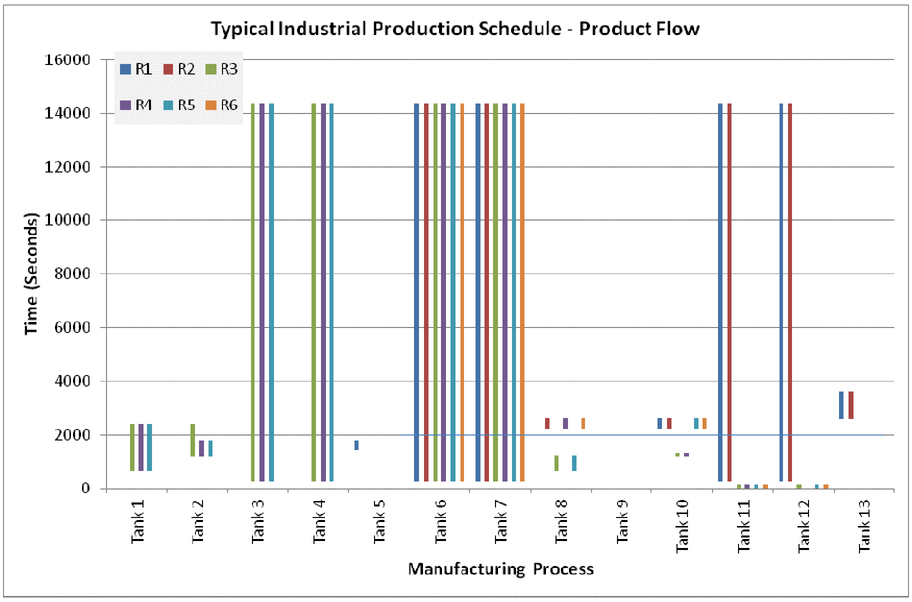


Figure 6-8 – Thirteen tank - industrial material (product) production schedule

A material flow profile within the adapted IBPT has been derived from the above production schedule data based on one material flowing through tanks 1-4, Figure 6-9. The vertical axis defines the location of the material during a typical 24hrs (treatment tanks 1 to 4). When the material is not assigned to a tank, the material is considered to be in the factory zone. The adapted IBPT is based on the H-Tool, heat transfer only. Therefore moisture and latent energy from material and the three water based treatment tanks is considered outside the scope of the work.

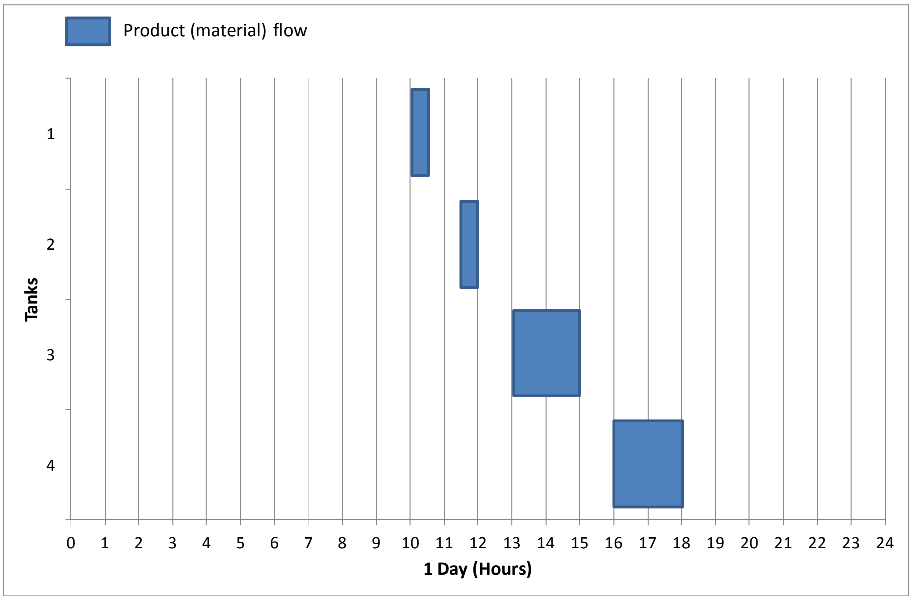


Figure 6-9 – A typical 24hr material (product) flow schedule in relation to location

The model uses the London Heathrow weather file 96-97 extracted from the IES software, as used in tool verification section 5.3. As in the case of the drying tank case study (section 6.4), the adapted IBPT was in part verified against results from the simulation in IES VE. However, the treatments case study includes material flow and liquid mediums such as water inside three of the tanks. At the time of writing IES VE is not capable of modelling material flow or liquid based manufacturing processes and cannot be used to verify the results of the adapted IBPT against. The verification work carried out in section 5.3 provides confidence in the results from the simulation of the adapted IBPT to model a factory, drying tank (air based process) and material flow. The change of medium inside the treatment tanks from air to water is an extension of the models capabilities. This requires a change in the mediums properties. This does not affect the models framework or structure, therefore the author believes that earlier verification work is still valid.

6.3.6. Results – macro level analysis

Scenarios 1 and 2 are based on an annual simulation period. Building infiltration rates of 1ACH and 0.25ACH are modelled in scenarios 1 and 2. Results can be found in Table 6-16. As would be expected the decrease in infiltration rate (i.e. 0.25ACH from 1.00ACH) has resulted in a lowering of the demand side energy consumption of the facility space heating in scenario 2. This is as a result of a reduction in the air exchange rate mixing external and internal factory air during the heating season. The overall energy consumption difference (i.e. facility and process energy) is approximately 35%, Table 6-16. Unexpectedly, process energy consumption (i.e. demand side process heating) to the four treatment tanks has reduced by approximately 2.2% (i.e. 893.3 from 913.1MWh/yr). This may be caused by the factory retaining higher air temperatures from the lowering of infiltration rates. The difference in energy consumption between tanks 3 (water) and 4 (air) highlights the difference in thermal properties of the mediums, to heat and maintain a constant temperature of 35°C.

Table 6-16 - Process/Facility energy consumption (adapted IBPT) including material

		Process energy (MWh/yr)				
	Facility energy (MWh/yr)	Tank 1 (50°C)	Tank 2 (40°C)	Tank 3 (35°C)	Tank 4 (35°C)	Total (MWh/yr)
Scenario 1 - (1 ACH)	2083.60	327.77	222.52	170.79	192.04	2996.72
Scenario 2 - (0.25 ACH)	1043.19	322.04	218.15	166.08	187.08	1936.53
					diff (%)	35.38%

Macro level data from a THERM industrial partner is shown in Figure 6-10. The figure outlines gas consumption for the treatments process area (i.e. facility space heating and process energy) against external weather data (i.e. daily mean dry bulb air temperature) for July 2006 to

July 2007. External weather data for the same period was unavailable. The nearest available weather data for 2010-11 is used in Figure 6-10 as an indication of the changing external air temperature over the year. Also, the treatments process energy data was not available for two consecutive years; therefore data from July 2006 to July 2007 was used. Units from Figure 6-10 have been removed due to the sensitive nature of data. Both space heating and process heating are metered from a single meter. This makes it difficult to determine how much gas is being consumed by the facility and process systems. From Figure 6-10, gas consumption can be seen to rise during the heating season October to April. Spikes in gas consumption during the remaining seasons (i.e. March and August), are in line with periods of shutdown and maintenance where a number of the tanks are emptied and refilled. Thus requiring increased energy loads to bring the tanks up to operational temperatures. From this an approximation of the annual process gas consumption is defined by the lower blue filled area, with the upper (red) area being that of factory space heating. It is hard to justify the assumption as the internal air temperature of the factory is unavailable. However the peaks and troughs of the heating energy consumption over the year roughly average out around the estimated consumption line, shown in Figure 6-10, though parts of this assumption lie outside the heating season.

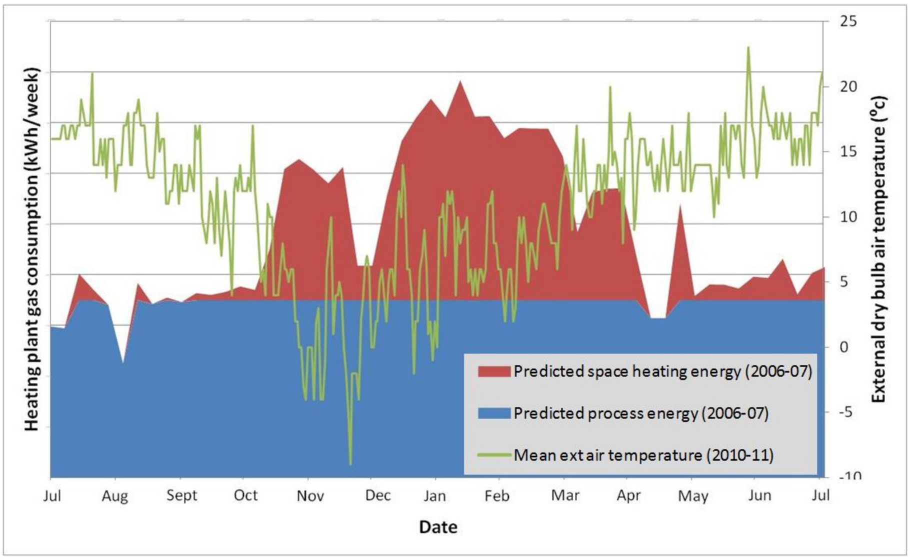


Figure 6-10 – Treatments – weekly gas consumption

From Figure 6-10, a monthly stacked bar chart of the treatments gas consumption for process and space heating, plotted against daily mean external dry bulb air temperature is shown in Figure 6-11.

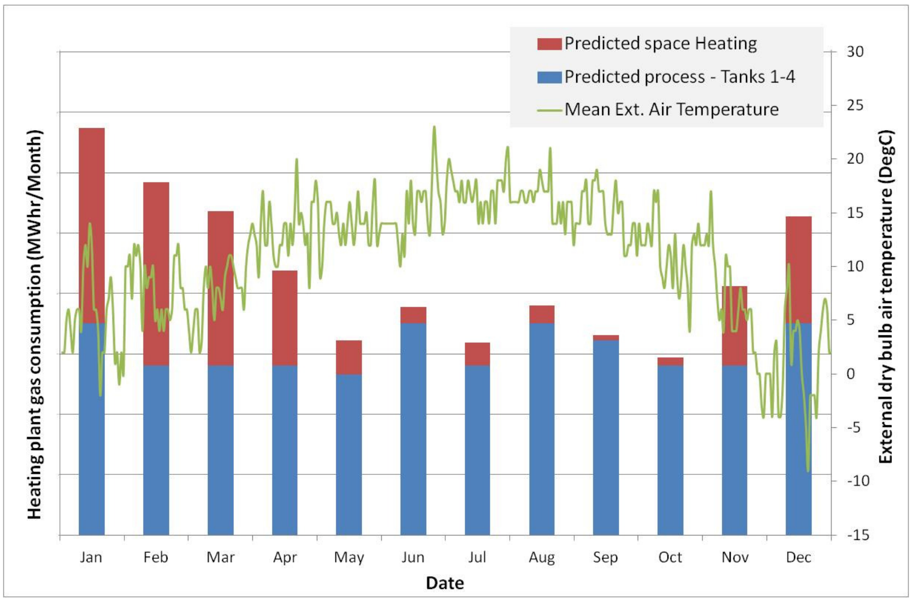


Figure 6-11 - Treatments – monthly gas consumption

For scenarios 1 and 2, monthly energy consumption for both facility and process system heating are shown in Figure 6-12 and Figure 6-13, respectively. Both graphs are plotted against daily mean external dry bulb air temperature. Note: the simulated scenarios 1 and 2 (Figure 6-12 and Figure 6-13) use a different weather data file to the industrial based example (Figure 6-11). The figures are used to compare patterns of energy use rather than actually quantitative data, as the modelled scenarios are simplified versions of the real life problem due to a lack of data from site.

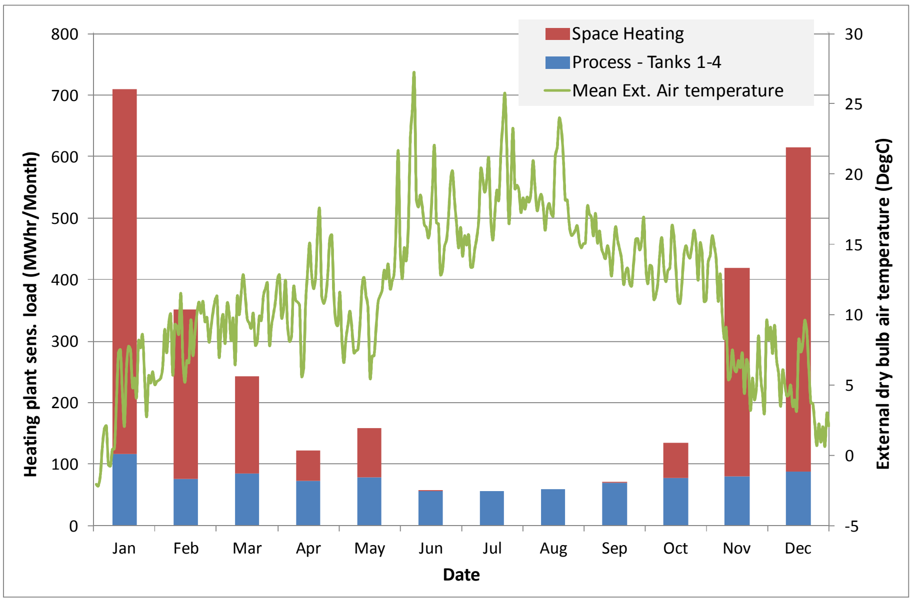


Figure 6-12 – Scenario 1 (1ACH) - Heating load (facility vs. process heating)

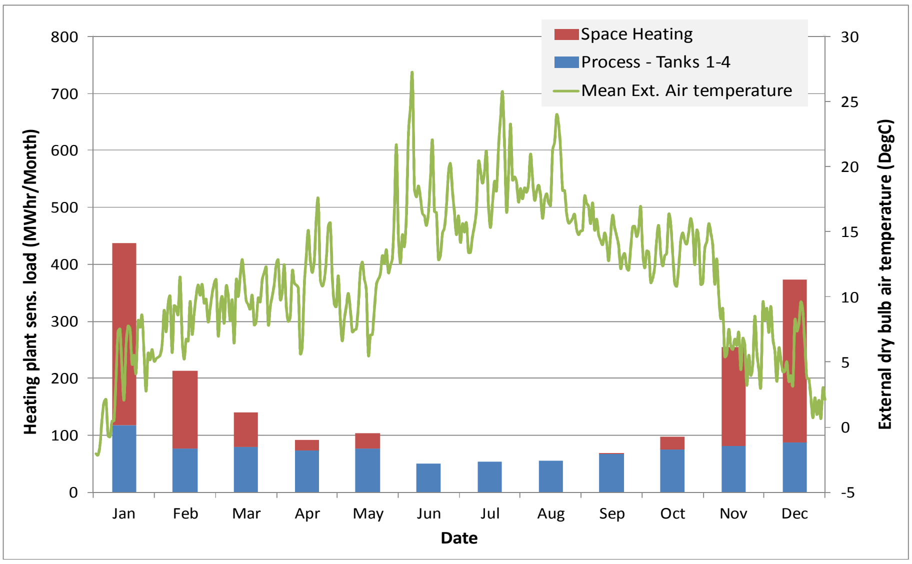


Figure 6-13 - Scenario 2 (0.25ACH) - Heating load (facility vs. process heating)

With the exception of the amounts of energy being consumed for scenarios 1 and 2 (Figure 6-12 and Figure 6-13), both graphs are similar in pattern to data obtained from site (Figure 6-11). Process energy consumption is at a steady rate, meaning that heat loss to its surroundings is at a constant rate. As shown in Table 6-16 and demonstrated on a monthly basis in Figure 6-12 and Figure 6-13, the facility heating energy consumption varies in relation to the infiltration rate. Energy consumed by the facility space heating is responsive to changes in weather (i.e. external air temperature).

6.3.7. Results – micro level analysis

Using a tool such as the adapted IBPT enables the user to explore the energy consumption of the factory not just at a macro level but also at a micro level (e.g. component level).

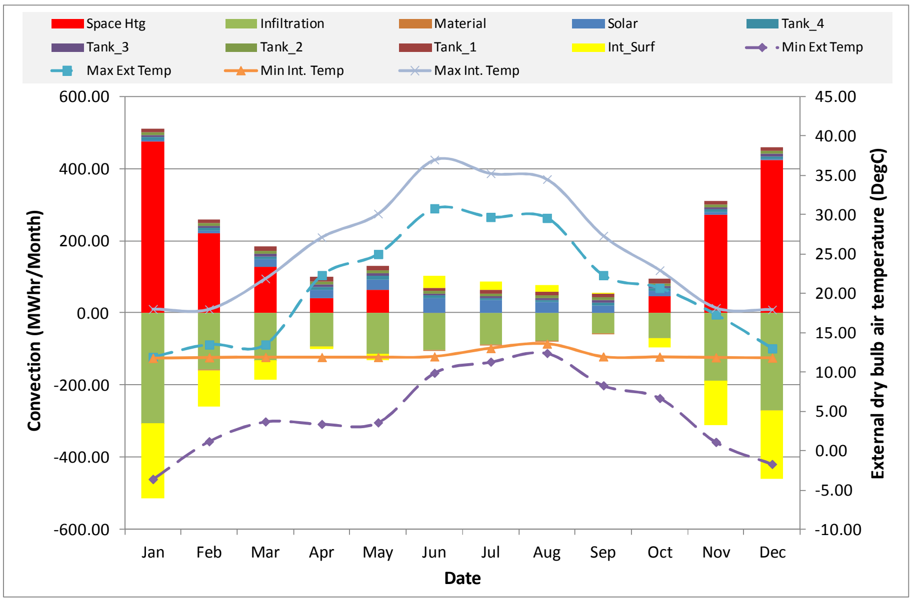


Figure 6-14 – Scenario 1 (1ACH) - Internal monthly convective heat transfer

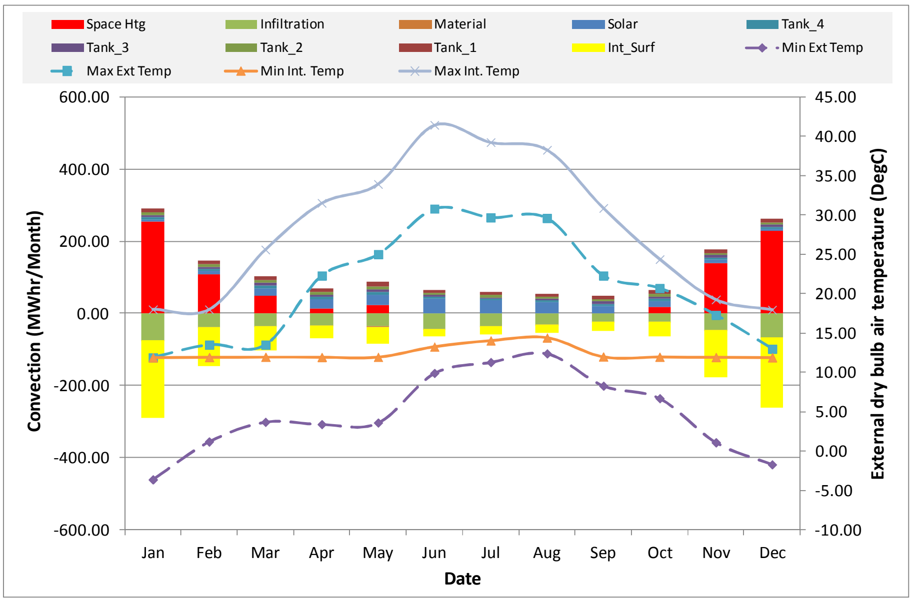


Figure 6-15 - Scenario 2 (0.25ACH) - Internal monthly convective heat transfer

At a micro level, components that contribute to convective heat gains/losses to the internal air temperature of the factory can be examined further (Ballarini et al. 2011), Figure 6-14 and Figure 6-15 for scenarios 1 and 2 respectively. These components consist of, factory internal surfaces (expanded in Figure 6-16 and Figure 6-17), tank and material surfaces, solar, facility (space) heating and infiltration. Radiant heat transfers do not have a direct effect on the internal air temperature of a zone. The absorption of radiation increases internal and external surface temperatures, to which convective heat transfers to the internal air temperature of the factory take place. The proportion of radiant heat transfers that occur within scenarios 1 and 2 are not discussed here. Figure 6-14 and Figure 6-15 are plotted against monthly maximum/minimum air temperatures for external weather and internal factory air temperatures. During the summer/spring seasons the higher infiltration rate has a cooling effect on the internal temperature of the factory thermal zone, reducing the internal air temperature from highs of 42℃ (scenario 2) to 36℃ (scenario 1) in June. The facility heating mainly offsets convective infiltration losses in the autumn/winter seasons for scenario 1, where in scenario 2 internal surfaces are dominant. Figure 6-16 and Figure 6-17 break down the internal components into individual surfaces of the factory building for scenarios 1 and 2 respectively. Where, wall and glazing orientations are denoted by N, S, E and W (i.e. north, south, east and west). Space heating and infiltration gains/losses are dominant, with the west wall (w_wall) and roof surfaces contributing the most from the remaining components, Figure 6-16 and Figure 6-17. The figures also indicate that the process tanks (1 to 4) produce significant positive convective heat transfer, especially in scenario 2 (Figure 6-17) when both facility and infiltration gains/losses are lower in comparison to scenario 1 (Figure 6-16).

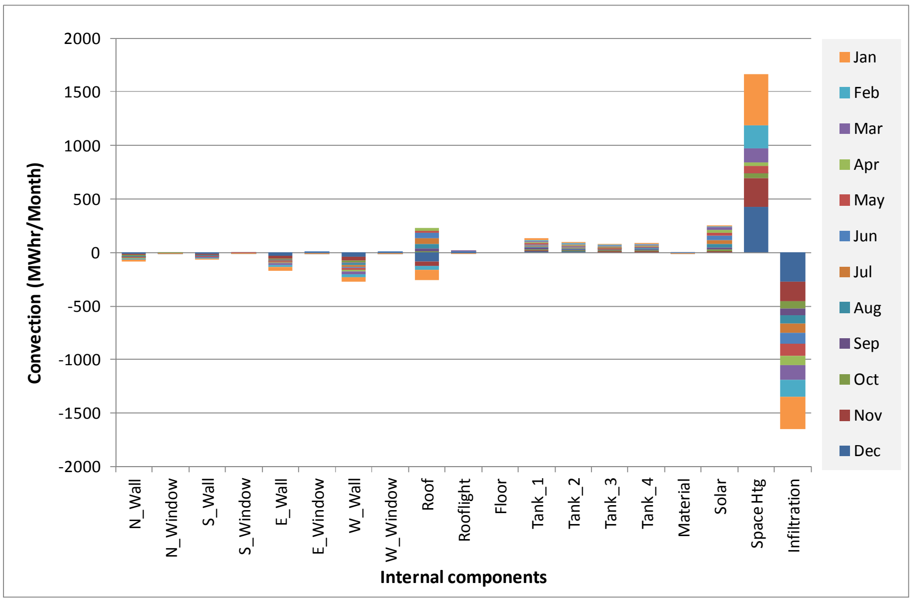


Figure 6-16 – Scenario 1 (1ACH) - Individual internal convective heat transfer

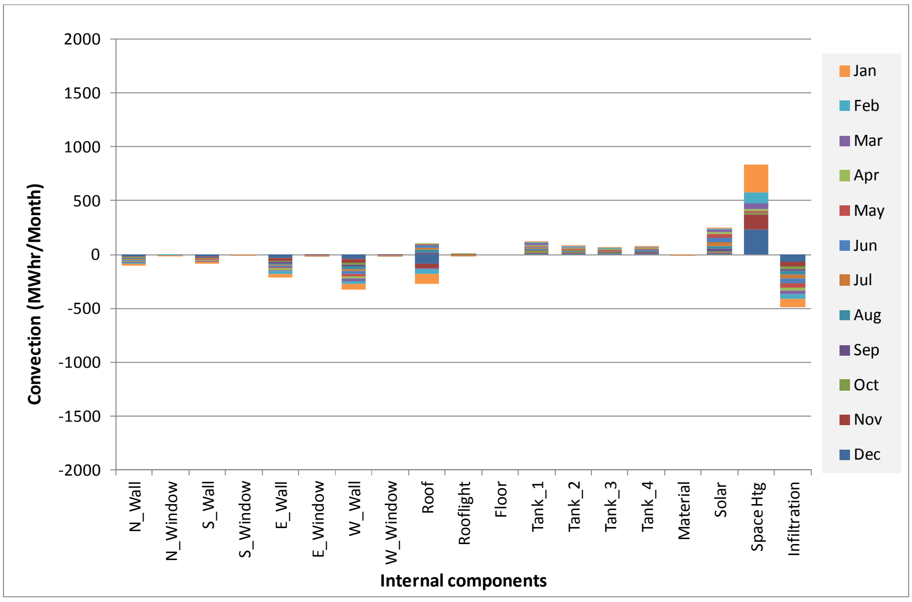


Figure 6-17 - Scenario 2 (0.25ACH) - Individual internal convective heat transfer

A more comprehensive look at internal convective heat transfer is shown in Figure 6-18 to Figure 6-21 during the periods of January 1st to 7th and June 1st to 7th for scenarios 1 and 2. The figures are compared against hourly internal (factory) and external (weather) dry bulb air temperatures. In Figure 6-18 (January 1st to 7th, scenario 1), convective heat transfer gains from space heating offset losses from infiltration and internal surfaces of the factory, as a result of the external dry bulb air temperature dropping below 0°C for parts of the week.

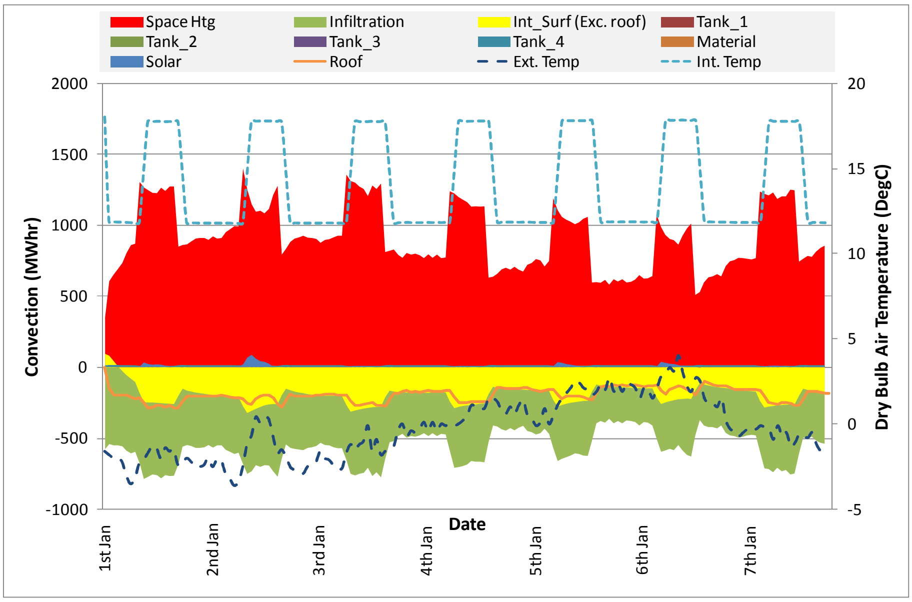


Figure 6-18 – Scenario 1 (1ACH) - Individual internal convective heat transfer (Jan 1-7)

In Figure 6-19 (June 1st to 7th, scenario 1), convective heat transfer gains from solar are dominant during June, as expected. Where, infiltration has a negative effect during the same period. This creates a cooling effect as the external air drawn into the factory environment is at lower temperature than the factory, thus providing free cooling.

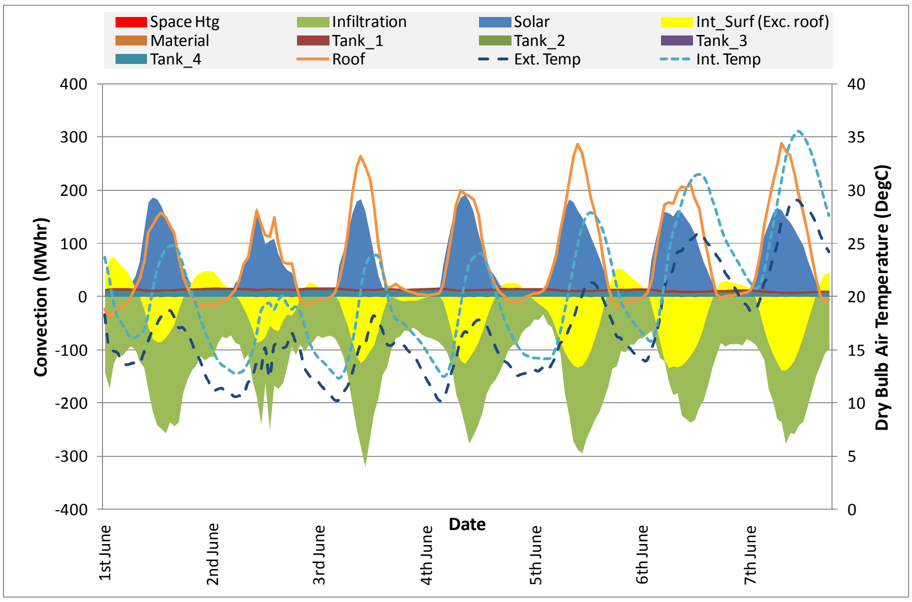


Figure 6-19 - Scenario 1 (1ACH) - Individual internal convective components (June 1-7)

In Figure 6-20 (January 1st to 7th, scenario 2), similar conclusions can be drawn to Figure 6-18 (January 1st to 7th, scenario 1), with exception to lower convective heat transfer losses from infiltration.

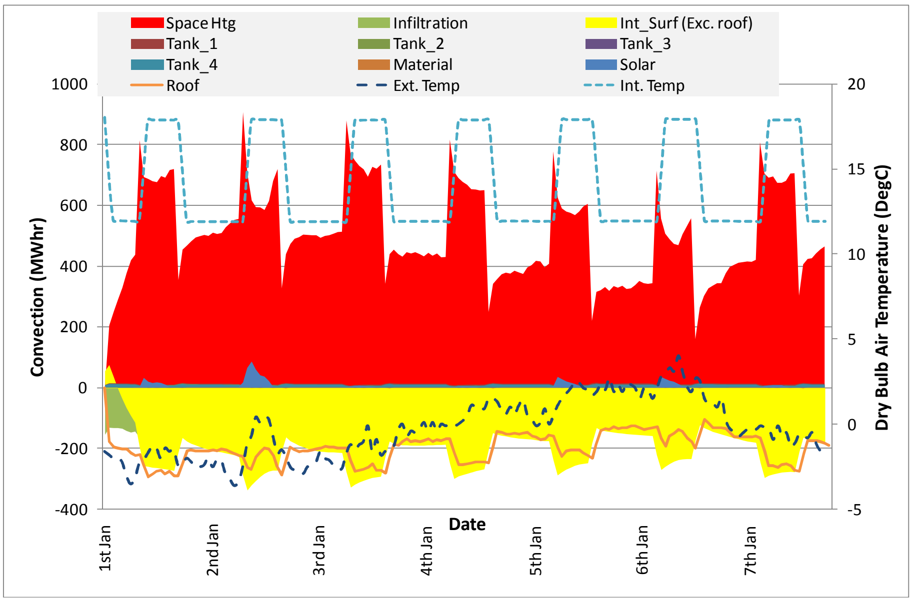


Figure 6-20 - Scenario 2 (0.25ACH) - Individual internal convective heat transfer (Jan 1-7)

In Figure 6-21 (June 1st to 7th, scenario 2), a reduction in infiltration convective heat transfer losses in comparison to Figure 6-19 (June 1st to 7th, scenario 1), results in an increase in factory air temperature between the two scenarios modelled.

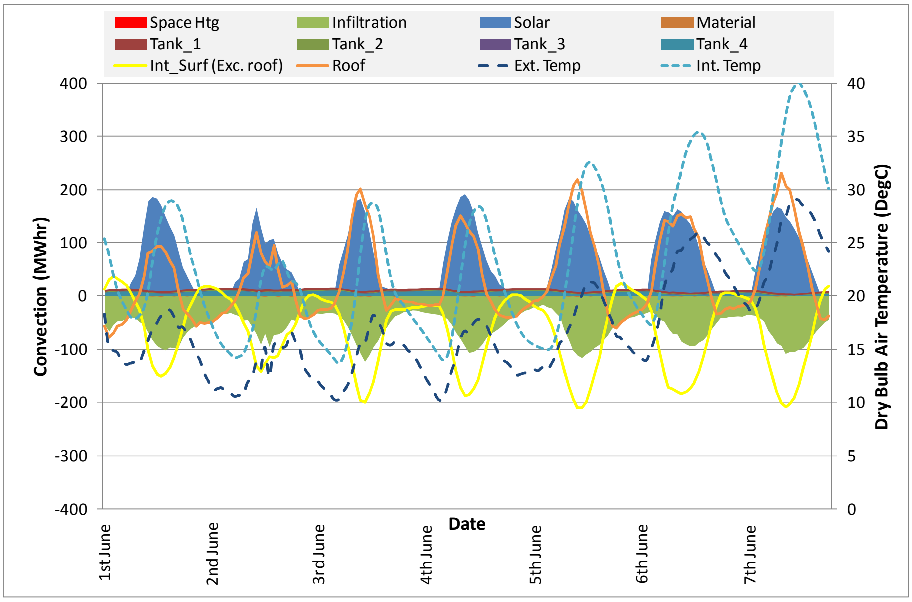


Figure 6-21 - Scenario 2 (0.25ACH) - Individual internal convective components (June 1-7)

It is noted that outside the heating season in Figure 6-14 and Figure 6-15 convective heat transfer from internal surfaces is positive for scenario 1 and negative for scenario 2. The reason for this can be seen more clearly in Figure 6-19 and Figure 6-21, when deducting the difference between gains/losses from the roof and other internal surfaces. Coupling this difference with the convective gains/losses from infiltration and solar gains, the differences between scenarios 1 and 2 can be understood more clearly. These outputs are compared in Table 6-17, at 13:00 on the 5th June.

Table 6-17 – Selected component convective gains/losses (13:00, 5th June)

	Component convective gains/losses (MWhr)					
	Internal surfaces (Exc. Roof)	Roof	Infiltration	Solar	Total	Int. Temp (℃)
Scenario 1 (1.00 ACH)	-133.58	285.66	-288.63	160.86	24.31	24.72
Scenario 2 (0.25 ACH)	-209.67	218.84	-112.11	160.86	57.92	28.48

6.3.7.1 Material (product) analysis

The convective heat transfer gains/losses to the factory environment from the material component are shown for January 1st to 7th and June 1st to 7th for Scenario 2, Figure 6-22 and Figure 6-23, respectively.

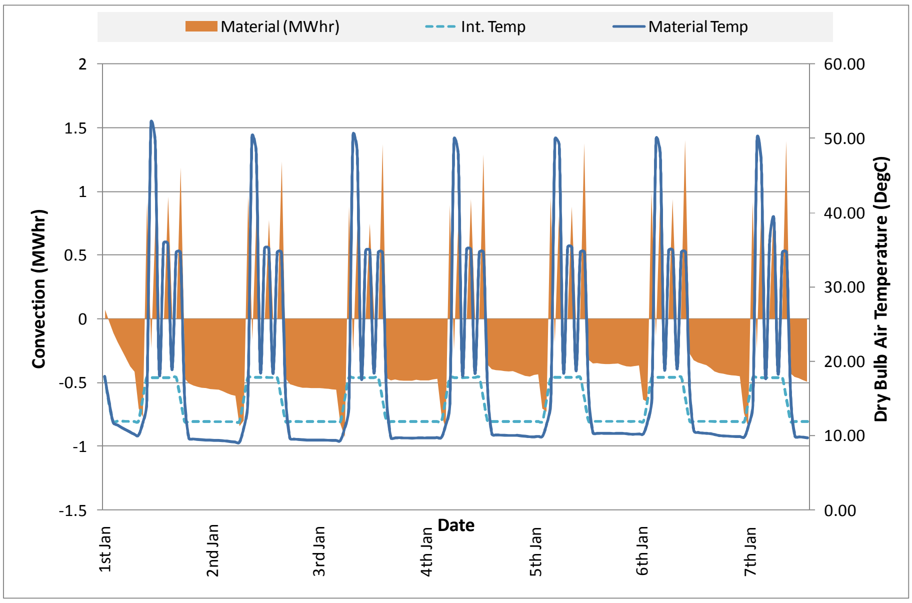


Figure 6-22 - Scenario 2 (0.25ACH) – material convective component (Jan 1-7)

Peaks in material temperature occur when the material resides inside the process treatment tanks (i.e. tank 1 (50°C), tank 2 (40°C), tank 3 (35°C) and tank 4 (35°C). Figure 6-22 shows convective heat transfer gains/losses to the thermal zone of the factory environment from the material. This is clear as the peaks in material temperature also occur at periods of zero convection heat transfer from the material to the factory zone, also demonstrated in Figure 6-23 (i.e. June 1st to 7th), as the material is inside the treatment tanks. During periods when the material is in the factory zone the temperature of the material is lower than the surrounding factory zone for sustained periods of analysis, resulting in a negative convective heat transfer to the central air node of the factory thermal zone, Figure 6-22.

During the period June 1st to 7th, the material temperature is greater than the surrounding factory air temperature, resulting in a positive convective gain to the factory thermal zone, Figure 6-23. Peaks in convective gain to the factory in Figure 6-22 and Figure 6-23 occur when the material leaves the treatment tanks in a higher temperature state than its factory surroundings.

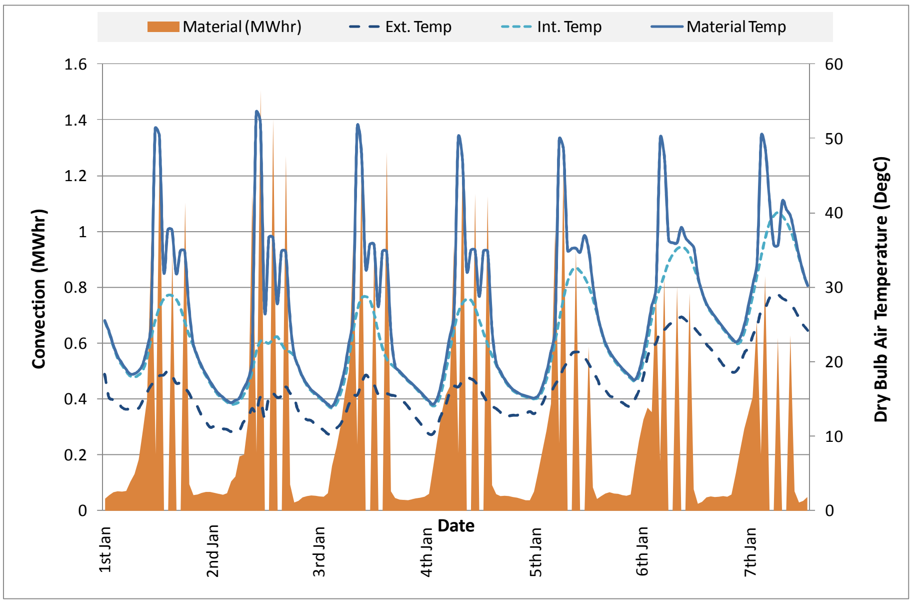


Figure 6-23 - Scenario 2 (0.25ACH) – material convective component (June 1-7)

6.3.8. Discussion

This case study has demonstrated the modelling of liquid based manufacturing processes and material flow within the framework of a building modelling tool. The case study has analysed data at both macro and micro levels. Simulated macro results have been compared and contrasted against data obtained from the industrial partners of the THERM project on a monthly basis, Figure 6-11 to Figure 6-13. The results demonstrated a similar pattern in process and space heating energy usage on-site against simulated outputs. The micro analysis explored components that contribute to convective heat gains/losses to the internal air temperature of the factory thermal zone. Further analysis can be made at this level as to which convective components are more dominant in effecting the balance of the internal air temperature of the factory. A decrease in factory building infiltration rate from 1ACH to 0.25AC in scenarios 1 and 2 demonstrated interesting observations such as, a decrease in summer time internal air temperature of the factory when simulating a higher infiltration rate, and a change in positive vs. negative convection heat transfer from the internal surfaces of the factory building during the summer months when comparing scenario 1 and 2. The case study only changed one parameter (i.e. infiltration rate) between scenarios, further analysis could investigate the effects on the convective heat transfer balance of the factory environment in relation to model changes such as, revised construction properties for both the factory and tanks, different tank mediums, increased/decreased glazing percentages etc. The concluding section demonstrates convective heat transfer from the material to the factory environment. Though in this case the convective energy flows from the material may be considered minimal in relation to other components discussed. For industries that operate high temperature manufacturing processes, the modelling of material and thus convective heat transfers from the material may have greater implications. An integrated tool such as the adapted IBPT enables the user to investigate energy flows within a factory environment.

6.4. Air supply house

6.4.1. Method

The air supply house (ASH) is a manufacturing process system representative of an industrial THERM partner process. The ASH supplies large volumes of air under controlled conditions (i.e. dry bulb temperature and relative humidity) and volumetric flow rate (i.e. laminar) to a desired destination. Block flow models of each of the main manufacturing plant (i.e. gas burner, biscuit humidifier, steam injection, closed loop cooling coil, closed loop steam re-heat and supply fan) constituting to the overall functionality of the ASH unit have been created within the Simulink environment. The effects from and upon the surrounding building environment are not included within the model. The reasons for this decision are discussed in section 6.4.4. Table 6-18, an extract from Table 3-2, outlines the modelling criteria of the case study. Some of the results do not include units, this is because the data is sensitive to the industrial partner to which the data has been sourced from.

Table 6-18 – ASH modelling criteria

Case study (section number, title)	**Criteria**									
	Factory	Windows	Space heating	Weather file	Process only	One internal process	> 1 internal process	Air (i.e. gas) process	Liquid process	Material flow
6.4_Air supply house				•	•			•		

6.4.2. Graphical representation

Figure 6-24 illustrates the configuration of the ASH unit. The ASH process conditions external air to achieve temperature and humidity conditions within a psychrometric control window (Figure 6-25) by-passing the air through a sequence of plant before supplying it to a desired destination.

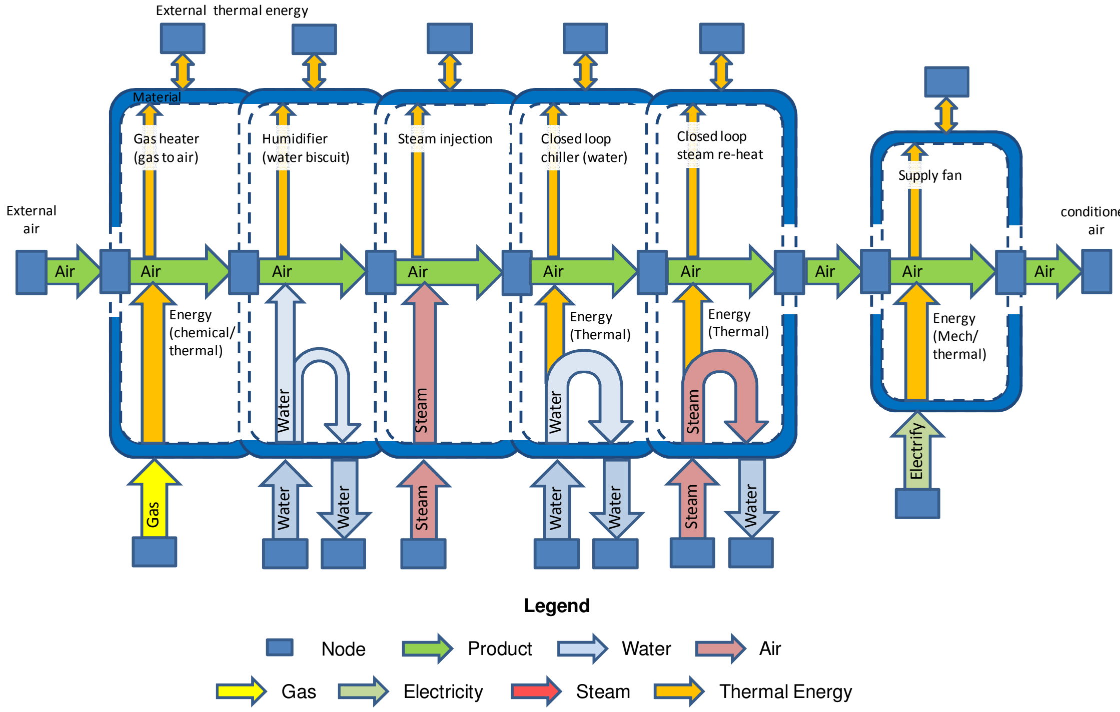


Figure 6-24 - Graphical representation of air supply house (compartmentalised plant) (Oates et al. 2012)

Figure 6-25 illustrates the psychrometric behaviour and sequence of plant: gas burner (1), humidifier (2), steam injection (3), closed loop chiller (5) and closed loop steam reheat (4). The blue circles represent warm/moist (upper right) and cold/dry (lower left) inlet conditions of the external air. Depending on the condition of the external air not all of the sequenced plant is required.

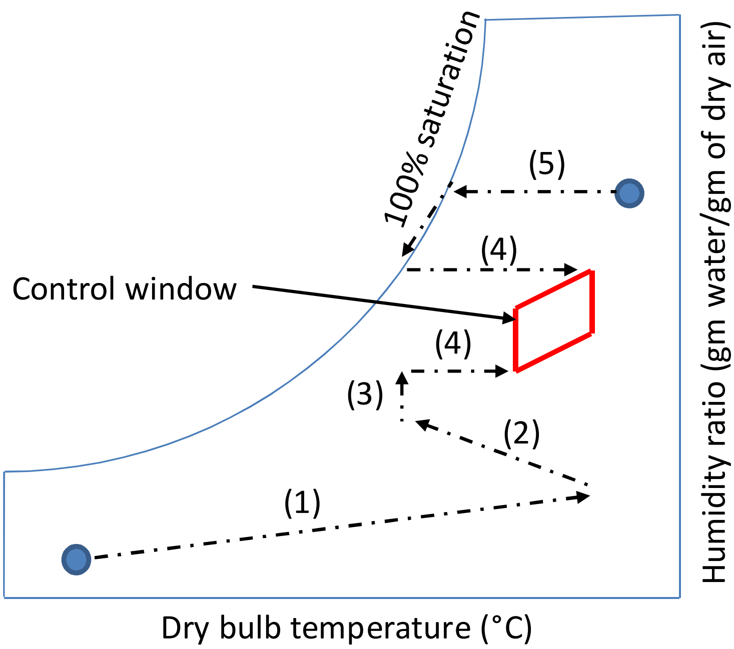


Figure 6-25 - Psychrometric chart with control window (Oates et al. 2012)

6.4.2.1. Key data

Qualitative data has been collated from a range of sources from the industrial partner of the THERM project, including, equipment data sheets, site visits (e.g. site walk around and discussions with senior engineers) and from the industrial partners supervisory control and data acquisition (SCADA) system. Data from equipment data sheets and diagrams are shown in Table 6-19. Metered and monitored data obtained from the SCADA system is shown in Table 6-20, where, wet bulb temperature (T_w), dry bulb temperature (T_d) and relative humidity (RH). The SCADA system records metered data at intervals of approximately 10seconds.

Table 6-19 – ASH unit equipment data

	Specifications
ASH unit dimensions (W/H/L)	9.5/ 4.1/ 9.5 (m)
Inlet (external) air condition	Weather dependant
Gas burner	6000 Rating (kW)
Water based biscuit humidifier	800 l/min 2.2 Rating (kW)
Steam injection humidifier	928,800 Rating (kcal/hr) ≈1080 Rating (kW) 1548 Kg/hr
Closed loop water chiller	700 Rating (kW/hr) 1161 l/min
Closed loop steam re-heat	928,800 Rating (kcal/hr) ≈1080 Rating (kW)
Supply fan	3250 m^3/hr 132 Rating (kW)
Conditioned outlet air (dry bulb temperature/ relative humidity)	(20.8-22.8℃)/ (63-68%)

Table 6-20 – Logged variables available from the SCADA system

	Air condition (after equipment) except inlet	Other logged data
Inlet (external) air condition	T_w, T_d, RH	-
Gas burner	T_d	Consumption (kWh), valve position (%)
Water based biscuit humidifier	4 x T_d	No. biscuits
Steam injection humidifier	-	Valve position (%)
Closed loop water chiller	-	Valve position (%)
Closed loop steam re-heat	-	Valve position (%)
Supply fan	-	Flow rate (m^3/hr)
Outlet air condition (dry bulb temperature/ relative humidity)	T_w, T_d, RH	-

6.4.3. Simulation (Macro)

6.4.3.1. Overview

Figure 6-26 is an extract of the ASH process modelled within the Matlab/Simulink environment using macro level data.

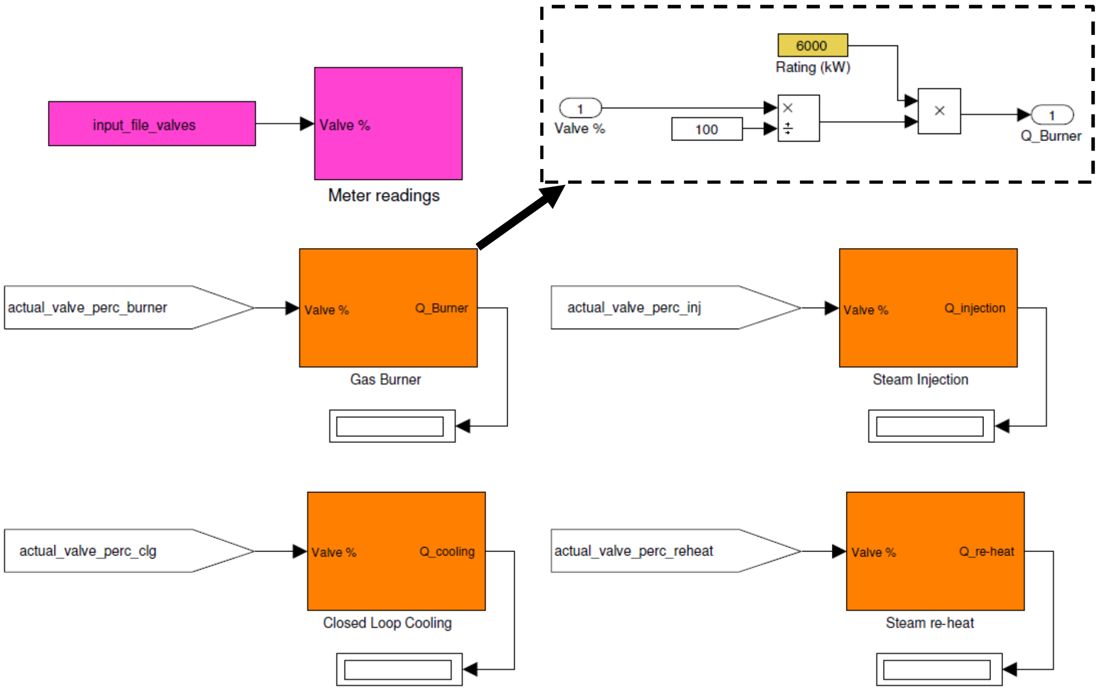


Figure 6-26 - Matlab/Simulink – Macro ASH case study (based on metered valve position)

This approach is based on site metered valve position data and manufacturing plant capacity ratings. The figure shows the key inputs of the model, site metered valve position data (magenta box), manufacturing plant (orange boxes) and plant capacity ratings (yellow box). The modelled approach does not include provisions for the surrounding built environment and fabric construction of the ASH unit, see section 6.4.4.

6.4.3.2. Physics and controls

The mathematics behind each of the manufacturing plant model blocks are the same for each component. The meter block (magenta) reads logged data at approximately 10 second intervals and directs this information to the appropriate manufacturing plant block (i.e. orange boxes - burner, injection, cooling and re-heat). Known capacity ratings (yellow box) for each plant are multiplied by the valve position to determine the demand side energy consumption for each of the manufacturing plant, as follows:

$$\dot{Q} = valve\ position \times capacity\ rating_{burner,\ injection,\ cooling,\ re-heat}$$

Equation 6-1

Where, $\dot{Q}_{burner,\ injection,\ cooling,\ re-heat}$ is the demand side energy consumption of the ASH plant components (kW), valve position is the percentage opening of the valve position of the ASH plant (%) and capacity rating is the capacity rating of the ASH plant (kW) . Valves are known and designed to be highly non-linear. Logged readings for the valve position from the industrial partners data are recorded at intervals of every 10 seconds; therefore the assumption of non-linearity in equation 6-1 between recordings will result in a small error in the results. This however will be considerably less than in comparison to recordings at greater time intervals, such as 1, 5, 10 and 30 minute intervals.

6.4.3.3. Model boundaries

The capacity rating values for the manufacturing plant do not take into account equipment and energy source efficiency losses. The macro level analysis calculates demand side energy consumption of the ASH plant only.

6.4.4. Simulation (Micro)

6.4.4.1. Overview

Figure 6-27 is an extract of the ASH process modelled within Matlab/Simulink using micro level data. The figure shows the key components of the ASH process, manufacturing plant (orange boxes) and air flow throughout the system (green interconnecting boxes).

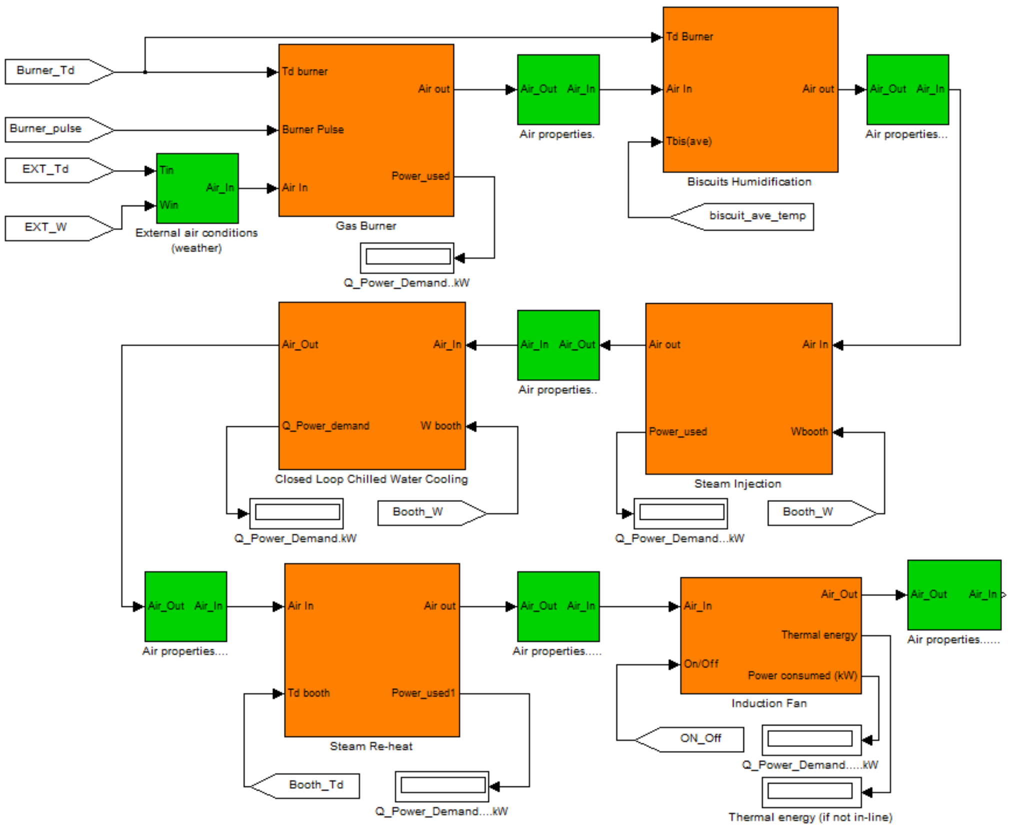


Figure 6-27 – Matlab/Simulink – Micro ASH modelled approach (compartmentalised plant)

The modelled approach does not include provisions for the surrounding built environment and fabric construction of the ASH unit. This is primarily due to the limitation of data available, Table 6-19 and Table 6-20. This data is focused on the performance of the manufacturing process system to supply controlled conditioned air to its target destination. There is a lack of data available to model the surrounding built environment and shell encasing the process. This does not detract from the importance of an integrated approach within the adapted IBPT. The modelled approach discussed in section 4.1, enables models to be built up through a nodal network as more data becomes available. Micro models can be integrated into macro models that include the built environment (i.e. factory environment) and networks of manufacturing process systems and material flow.

6.4.4.2. Fundamental physics and controls

The ASH process is made up of block flow models created in Simulink and are representative of the manufacturing plant (i.e. gas burner, biscuit humidifier, steam injection, closed loop cooling coil, closed loop steam re-heat and supply fan). Each modelled block is based on fundamental physics and air-based psychrometrics (ASHRAE 2001; Jones 2005; Incropera et al. 2006). The drivers behind the controls of the models are discussed below.

<u>Control window</u>

The ASH process operates under a control system designed to condition the passing air to within limits of a psychrometric control window of $Td_{control}$ 20.8-22.8°C and $RH_{control}$ 63-68%, Figure 6-25.

<u>Gas burner</u>

Parameters from Table 6-20:

- Metered data: external environmental conditions (wet bulb temperature (Tw), dry bulb temperature (Td) and relative humidity (RH))
- Metered data: pulse metered consumption (kWh) and valve position (%)
- Metered data: post burner (Td)

The psychrometric behaviour of the gas burner (1) is illustrated in Figure 6-28.

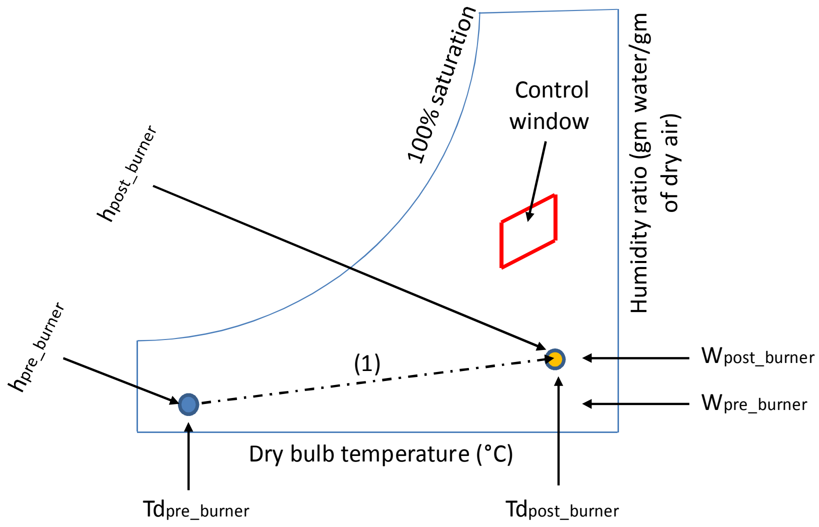


Figure 6-28 – Gas burner - psychrometric chart with control window

The inlet condition of the air can be accessed psychrometrically to derive the specific enthalpy (h_{pre_burner}) and humidity ratio (W_{pre_burner}) of the air pre-burner (i.e. external weather condition). The burner increases the thermal energy of the passing air to a higher temperature state (i.e. logged post Td_{post_burner}). However, it is believed that the passing air will also increase in moisture and thus in humidity ratio after the gas burner (W_{post_burner}). The combustion of methane (CH_4) is 50.0x10^6 J/kg (this is the 'lower heating value' which assumes that the water ends up as vapour), where, One mole (0.018 kg) of CH_4 releases 50.0x10^6 x 0.018 Joules of heat and two moles (2 x 16g = 0.032 kg) of water vapour.

$$\Delta W = \Delta Td \times 0.0362$$

$$W_{post\_burner} = \left(\left(\mathrm{Td}_{\mathrm{post\_burner}} - \mathrm{Td}_{\mathrm{pre\_burner}}\right) \times 0.0362\right) + W_{pre\_burner}$$

Equation 6-2

Where, W_{post_burner} and W_{pre_burner} are the humidity ratio of the air condition post and pre burner (g of moisture/kg of dry air) and $\mathrm{Td}_{\mathrm{post\_burner}}$ and $\mathrm{Td}_{\mathrm{pre\_burner}}$ are the dry bulb air temperature of the air, post and pre burner (°C).

The specific enthalpy of the air post-burner (h_{post_burner}) and the demand side energy consumption can be derived as follows, where $\dot{m}$ = mass flow rate of dry air (kg/s):

$$h_{post\_burner} = \left(1.006 \times Td_{post\_burner}\right) + W_{post\_burner}\left(2501 + 1.805 \times Td_{post\_burner}\right)$$

Equation 6-3

Where, h_{post_burner} is the enthalpy of the air condition post burner (KJ/Kg).

$$\dot{Q}_{burner} = \dot{m}\Delta h \quad = \quad \dot{m} \times \left(h_{post\_burner} - h_{pre\_burner}\right)$$

Equation 6-4

Where, $\dot{Q}_{burner}$ is the energy consumption of the gas burner (kW), $\dot{m}$ is the mass flow rate of air (kg/s) and h_{pre_burner} is the enthalpy of the air condition pre burner (KJ/Kg).

<u>Biscuit humidification</u>

Parameters from Table 6-20:

- Metered data: 4No. dry bulb temperature ($Td_{post\_biscuit}$) post-biscuit readings
- Derived: h_{post_burner}, W_{post_burner}

The psychrometric behaviour of the biscuit humidification (2) is illustrated in Figure 6-29.

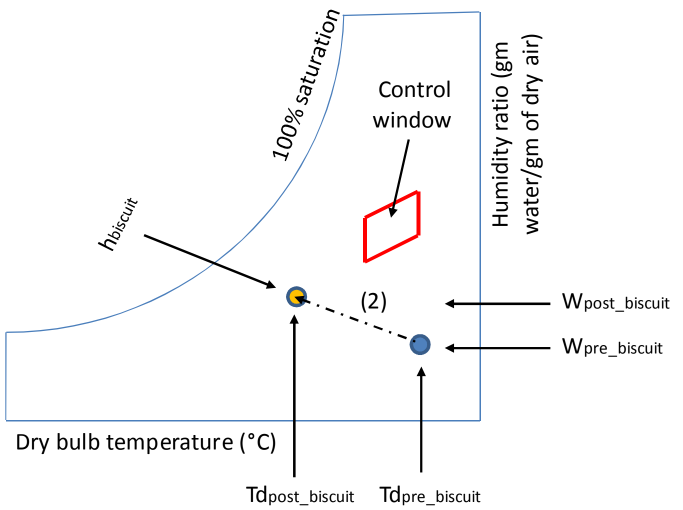


Figure 6-29 – Biscuit humidification - psychrometric chart with control window

It can be assumed that the humidification of the passing air follows a line of constant specific enthalpy $h_{post\_burner} = h_{biscuit}$ (i.e. close match to the constant wet bulb line) (Jones 2005). The humidity ratio post biscuit humidification ($W_{post\_biscuit}$) can be derived from the following:

$$W_{post\_biscuit} = \frac{h_{biscuit} - \left(1.006 \times Td_{post\_biscuit}\right)}{\left(2501 + 1.805 \times Td_{post\_biscuit}\right)}$$

Equation 6-5

Where, $W_{post\_biscuit}$ is the humidity ratio of the air condition post biscuit (g of moisture/kg of dry air), $h_{biscuit}$ is the enthalpy of the air condition during humidification (KJ/Kg) and $Td_{post\_biscuit}$ is the dry bulb air temperature of the air, post biscuit (ºC).

Steam injection

Parameters from Table 6-20:

- Metered data: valve position (%)
- Derived data: $Td_{post\_biscuit}$, $W_{post\_biscuit}$, $h_{biscuit}$

The psychrometric behaviour of the steam injection (3) is illustrated in Figure 6-30.

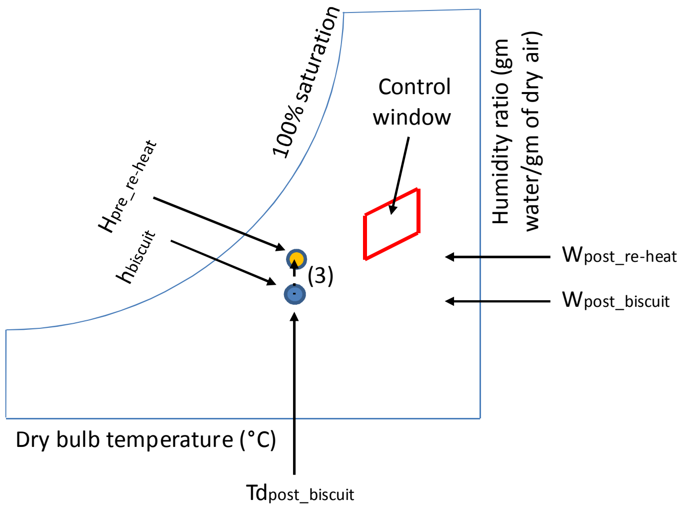


Figure 6-30 – Steam injection - psychrometric chart with control window

It can be assumed that the injection of steam into the passing air increases the humidity ratio of the air at a line of constant dry bulb temperature between limits of specific enthalpies (Jones 2005). The increase in humidity ratio could be calculated based on known parameters about the steam (i.e. specific enthalpy, pressure and temperature). However this data is not known, therefore the modelled approach assumes that the steam injection will not increase the humidity ratio of the air, further than the final metered condition (i.e. post-re-heat). The final air condition is metered for values: $Tw_{post\_re\text{-}heat}$, $Td_{post\_re\text{-}heat}$ and $RH_{post\_re\text{-}heat}$, to which $W_{post\_re\text{-}heat}$ can be derived psychrometrically.

The specific enthalpy of the air post injection ($h_{post\_injection}$) and the demand side energy consumption can be derived as follows:

$$h_{post\_injection} = (1.006 \times Td_{post\_biscuit}) + W_{post_{re}-heat}(2501 + 1.805 \times Td_{post\_biscuit})$$

Equation 6-6

Where, $h_{post\_injection}$ is the enthalpy of the air condition post steam injection (KJ/Kg) and $W_{post_{re}-heat}$ is the humidity ratio of the air condition post steam re-heat (g of moisture/kg of dry air)

$$\dot{Q}_{injection} = \dot{m}\Delta h \quad = \quad \dot{m} \times \left(h_{post\_injection} - h_{post\_burner}\right)$$

Equation 6-7

Where, $\dot{Q}_{injection}$ is the energy consumption of the steam injection (kW) and h_{post_burner} is the enthalpy of the air condition post burner (KJ/Kg).

<u>Closed loop steam re-heat</u>

Parameters from Table 6-20:

- Metered data: valve position (%)
- Metered data: final air condition post re-heat i.e. $(Tw, Td, RH)_{post\_re\text{-}heat}$
- Derived data: $h_{post\_injection}$

The psychrometric behaviour of the steam re-heat (4) is illustrated in Figure 6-31.

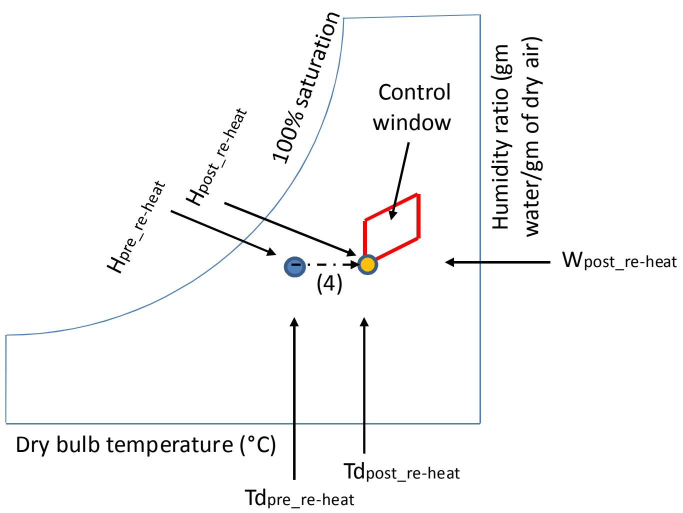


Figure 6-31 - Steam re-heat - psychrometric chart with control window

The specific enthalpy of the air post re-heat ($h_{post\_re\text{-}heat}$) can be derived as follows:

$$h_{post_{re}-heat} = \left(1.006 \times Td_{post_{re}-heat}\right) + W_{post_{re}-heat}\left(2501 + 1.805 \times Td_{post_{re}-heat}\right)$$

Equation 6-8

Where, $h_{post_{re-heat}}$ is the enthalpy of the air condition post re-heat (KJ/Kg) and $W_{post_{re-heat}}$ is the humidity ratio of the air condition post steam re-heat (g of moisture/kg of dry air).

The demand side energy consumption can be derived as follows:

$$\dot{Q}_{re-heat} = \dot{m}\Delta h \quad = \quad \dot{m} \times (h_{post\_re-heat} - h_{post\_injection})$$

Equation 6-9

Where, $\dot{Q}_{re-heat}$ is the energy consumption of the closed loop steam re-heat (kW).

<u>Closed loop cooling</u>

Parameters from Table 6-20:

- Metered data: valve position (%)
- Metered data: external environmental conditions i.e. $(Tw, Td, RH)_{external\_weather}$
- Metered data: final air condition post re-heat i.e. $(Tw, Td, RH)_{post\_re-heat}$

The closed loop cooling component is positioned after the steam injection. It has been taken out of the sequence of explanation, as the cooling process should only occur when the external air condition is greater than the control window limits and not as a consequence of a prior conditioning process requiring the cooling to engage. The cooling coil operates under two conditions, sensible cooling and sensible cooling/dehumidification.

The psychrometric behaviour of the closed loop cooling coil in sensible mode (5) is illustrated in Figure 6-32.

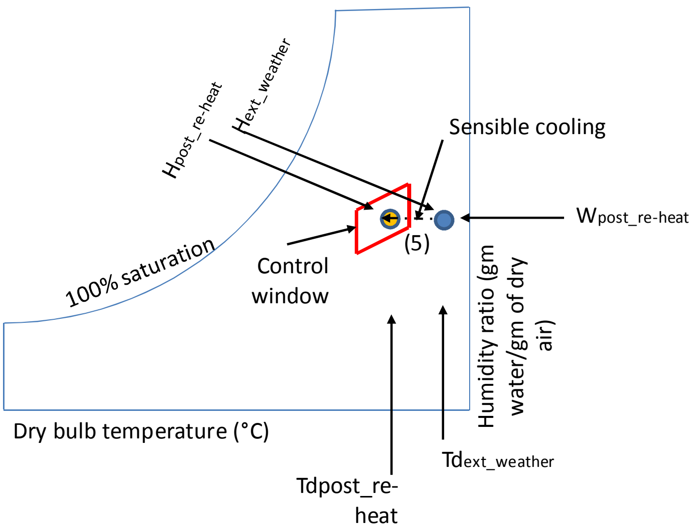


Figure 6-32 - Cooling coil (sensible mode) - psychrometric chart with control window

For sensible cooling mode only, the external air condition should be greater than the control window settings Td=22.8℃, and between the humidity ratio $W_{control\_bottom\_left}$ (i.e. Td=20.8℃ and RH=63%) and $W_{control\_top\_right}$ (Td=22.8℃ and RH=68%).The demand side energy consumption can be derived as follows:

$$\dot{Q}_{sensible\_cooling} = \dot{m}\Delta h \quad = \quad \dot{m} \times \left(h_{external\_weather} - h_{post\_re-heat}\right)$$

Equation 6-10

Where, $\dot{Q}_{sensible\_cooling}$ is the sensible energy consumption of the closed loop cooling (kW) and $h_{external\_weather}$ is the enthalpy of the external air condition (KJ/Kg).

The psychrometric behaviour of the closed loop cooling coil in sensible and dehumidification mode (5) is illustrated in Figure 6-33.

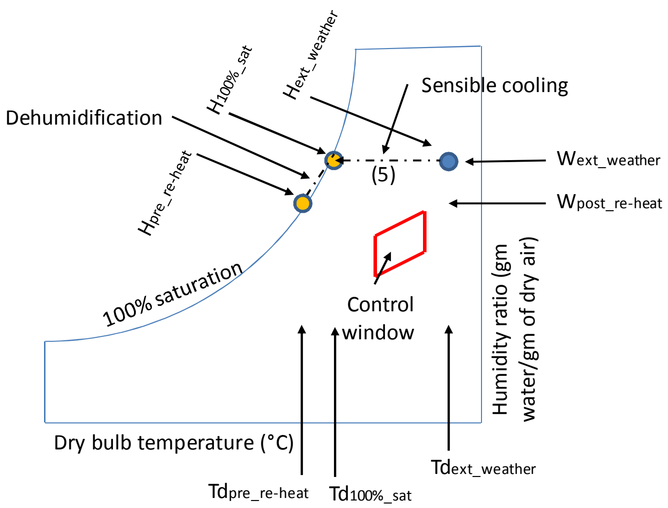


Figure 6-33 – Cooling coil (sensible and dehumidification modes) - psychrometric chart with control window

For sensible cooling and dehumidification mode, the humidity ratio of the external air condition should be greater than the condition at the upper right hand corner of the control window $W_{control\_top\_right}$ (i.e. Td=22.8℃ and RH=68%). The demand side energy consumption is in two parts and can be derived as follows:

$$\dot{Q}_{sensible\_cooling} = \dot{m}\Delta h \quad = \quad \dot{m} \times \left(h_{external\_weather} - h_{100\%\_saturation\_line}\right)$$

Equation 6-11

$$\dot{Q}_{dehumidification\_cooling} = \dot{m}\Delta h \quad = \quad \dot{m} \times \left(h_{100\%\_saturation\_line} - h_{pre\_re-heat}\right)$$

Equation 6-12

$$\dot{Q}_{total} = \dot{Q}_{sensible} + \dot{Q}_{dehumidification}$$

Equation 6-13

Where, $\dot{Q}_{total}$ is the total sensible and dehumidification energy consumption of the closed loop cooling, if both parts are required (kW). $\dot{Q}_{dehumidification\_cooling}$ is the dehumidification energy consumption of the closed loop cooling (kW) and $h_{100\%\_saturation\_line}$ is the specific enthalpy at 100% saturation (i.e. 100% RH) (KJ/Kg).

6.4.4.3. Model boundaries

The block models of the ASH process are based on fundamental physics and air based psychrometrics analysis. The models are designed to model the changing condition of air throughout the ASH process. The fundamental models do not take into account the following:

- Residual heat in:
  - Plant elements (i.e. gas burner and re-heat)
  - Construction of the ASH process
- Residual moisture (e.g. retained on the biscuit mesh system and condensate on the cooling coils during the dehumidification stage)
- Effects on the ASH process from external sources (i.e. factory thermal zone and sourced gains)

6.4.5. Scenarios

The macro and micro approaches both use metered data for the month of June 2011. The production hours of the ASH process are, Monday to Friday 07:30-15:48 and 20:30-04:48. Weekend production did not occur through June. This has lead to a gap in metered data for the external weather during this period. Periods of none metered data are set at zero, this does not affect the analysis of the approaches. Metered data is logged at intervals of approximately 10seconds.

Following several site visits to the THERM industrial partner, the control strategy of the ASH unit was discussed with the control engineers. The control window is designed to improve the demand side energy consumption of the manufacturing process system by controlling the final air condition towards the extremities of the control window. For example, if the inlet air temperature is low in dry bulb temperature (i.e. 10-20℃) and low in RH (i.e. 40-60), then the controller will aim to condition the air to the bottom left hand corner of the control window, 20.8℃ and 63%.

The macro and micro modelled approaches apply site obtained metered and data to analysis the process at different levels of analysis to further understand the principle of the process and to derive opportunities to improve energy efficiency and reduce energy consumption and associated carbon.

6.4.6. Results – Macro approach

6.4.6.1. Macro level data

Figure 6-34 illustrates simulated ASH energy consumption results based on valve position and manufacturing plant capacity ratings for June 2011, as outlined in section 6.4.3. From the figure, it is clear that the ASH process utilises all of the plant components of the ASH unit, from gas burner through to steam re-heat, during different parts of the month.

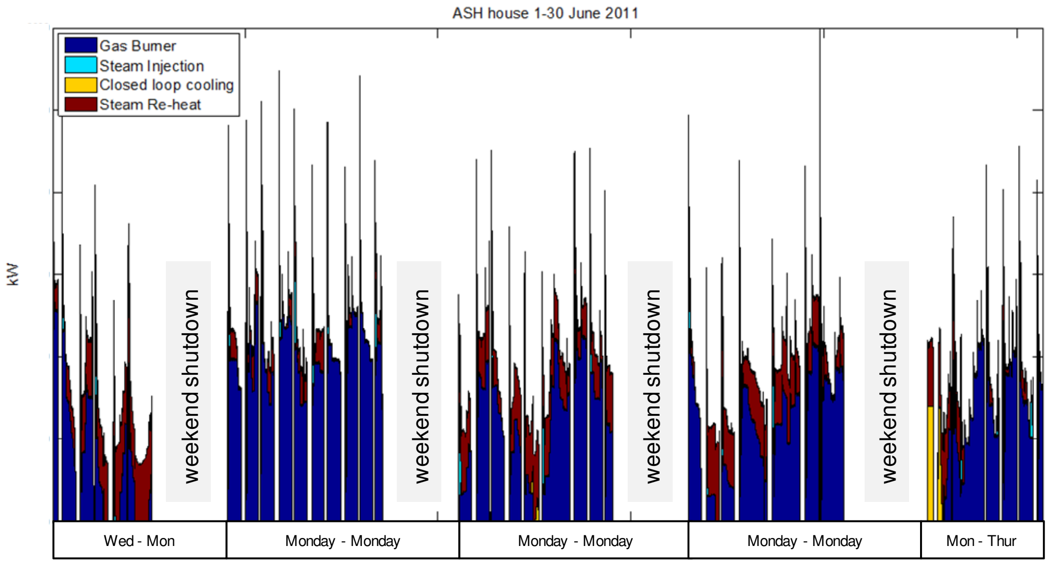


Figure 6-34 – Macro approach – all equipment component (June 1-30)

A snapshot of the derived energy consumption for June 1 to 5 is shown in Figure 6-35. During this period, the cooling equipment is not required. From Figure 6-34 and Figure 6-35, the following observations can be made: the gas burner is the largest energy consumer, the sequence of plant operation changes from a combination of gas burner and steam re-heat to steam re-heat only. Steam injection seems to operate only during the start-up stages of the production schedule. The gas burner is the largest energy consumer as it raises the dry bulb temperature of the external air, prior to the air being humidified by the biscuit humidification plant. Though during some parts of the year (i.e. hot and humid days), the gas burner is not required, as stated in the second observation. This behaviour is discussed further within the micro approach analysis, section 6.4.7. The final observation makes note that the steam injection plant is only operated during the start-up period of the ASH process. Further annual analysis is required to verify this observation. The importance of using steam during system start-up should be investigated, to ensure steam is being consumed in an appropriate manner.

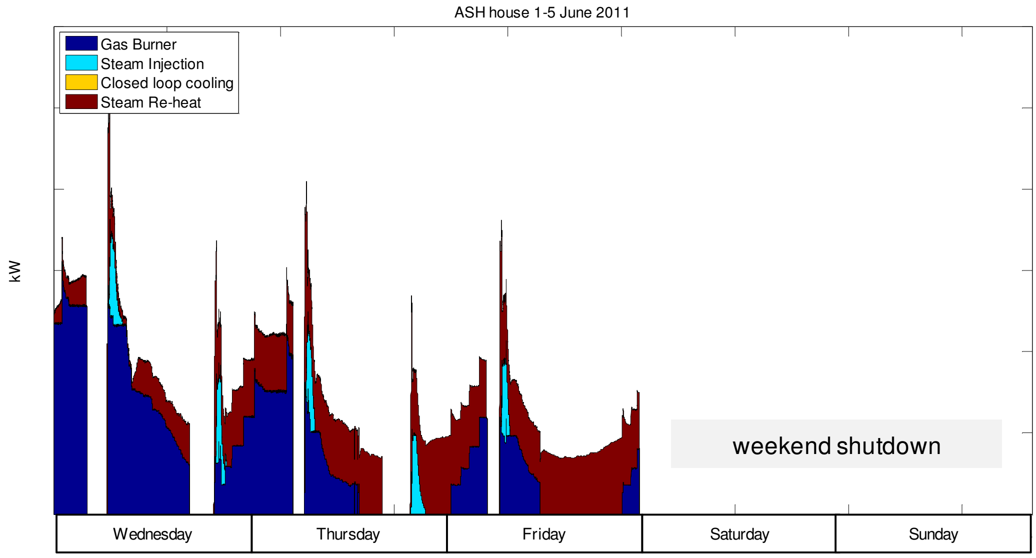


Figure 6-35 – Macro approach (June 1-5)

6.4.6.2. Summary

The macro approach enables engineers to make snapshot observations such as the gas burner is the largest energy consumer and why is steam injection used during start-up only. There is some difficulty in making defined observations in that the plant capacity rating values do not take into account plant and energy source efficiency losses, with exception to the gas burner (i.e. the gas burner energy consumption is from on-site metered gas consumption pulse data). In retrospect the macro level data does enable engineers to observe the behavioural aspects of the system, without knowing the true energy consumption of the overall system from supply to demand.

6.4.7. Results – Micro approach

6.4.7.1. Micro level data

This section discusses and illustrates simulated ASH results for June 2011 1st to 5th, as outlined in section 6.4.4. Figure 6-36 and Figure 6-37 compare metered dry bulb air temperature and humidity ratio values against simulated outputs for the final air condition of the ASH manufacturing process. The two figures show good correlation between metered and simulated results. During non production hours, the two results for the conditioned air (i.e. dry bulb and humidity ratio) differ. The reason is that the simulation approach does not model the building and ASH process construction. Therefore, when the process is turned off, the simulation approach returns the air condition within the ASH process to that of the external weather condition. In reality the construction of the ASH house and equipment (i.e. heater elements of the gas burner and the re-heat) will retain residual heat for a sustained period, returning to a condition similar to that of the ambient surrounding air condition over time. This is shown during non production hours, as the logged dry bulb readings in Figure 6-36 differ greatly from the simulated external weather condition. A clear example of this can be seen in Figure 6-36 during mid Thursday afternoon. An integrated approach that not only models the flow of air through the ASH process but also includes construction properties of the ASH process would go some way to resolving the difference in the two results.

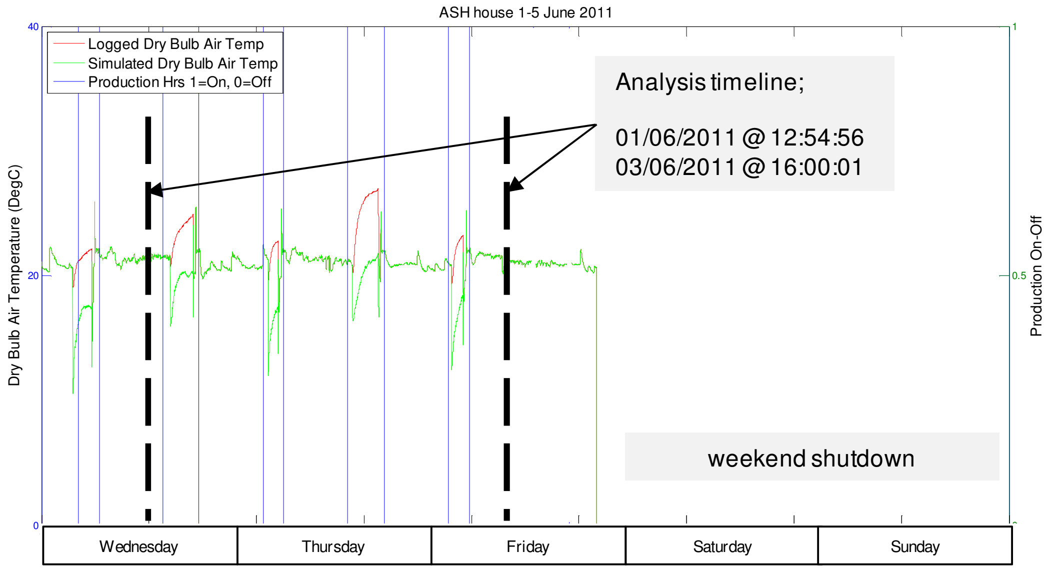


Figure 6-36 - Micro approach (logged vs. simulated) – final condition dry bulb air temperature (June 1-5)

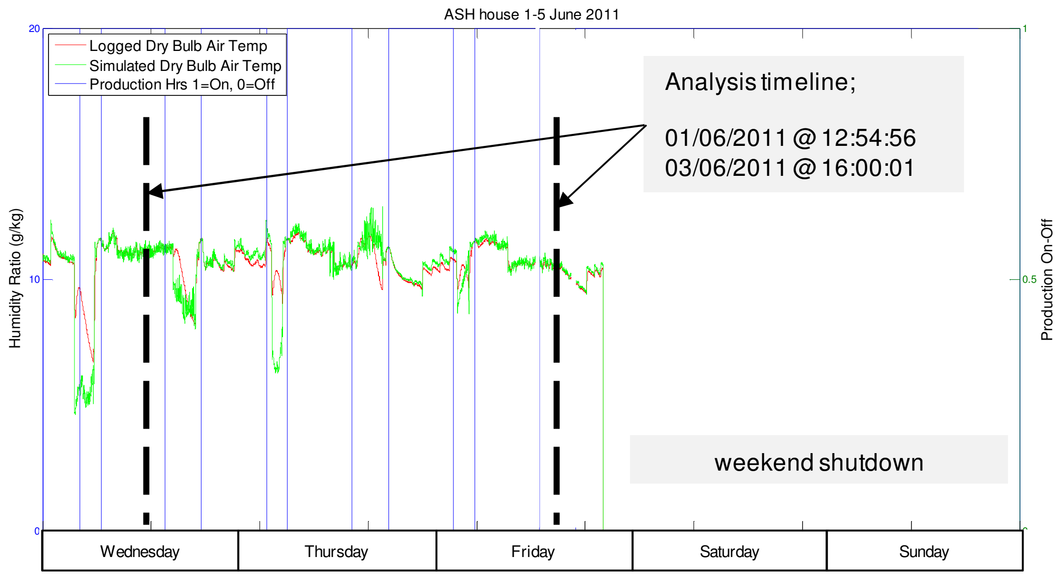


Figure 6-37 - Micro approach (logged vs. simulated) – final condition humidity ratio (June 1-5)

Figure 6-36 and Figure 6-37 are labelled with two timelines that have been investigated psychrometrically (Tedngai 2012), they are, 1st June at 12:54:56pm and 3rd June 16:00:01pm. The two timelines are positioned at select periods of time when there is a difference in plant sequence, discussed in section 6.4.6. Figure 6-38 illustrates the sequence of the plant: gas burner, biscuit humidification and closed loop steam re-heat on a psychrometric chart.

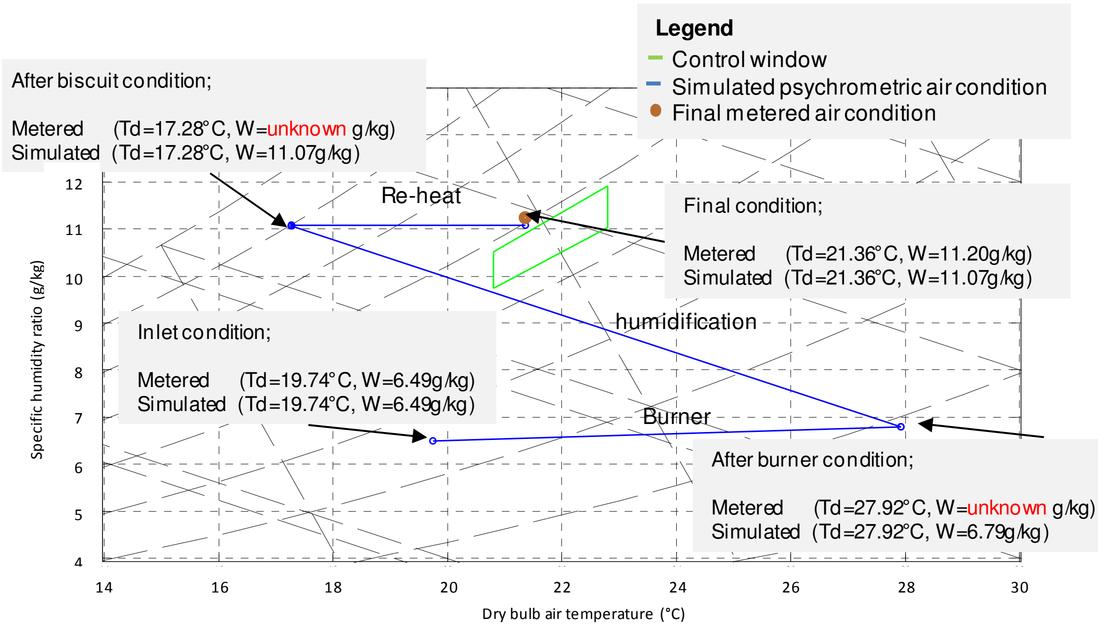


Figure 6-38 - Micro approach – psychrometric analysis (June 1st @ 12:54.56pm)

The psychrometric analysis of the ASH process on 1st June at 12:54:56pm indicates the change in air properties at inlet and after each of the ASH plant. The figure indicates simulated results and metered known and unknown values taken from site data. There is good agreement in results.

Figure 6-39 is a psychrometric analysis of the ASH process on 3rd June at 16:00:01pm. The gas burner is not used as a result of the warm and humid external air condition at inlet i.e. Td 22.80°C and W 8.04g/kg. Once again the simulated metered values show good agreement.

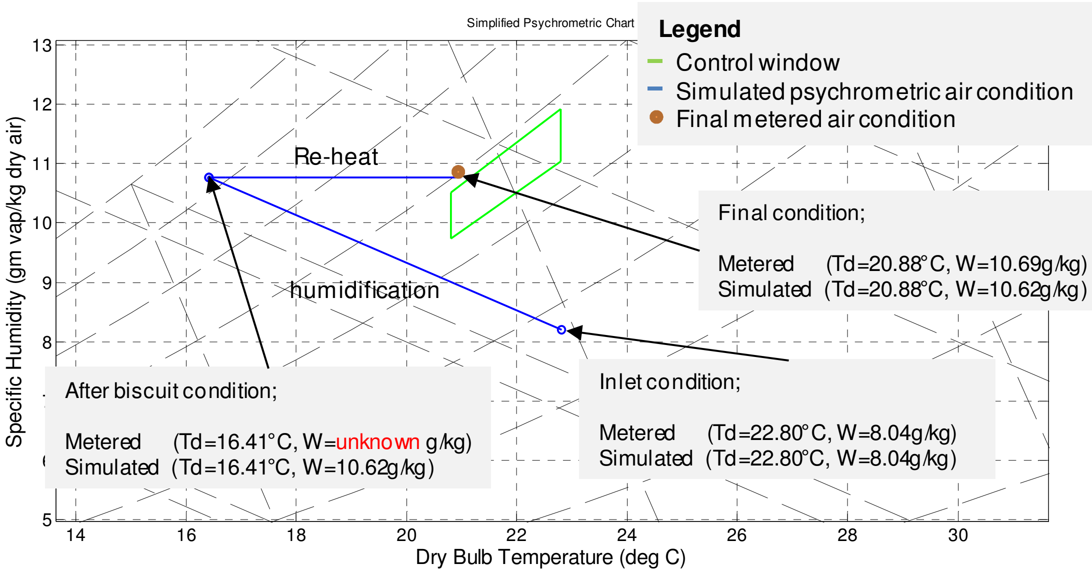


Figure 6-39 - Micro approach – Psychrometric analysis (June 3rd @ 16:00:01pm)

6.4.7.2. Summary

The micro approach provides an area of analysis that can be further explored than the macro approach. Though this is beneficial, the approach requires extensive time and resources. The study analyses data at approximately 10 seconds for the month of June. Data logged at short time steps is insightful, but can lead to data management issues. These issues extend around transferring and formatting of data. Microsoft Excel was used to manage data in this case. A month's worth of data at time steps of approximately every 10 second for June resulted in file sizes upwards of 20mb. Larger file sizes were created when formulating the data and analysing the results in graphs. Large file sizes are problematic in Excel, as documents become slow, hard to work through and can result in the document crashing, which happened on several occasions. The air supply house case study imports raw data from Excel into the Simulink environment. Charting options are available in the Matlab/Simulink environments that are not restricted by data limits as in Excel (i.e. 32,000 data per series restriction). The micro approach has provided assistance in understanding the behaviour of the system in greater detail, largely in part due to the psychrometric analysis. Work undertaken outside the scope of this research, highlighted that psychrometric analysis of the macro valve position data resulted in air conditions falling outside the psychrometric boundaries (i.e. greater than 100% RH). The micro approach can quickly identify if this occurs, and investigate as to why this may have happened (e.g. faulty metered data). Difficulties encountered during the micro approach were largely as result of the complex nature and size of the ASH process. Stratification of the air across the process may lead to unreliable meter readings that have formed fundamental drivers within the analysis (e.g. dry bulb air temperature after the gas burner and biscuit humidification). As a result of analysing historic data, fundamental psychrometric properties were not available after each of the manufacturing plant (i.e. dry bulb air temperature and RH). This makes it difficult to verify simulated outputs against real life system behaviour. Another area of difficulty was the control system of the ASH process. This research used metered data to mimic the control strategy, though some plant behaviour may be further explained by understanding the control strategy in greater detail (e.g. why is steam injection used during start-up throughout June?). The micro approach can be further expanded to include modelled approaches that are representative of the supply chain (i.e. steam, gas, deionised water and cooling water). The expansion of the model to include supply side models would aid in identifying opportunities to improve energy efficiency and reduce energy consumption and associated carbon emissions of the process.

6.4.8. Results – Mixed approach

6.4.8.1. Mixed approach data

Figure 6-40, Figure 6-41 and Figure 6-42 are graphed comparisons between the macro (i.e. valve and capacity rating) and micro (i.e. fundamental physics and air-based psychrometrics) level analysis for the gas burner, steam injection and closed loop steam re-heat, during June 1st to 5th. The macro and micro approaches are discussed in Sections 6.4.3 and 6.4.4. The simulated values are based on demand side energy consumption. The gas burner results are similar in comparison, Figure 6-40. The macro approach gas burner data is derived from gas pulse metered data, resulting in a close comparison to the simulated demand side energy requirement of the gas burner.

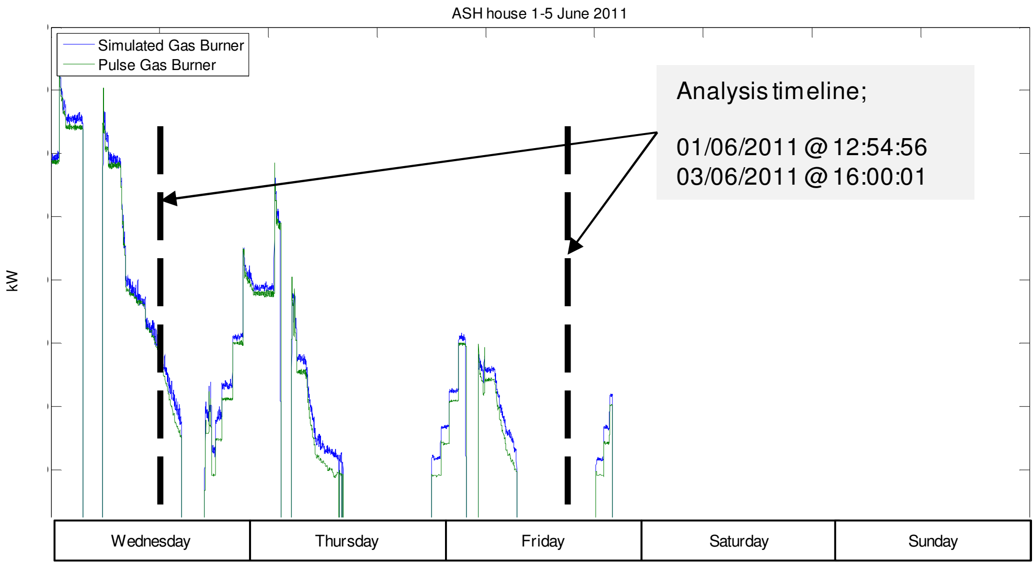


Figure 6-40 – Mixed approach (valve vs. simulated) – gas burner (June 1-5)

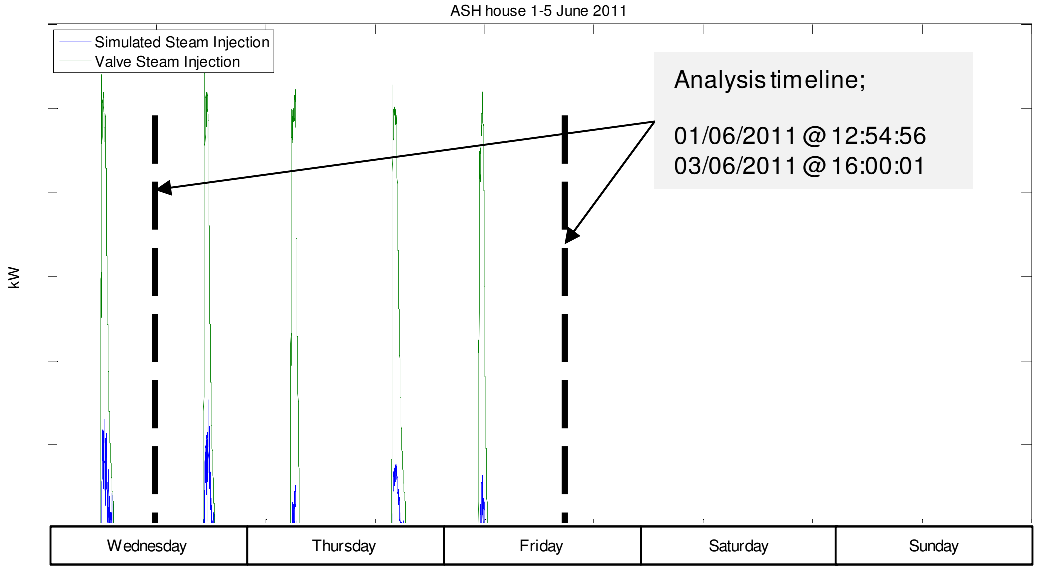


Figure 6-41 - Mixed approach (valve vs. simulated) – steam injection (June 1-5)

The steam injection results shown in Figure 6-41 follow a similar energy consumption pattern, but are out by a factor of 5 in some cases. Further work is required to determine whether the steam injection model block needs further attention. At this stage in the analysis the author is not concerned, as the steam injection component only seems to operate during the start-up phase for short periods of time.

The closed loop steam re-heat results shown in Figure 6-42, demonstrate good correlation for parts of the week June 1st to 5th. The greatest disparity between the two results is during the morning shift on Wednesday 1st. Figure 6-43 psychrometrically analyses this difference.

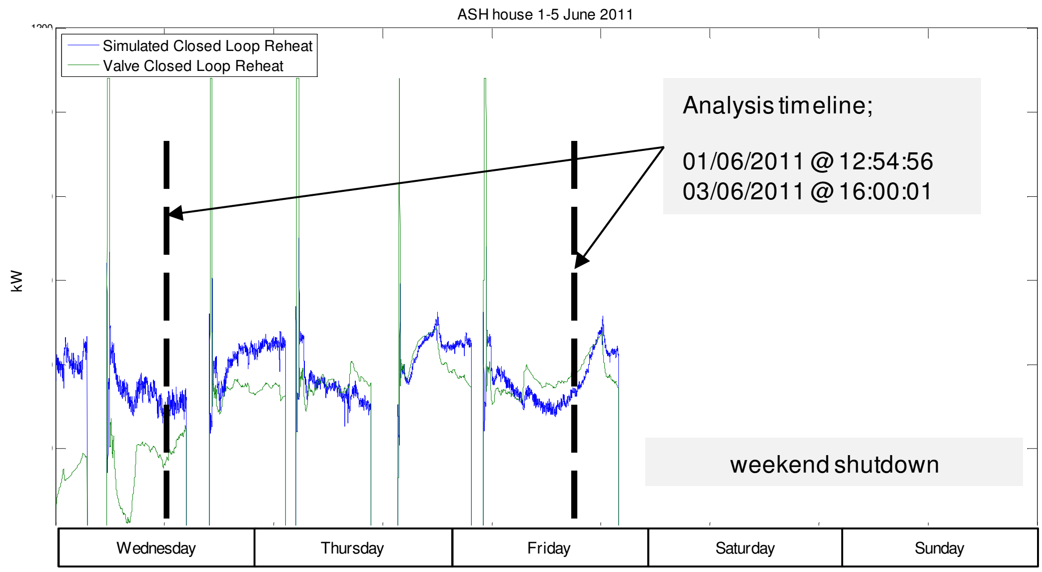


Figure 6-42 - Mixed approach (valve vs. simulated) – closed loop steam re-heat (June 1-5)

During the timeframe 1st June at 12:54:56pm, the macro analysis indicates that the closed loop steam re-heat plant consumes approximately 40% less energy than the simulated micro analysis results, Figure 6-42. As illustrated in Figure 6-43 the decrease in closed loop steam re-heat (indicated by the red dashed line) as suggested by the macro valve simulation method would result in an increase in on-site pulse meter gas burner consumption by approximately 23%. This increase has been derived from Equation 6-4 from the change in enthalpies between pre and post gas burner air conditions, indicated in Figure 6-43 by the diagonal dashed red line. Figure 6-40 illustrates good correlation between the macro (i.e. valve and capacity rating) and micro (i.e. Matlab/Simulink simulated) level analysis for the gas burner. Further work is required to determine why this anomaly has occurred in the results.

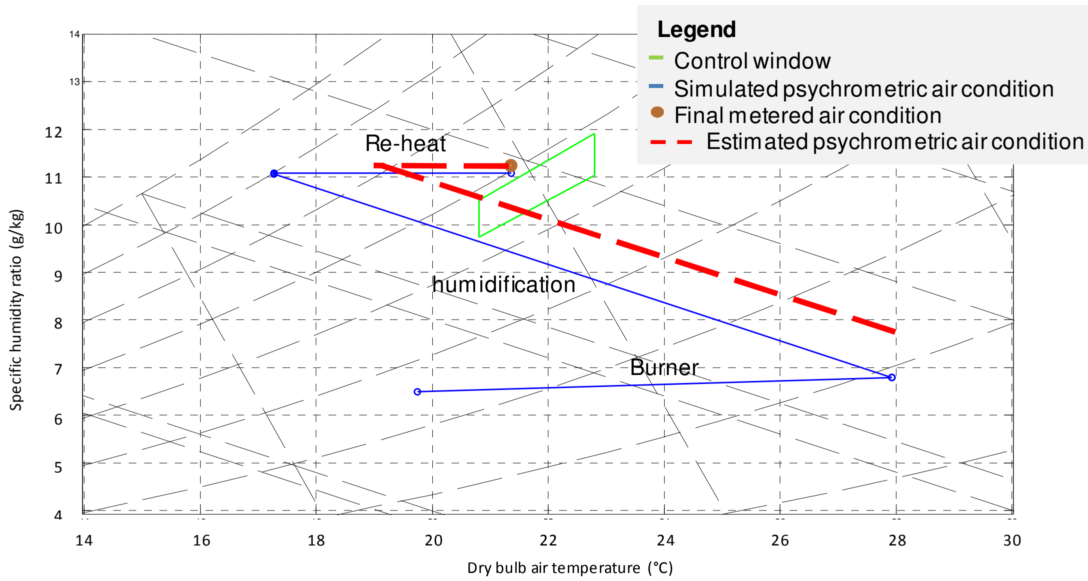


Figure 6-43 – Simulated vs. metered psychrometric analysis (June 1st @ 12:54.56pm)

Figure 6-44 compares total macro and micro energy consumption data and control window upper ($Td_{control}$ 22.8℃ and $RH_{control}$ 68%,) and lower ($Td_{control}$ 20.8℃ and $RH_{control}$ 63%) boundaries for the period 1st to 3rd June. The graph draws on two observations, firstly, a comparison between valve (macro) and simulated (micro) total energy consumption. The two approaches show tolerable correlation with one another (i.e. 4% difference in total energy consumption for June 1st to 3rd), with exception to the steam injection energy consumption during start-up, discussed above.

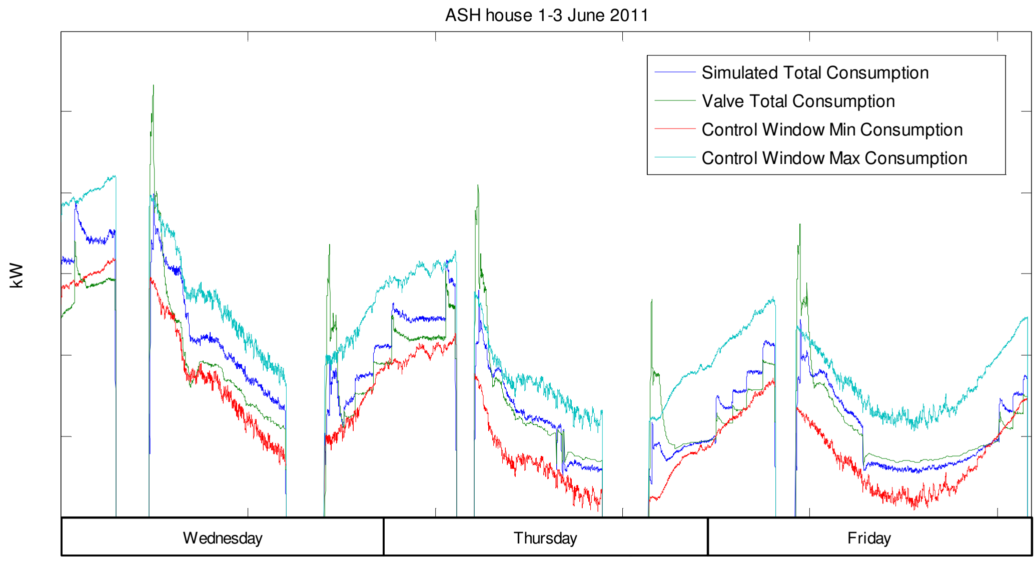


Figure 6-44 - Mixed approach (simulated/valve vs. control window limits) – (June 1-3)

Secondly, the graph indicates whether the ASH process is operating within the control windows, upper and lower limits. The lower limit of the control window (i.e. red line) is a driving force for reducing the energy consumption of the process when the external dry bulb air temperature is lower than $Td_{control}$ 20.8℃ and $RH_{control}$ 63%. The graphed macro and micro energy consumption data lines highlight that the process is consuming energy above the lower condition of the control window. This can seem more clearly in the psychrometric charts, Figure 6-38 and Figure 6-39. The micro approach simulates a potential demand side energy saving of 25% for June 1st to 3rd, if it were possible to condition the air to the lower left hand corner ($Td_{control}$ 20.8℃ and $RH_{control}$ 63%) of the control window as illustrated in Figure 6-45 for the time frame 1st June at 12:54:56pm.

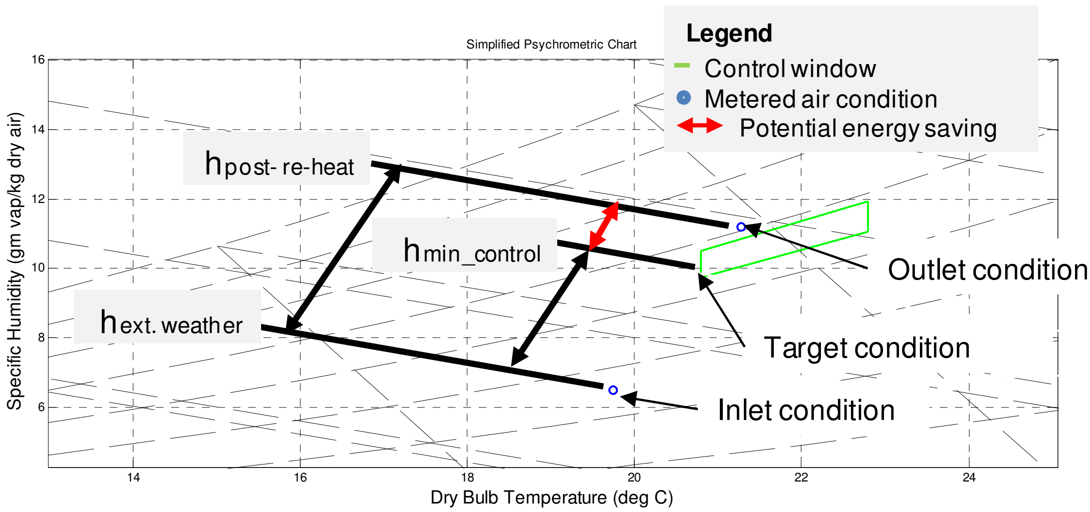


Figure 6-45 – Potential energy saving

6.4.8.2. Summary

The combination of analysing both macro and micro data provides a strong basis for further understanding the behaviour of the ASH process and to potential opportunities to improve the performance of the system. Figure 6-44 and Figure 6-45 highlight the potential opportunity to reduce the demand side energy consumed by the ASH process by nearly 25% based on simulated results.

6.4.9. Discussion

This case study demonstrates the beneficial use of analysing data at a macro, micro or a combination i.e. mixed approach. Two main observations can be drawn from this work. Firstly, is the ASH process consuming the least amount of energy required to meet the minimal condition of the psychrometric control window? This question is weather dependant, as the minimal condition of the control window will change in respect to the external weather condition (i.e. control window boundary). For June 1^{st} to 5^{th}, it has been demonstrated that there is a potential 25% saving on total demand side energy consumption. A reason why the process is not operating at its full potential may lie with the control behaviour of the system and its ability to control the manufacturing plant to achieve tight tolerance control. Further work is required on-site. Secondly, is the ASH process being supplied by an appropriate fuel source and manufacturing plant, ensuring maximum energy efficiency of the system and low level carbon emissions? Psychrometrically, to condition the air from the inlet to the desired outlet condition requires the same amount of demand side energy, independent of the sequence in events of the ASH components. For example, the specific enthalpy difference for demand side energy of the system is the same for either: gas burner and then steam injection or gas burner, then biscuit humidification and then closed loop steam re-heat. The efficiency of the manufacturing plant, fuel source type and associated carbon emissions are influenced from the supply side of the system. The author believes it would be advisable to replace the energy carrier steam supplying the injection and closed loop re-heat plant for a less carbon intensive energy source. For example, steam supplied to the closed loop re-heat through an extensive pipe network could be replaced by a high efficiency localised gas burner providing high temperature hot water to the closed loop system. Future models of the ASH process should be expanded to include block flow models of the supply side network to investigate possible changes to the system, manufacturing plant and fuel source. This case study does not include aspects of the surrounding building and ASH process construction properties due to a lack of data. Future work can include these components through expansion of the model, in line with further data been gathered. Figure 6-36 demonstrates a difference in the metered and simulated dry bulb air temperature as a result of residual heat being retained by the ASH unit. The future potential for modelling this aspect of the process may lead to changes in production hours to maximise the retained heat in the system and increased levels of installed insulation to reduce heat loss from the process.

7. Concluding discussions

This research has demonstrated an integrated simulation approach to modelling energy flows within a factory environment. Current building modelling and manufacturing simulation tools are not currently capable of modelling energy flows within a factory environment at the level shown within this research. Case studies based on data from the industrial partners of the THERM project are representative of the outcomes of such a novel approach to modelling.

7.1. Simulation tool

7.1.1. Approach

The first conclusion that can be drawn is that an integrated approach to modelling factory energy flows through development of a building modelling framework has real benefits for manufacturing industry and that these are very unlikely to be realised by modelling processes and buildings separately. From the beginning, complexities of simulating energy flows within a factory environment have been discussed. This work has gone some way to representing these flows through modelling of manufacturing processes, plant and material flow coupled with the built environment; both graphically and through simulation. By extending the capabilities of a traditional building modelling tool, factory related energy flows have been modelled. The case studies have demonstrated the flexibility of the tool to analyse energy flow paths at both a process and facility level. This is an important outcome of the research as current methods in industry focus on individual manufacturing process behaviour and energy consumption (Dahmus et al. 2004; Vijayaraghavan et al. 2010). In reality, a factory environment is a complex system of inter-connecting energy flows (Oates et al. 2011a). By incorporating a building modelling tool, traditional building energy flows can be combined with those that occur within a factory environment. The main advantage of this approach is that the user can explore a range of complex energy flows that are not normally modelled within a manufacturing simulation tool. For example, by simulating weather conditions, the effects on energy consumption not only at a facility level but also at a process level can be explored. This is one of a number of possible variables that can affect the performance and associated energy consumption of a factory building, manufacturing processes and manufacturing plant. Case studies demonstrate the ability of the adapted IBPT to model material flow. Heat transfer from the material to its surroundings may in part be more beneficial to industries that operate high temperature processes (e.g. steelworks, foundries etc). It is this complex balance of energy flows from external and internal energy sources that can be investigated by modelling within the adapted IBPT integrated tool.

7.1.2. Tool verification

The second finding is that real energy flows that occur within a factory building may be very significant and are difficult to measure and validate against (Wright et al. 2012). For example, energy consumption and production schedule data may be known for a typical industrial process, such as an oven. Heat flux from the oven construction, energy absorbed by the thermal mass of the material being processed and other associated forms of heat transfer will occur (Paton et al. 2012). The modelling of material flow within this research takes into account heat transfer between the material and its surroundings, before, during and after being processed. These types of energy flow paths are difficult to measure in real life settings, especially for sustained periods of analysis. Through development of a building modelling tool based on first principle mathematical heat transfer equations, heat loss and gains to and from thermal mass elements (e.g. building, volumetric thermal manufacturing processes and material) can be approximated. Building models are simplifications of reality. The ASHRAE 140 tests to which IES VE is validated against provides a valuable benchmark by which the predictions of a simulation program may be compared with those of its peers, as means to establishing a degree of confidence in the correctness of its algorithms and their implementation (ASHRAE 2008). The adapted IBPT (section 5.2) is software verified with some confidence against the commercially used and validated building modelling tool IES VE, in comparable areas of building modelling, section 5.3. This approach uses software validation. Great effort has been undertaken to ensure that models in both tools have been populated with similar inputs of data. Further effort has been carried out by narrowing the mathematical approaches used by the tools, section 5.2.

Data collected from the industrial partners of the THERM project have been used in part to validate results from the adapted IBPT simulation model for the case studies: drying tank (section 6.2), treatments process (section 6.3) and ASH (section 6.4). The temperature of a material processed in a drying tank has been recorded on-site and verified against results from the integrated tool, section 6.2.8. The modelling of material is currently outside the capabilities of existing building modelling tools. The lack of data i.e. factory air temperature, internal gains, infiltration rates etc, meant that the surrounding factory environmental conditions were not available. By modelling the drying tank within the framework of a building modelling tool, weather data has been simulated resulting in a dynamic internal air temperature of the factory environment. By using the adapted IBPT, simulated material temperatures when the process is turned off are best fit against recorded data. Good correlation between recorded material temperature and simulated results has been demonstrated, Figure 6-5. The industrial treatments case study compares pattern usage of gas consumption obtained from the industrial partners of the THERM project against simulated results, section 6.3.6. The validation method is considered valuable as the case study combines empirical data with assumptions to create a model within the adapted IBPT. This is as a result of data availability. The main reason is due to the complexity of the energy flows that occur within the factory building which the industrial tanks reside in. The factory is adjoined with connecting walk ways to neighbouring buildings, promoting transfer of air between the zones. Other influences occur from energy flows from solar, internal gains, manufacturing plant, infiltration etc. The air supply house (ASH) case study analyses data obtained from the industrial partners of the THERM project at metered intervals of approximately 10 seconds for the month of June. Data logged at short time steps is insightful, but can lead to data management issues. These issues extend around transferring and formatting of data. The psychrometric chart (Tedngai 2012) proved a powerful tool for analysing the behaviour of the system during early development of the case study, Figure 6-38 and Figure 6-39. In sections 6.4.7 and 6.4.8 the charting of simulated results against metered data provides confidence in the modelled approach. Case studies discussed above make use of real life situations to test and compare the adapted IBPT and Simulink work against. This provides important validity when developing a tool from theory to conception.

7.1.3. Modelling boundaries

This research considers manufacturing process systems in two way: thermal and electrical. As discussed there are some limitations to this approach. Firstly, thermal processes are represented in the tool as thermal zones (i.e. single interior air mass node per thermal zone) and are limited to a maximum internal air temperature of 100℃ (section 3.5.2) based on linear mathematical equations for modelling air. By modelling thermal processes as volumetric thermal zones, convective and radiant heat transfers can be simulated to and from the process to the surrounding environment, improving the accuracy of the tool. Internal convective and radiant heat transfers are also included, along with conductive heat transfer through the construction elements of the process. Electrical processes are modelled as convective and radiative heat gains to the surrounding environment. This approach is in line with the modelling of traditional internal gains in current building modelling software. This approach does not however account for modelling in detail of surface temperatures and reciprocal heat transfers to and from the surrounding environment, as is in the case when modelling thermal processes, section 5.2. The approach to modelling in this research does not account for the transfer of moisture, as the adapted IBPT is based on the framework for modelling heat transfer only, IBPT H-Tool (Rode et al. 2002). Therefore the tool does not take into account moisture transfer from the surface of products (material) and manufacturing process systems such as open surface vats, steam and other liquid based manufacturing processes. Other work outside this research have extended the IBPT library to model heat, air and moisture within a building, HAM-Tool (Rode et al. 2002). The H-Tool and HAM-Tool are structured on the same input and output data array structure, therefore work initiated in this research should be compatible with the HAM-Toolbox for future use. The H-Tool approach was chosen based on its reduced complexity and simulation time. This is an important aspect in the development of the adapted IBPT from theory to the application of the tool in the presented case studies. Material flow is modelled within the adapted IBPT. The lumped capacitance method approximates material increasing and decreasing in temperature in relation to its stored energy, long wave radiation to and from its surrounding environment and convective heat transfer (Incropera et al. 2006). In this research, material flow is driven by time variant deterministic profiles enabling material to move location within the model boundary in line with production schedule data, as simulated in the drying tank (section 6.2) and treatments case study (section 6.3). The modelling of material flow is outside the capabilities of current building modelling tools and is considered novel.

7.2. Application

7.2.1. Case studies

Ingalls (2002) defines simulation as "the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system". The case studies in chapter 6 demonstrate the functionality of the integrated tool to model energy flows within a factory environment. The integrated tool can be utilised to explore energy interactions without the need to interrupt the production of manufactured items on-site. The advantage to using simulation is in the ability to investigate simulated energy flows at varying levels of detail. The industrial drying tank case study (section 6.2) is a good example of the capability of the integrated tool to analyse energy flows at both process and facility level. The selection of scenarios highlights the effects on the energy consumed at both a process and facility level from changes in production schedule, facility heating control and material flow. The industrial treatments case study (section 6.3) models gas (i.e. air) and liquid based manufacturing processes. The modelling of volumetric thermal zones filled with liquid mediums is currently outside the capabilities of existing building modelling tools. The case study analyses energy flows at both a macro and micro level. At a macro level, process energy consumption is simulated for all four tanks, one being air based, along with factory demand side heating consumption. Two scenarios have been modelled, making changes to the air infiltration rate of the building (i.e. 1ACH and 0.25ACH, scenario 1 and 2 respectively). In scenario 2, the reduction in infiltration rate to the building from 1ACH to 0.25ACH results in a energy decrease in space heating demand (Table 6-16), in comparison to scenario 1. The reduction in infiltration rate means that less external air is mixed with the internal air of the factory during the heating season. This has an opposite effect in the summer/spring season, as in scenario 1 the higher infiltration rate over these seasons provides free cooling to the factory. On the other hand, in scenario 2, there is an increase in internal air temperature of the factory, Figure 6-15. This leads to a small decrease in process energy consumption. The simulated results also highlight the difference in energy consumption between the two different process mediums of air (tank 3) and water (tank 4) treated to the same temperature, as a result of the difference in properties of the mediums simulated, Table 6-16. At a micro level, components that contribute to convective heat gains/losses (Ballarini et al. 2011) to the internal air temperature of the factory thermal zone are examined further. Interesting observations were made, such as a decrease in summer time internal air temperature of the factory when simulating a higher infiltration rate (Table 6-17), and a change in positive vs. negative convection heat transfer from the internal surfaces of the factory building during the summer months when comparing scenarios (Figure 6-14 and Figure 6-15). The air supply house case study (section 6.4) demonstrates the beneficial use of analysing data at, macro, micro and a combination, mixed approach. The modelling approach considers the manufacturing process aspect only, excluding the building in this occasion. The case study models two approaches to using data from the industrial partners of the THERM project. The first approach multiplies metered valve position data with capacity rating of plant; deriving macro level results. The second approach uses micro level analysis to model metered data psychrometrically on a plant by plant basis. Site metered data is used to validate the simulated results. The use of data obtained from the industrial partners of the THERM project strengthens the theoretical basis for the modelling of factory energy flows within the framework of an existing building modelling tool.

7.2.2. Wider industries

The block flow modelling approach used within the adapted IBPT enables users to formulate components at an appropriate level of abstraction. The drying tank case study models plant (i.e. fan, heat exchanger and air re-circulation ductwork) that operates and controls the internal temperature of the tank. The ASH case study uses fundamental physics and air-based psychrometrics to model each of the manufacturing plants that make up the process; excluding the building. The building in this case study has not been modelled due to lack of data with regards to the factory building and internal environment. The building aspect can be added at a later date as more data becomes available. This illustrates the flexibility of the block flow model approach used within the adapted IBPT. The conceptual modelling of manufacturing processes and plant demonstrated graphically in section 4.1 enables users to depict the extensive typology and taxonomy of manufacturing processes (DeGarmo et al. 2003; CO_2PE 2012) used widely across the economy sector of industry (Office-for-National-Statistics 2011). The integrated approach to modelling a factory environment within the framework of a building modelling tool strengthens the tools approach not only in modelling manufacturing process systems but also energy flows that occur in relation to time and location, inside and outside of the factory envelope, enabling the tool to be used across a diverse range of industries.

8. Conclusions

8.1. Contribution to knowledge

The scientific contribution to knowledge from this research includes:

- The research study demonstrates a novel approach to modelling factory energy flows using the framework of a building modelling tool. The work presented goes beyond existing studies and applications of building and manufacturing process simulation to formulate an integrated approach to modelling factory energy flows in the development of the adapted IBPT. The advances in modelling are:

    - The approach extends the capabilities of building simulation to model energy flows related to manufacturing process systems, manufacturing plant and material flow coupled with the built environment.

    - Manufacturing process systems are modelled in two ways, thermal and electrical. Thermal processes are modelled as volumetric thermal zones (i.e. single interior air mass node per thermal zone). This approach enhances the model capabilities of the tool by simulating convective and reciprocal radiant heat transfers to and from the process to the surrounding environment. Electrical processes are included within the tool and represented as convective and radiant gains to the surrounding environment. Manufacturing plant has been modelled at either a macro or micro level in relation to known data and model granularity.

    - Material (product) flow is modelled within the adapted IBPT using the lumped capacitance method. This method approximates material increasing and decreasing in temperature in relation to its stored energy, long wave radiation to and from its surrounding environment and convective heat transfer (Incropera et al. 2006). This approach not only accounts for material flow controlled via a production schedule, but also simulates the energy state of the mass.

- Three multiple (holistic) case study designs formulated from real life manufacturing situations demonstrate the application of the tool to model factory energy flows and associated energy consumption at both facility and process level.

- The case studies differentiate between energy flows occurring from a wide range of sources such as, solar, air temperature differential from external to internal environments, manufacturing processes and material gains, internal gains from lighting, occupants etc.

- Scenario driven case studies demonstrate new ways of analysing energy consumption data at macro, micro and combined level of analysis (i.e. mixed approach).

- The outcome of the approach provides assistance to energy managers in assessing energy used at both facility and process level, in order to identify efficiency improvements and reduce energy use and associated carbon emissions.

This research contribution to industrial knowledge and practice includes:

- The study demonstrates the flexibility of the tool in modelling energy flows in a factory environment at different levels of abstraction from factory and process/plant to process only. The conceptual methodology (i.e. graphically representing manufacturing processes and associated energy flows) to model design enhances the tool application for use across the economy sector of industry. Through further understanding of the overall energy balance of an industrial factory environment, the tool provides assistance in decision making, aiding energy managers to use energy in a more sustainable manner.

- Further to the work presented in the thesis, the research has also assisted work undertaken in the industrial and academic collaborative project of THERM. Such work include:

    - The drying tank case study modelled in the adapted IBPT which was used to provide valuable inputs into the development of early stage THERM tool prototypes.

    - The air supply house case study as been used to assist in the modelling of the industrial process in IES VE using the ApacheHVAC application. Outputs from the air supply house case study modelled in the adapted IBPT have been used as derived inputs into the ApacheHVAC application. The approach to software validation used in the case study lead to the development of a new tool in IES

VE called free-form profiles (ffp). Free-form profiles import site metered data into the IES VE software to mimic control system behaviour in the case of the air supply house process.

- Data management used in analysing and formulating of the ASH process (cases study) metered data has been used to provide assistance in developing the latter stages of the THERM tool and modelled prototypes.

- Learning outcomes acquired in the development of the adapted IBPT have been transferred into the development of the THERM tool.

8.2. Strengths and weaknesses of the work

The listing of strengths and weaknesses can be highly subjective. Below are the author's opinions on the strengths and weaknesses of the work:

- Integrated tool approach:
  - Strengths:
    - Real benefits for manufacturing industry and that these are very unlikely to be realised by modelling processes and buildings separately.
    - A general approach to representing and modelling energy flows at both macro and micro levels.
    - Extends the current capabilities of traditional building modelling tools by including the modelling of liquid manufacturing processes and material flow.
  - Weaknesses:
    - Added modelling complexity
    - It could increase modelling and simulation time, though in comparison to the integrated approach, separate models would have to be created for each discipline.

- Tool verification:
  - Strengths:
    - The IBPT and the adapted IBPT have been software verified against the commercially used and validated building modelling tool IES VE, in comparable areas of building physics.
    - Case studies provide confidence in the tools ability to model real life industrial processes, especially in areas of advancements in building modelling (i.e. liquid processes and material flow).

- Weaknesses:
  - Limited options to validate novel approach to modelling two widely regarded discipline areas
  - Slightly different approaches used by the IBPT and IES VE to building modelling during the software verification exercise will in doubtingly result in errors. These errors were best minimised by revising the IBPT mathematical approach in line with IES VE and using same modelling inputs where possible.

- Modelling boundaries:
  - Strengths:
    - The modelling of liquid manufacturing processes and material flow is outside the capabilities of current building modelling tools and is considered novel.
    - The IBPT (heat transfer only) approach was chosen based on its reduced complexity and simulation time.
      - This is an important aspect in the development of the adapted IBPT from theory to the application of the tool in the presented case studies.
    - The IBPT (heat transfer only) is based on the same input and output data array structure as the IBPT HAM-tool (heat, air and moisture), enabling future development and use of the tool.

  - Weaknesses:
    - Thermal process:
      - Single interior air mass node per thermal zone limited to 100℃ based on linear mathematical equations for modelling air.
    - Electrical process:
      - Long wave radiation and convective heat transfer to surroundings only. Heat transfers are not reciprocal to and from surroundings
      - Surface temperatures are not modelled
    - Moisture transfer:
      - Evaporation losses (e.g. from liquid surfaces, steam processes etc) are not modelled, due to the fact that the adapted IBPT is structured on a heat transfer model only.
    - Product flow (material):
      - At present, material flow is driven by time variant deterministic profiles.

- Case studies:
  - Strengths:
    - Demonstrates the capabilities and the flexibility of an integrated approach to modelling energy flows
    - Demonstrates the capabilities of the tool to model material flow, including reciprocal thermal energy flows.
    - The integrated tool can be utilised to explore energy interactions without the need to interrupt the production of manufactured items on-site.
    - The advantage to using simulation is in the ability to investigate simulated energy flows at varying levels of detail
    - The tool is applicable to the extensive typology and taxonomy of manufacturing processes (DeGarmo et al. 2003; CO_2PE 2012) used widely across the economy sector of industry (Office-for-National-Statistics 2011).

  - Weaknesses:
    - Lack of available data i.e. weather data and other thermal influences such as neighbouring processes, solar, occupants etc.
    - Quantity of data required to validate the case studies
    - Variability in the case studies from different typology and taxonomy of manufacturing processes and industries

8.3. Final conclusions

Below is a list of final conclusions. The research:

- presents a novel integrated tool approach to modelling building and manufacturing processes.
- through conceptual modelling, details in great depth the thermal energy flows that exist within a factory environment
- through model design, details in great depth the development of the simulation approach used
- advances the capabilities of existing building modelling through modelling of liquid manufacturing processes and material flow.
- software verifies the IBPT and the adapted IBPT against the commercially used and validated building modelling tool IES VE, in comparable areas of building physics.

Providing confidence in the fundamental building modelling tool used as part of the integrated tool.

- uses real life case studies to demonstrate the flexibility and capabilities of the integrated tool
- uses case studies to verify the approach of the integrated tool to identify opportunities for efficiency improvements and to reduce energy use and associated carbon emission.
- through further understanding of the overall energy balance of an industrial factory environment, provides assistance in decision making, aiding energy managers to use energy in a more sustainable manner.
- is applicable to wider economy sectors of industry

9. Further work

This research has demonstrated that an integrated approach to modelling factory energy flows through development of a building modelling framework has practical implications for the manufacturing industry. Further research within this area could include the following:

- Further work to include the modelling of moisture transfer from climatic conditions and occupants simulated within traditional building modelling tools to an extended framework that includes moisture transfer from manufacturing process systems, plant and material flow as this research is based on the framework for modelling heat transfer only, IBPT H-Tool (Rode et al. 2002).

- To extend the manufacturing processes modelled within the adapted IBPT as there is an extensive number of typology and taxonomy of manufacturing processes (DeGarmo et al. 2003; CO_2PE 2012), used widely across the economy sector of industry (Office-for-National-Statistics 2011).

- To include the energy interactions at a material level during work, such as, heat transfer from laser cutting. How much of the energy is absorbed by the material? How much is dissipated to the surrounding environment? How much energy goes into breaking material bonds? As the case studies presented simulate energy flow interactions at levels of abstraction that include, factory environment, weather, thermal and electrical process, process air flow (ASH) and material. Similar understandings can be applied to a wide range of manufacturing processes such as, grinding, cutting, forming etc. Material level energy interactions can be coupled with the energy interactions modelled within the adapted IBPT, further enhancing the capabilities of tool.

- Further work is required to include algorithms applicable to high temperature processes formulated from linear and non-linear mathematical relationships. At present the adapted IBPT is limited to modelling volumetric thermal processes up to a maximum temperature of 100°C based on linear mathematical equations for modelling air (ASHRAE 2001). To retain the tools functionality of modelling thermal processes as thermal zones and therefore responsive to surrounding environments

- Future scope in applying a time-driven and event-driven hybrid approach (Clune et al. 2006) to modelling material flow in the framework of the adapted IBPT as the novel approach to modelling material (product) flow within the adapted IBPT is based on time-driven profiles. Event-driven modelling is based on discrete event simulation (DES), widely applied in business process modelling (Pidd 2004). Building modelling tools are time-driven. A future area of research could examine whether time-driven variables related to the material such as surface temperature, convective and reciprocal radiation heat transfers to and from the surrounding environment, can be coupled with event-driven profiles that model materials moving around a factory.

References

Al-Homoud, M. S. (2001). "Computer-aided building energy analysis techniques." Building and Environment 36(4): 421-433.

Amaratunga, D., D. Baldry, M. Sarshar and R. Newton (2002). "Quantitative and qualitative research in the built environment: application of “mixed” research approach." Work Study 51(1): 17-31.

Ashby, M. F. and D. R. H. Jones (1996). Engineering Materials 1: An Introduction to Their Properties and Applications, Butterworth-Heinemann.

ASHRAE (1999). HVAC 1 - A toolkit for primary HVAC system energy calculation, ASHRAE.

ASHRAE (2001). 2001 ASHRAE Handbook: Fundamentals, ASHRAE.

ASHRAE (2008). ANSI/ASHRAE Standard 140-2007: Standard method of test for the evaluation of building energy analysis computer programs, ASHRAE.

Avram, O. and P. Xirouchakis (2010). "Evaluating the use phase energy requirements of a Machine Tool System." Journal of Cleaner Production In Press, Accepted Manuscript.

Ball P. D, M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, M. R. Oates, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2011). Modelling energy flows across buildings, facilities and manufacturing operations. IMC 28, Manufacturing Sustainability, Dublin City University, August 2011.

Ball, P. D., M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012a). Factory modelling: combining energy modelling for buildings and production systems. International Conference on Advances in Production Management Systems APMS Greece, September 2012 - Submitted.

Ball, P. D., M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012b). Modelling buildings, facilities and manufacturing operations to reduce energy consumption. Proceedings of the Production and Operations Management Society (POMS) international conference, Chicago, USA, April 2012.

Ballarini, I. and V. Corrado (2011). A new thermal analysis by numerical simulation to investigate the energy performance of buildings, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

Baniszewski, B. (2005). An environmental impact analysis of grinding. Bachelor of science in mechanical engineering at the Massachusetts Institute of Technology.

BBC (2011). File on 4. Energy prices: Are households and businesses being overcharged for gas and electricity?, Radio. BBC Radio 4. 9th October 2011.

BEE. (2010). "Waste heat recovery, chapter 8 (National Certificate Examination for Energy Managers and Energy Auditors)." [WWW] Retrieved 01/12/2010, from http://www.em-ea.org/Guide%20Books/book-2/2.8%20Waste%20Heat%20Recovery.pdf.

Bombardier (2009). Bombardier Aerospace, Belfast. Metering monitoring & targeting - CTS063. Carbon Trust.

Boustead, I. and G. F. Hancock (1979). Handbook of industrial energy analysis, Ellis Horwood.

BP (2011). BP Statistical Review of World Energy BP.

Bryman, A. (2006). "Paradigm Peace and the Implications for Quality." International Journal of Social Research Methodology 9(2): 111-126.

Bryman, A. (2007). "Barriers to Integrating Quantitative and Qualitative Research." Journal of Mixed Methods Research 1(1): 8-22.

BSRIA (2003). A practical guide to HVAC Building Services calculations. BSRIA Guide 3 0/2003.

BSRIA (2003). Rules of Thumb (UK 4th Edition), BSRIA.

Building.co.uk. (2011). "Bombardier aircraft factory." [WWW] Retrieved 04/02/2012, from http://www.building.co.uk/5010542.article?origin=bldgtechnicalnewsletter.

Building.co.uk. (2012). "Bombardier aircraft factory." [WWW] Retrieved 04/02/2012, from http://www.building.co.uk/5010542.article?origin=bldgtechnicalnewsletter.

Cambridge_dictionary. (2011). "On-line Cambridge dictionary." [WWW] Retrieved 2011-01-12, from http://dictionary.cambridge.org/.

Cameron, I., T. and D. Ingram, G. (2008). "A survey of industrial process modelling across the product and process lifecycle." Computers and Chemical Engineering 32: 420-438.

Carbon-Trust (2002). Good Practice Guide 316 - Undertaking an Industrial Energy Survey. Carbon-Trust.

Carbon-Trust (2004a). GIL125 - Industrial Buildings, Carbon Trust.

Carbon-Trust (2004b). Energy Consumption Guide 81 - Benchmark Tool for Industrial Buildings: Heating and Lighting. Carbon-Trust.

CIBSE (1998). AM11 Building energy and environmental modelling, CIBSE.

CIBSE (2006a). Guide A - Environmental Design, CIBSE.

CIBSE (2006b). TM39: A guide to energy sub-metering in non-domestic buildings, CIBSE.

CIBSE (2006c). TM33: Tests for software accreditation and verification, CIBSE.

Ciceri, N., T. Gutowski and M. Garetti (2010). "A Tool to Estimate Materials and Manufacturing Energy for a Product." Sustainable Systems and Technology (ISSST): 1 - 6.

Clarke, J. A. (1986). Simulation of building energy systems. Proc. 5th CIB Symp. on Energy Conservation in the Built Environment, Bath.

Clarke, J. A. (2001). Energy simulation in building design, Butterworth Heinemann.

Clune, M., P. Mosterman and C. Cassandras (2006). "Discrete Event and Hybrid System Simulation with SimEvents. ." Proceedings of the 8th International Workshop on Discrete Event Systems Ann Arbor, Michigan, USA, July 10-12.

CO2PE. (2012). "Cooperative Effort on Process Emissions in Manufacturing." [WWW] Retrieved 2012-06-22, from http://www.co2pe.org/?Homepage.

Dahmus, J. B. and T. G. Gutowski (2004). "An Environmental Analysis of Machining." ASME Conference Proceedings 2004(47136): 643-652.

Dalquist, S. and T. Gutowski (2004). "Life Cycle Analysis of Conventional Manufacturing Techniques - Sand Casting." 2004 ASME International Mechanical Engineering Congress & Exposition.

Dalquist, S. and T. Gutowski (2006). "Life Cycle Analysis of Conventional Manufacturing Techniques - Die Casting." LMP-MIT-TGG.

DECC. (2011b). "UK Energy flow chart, 2010." [WWW] Retrieved 04/01/2011, from http://www.decc.gov.uk/en/content/cms/statistics/publications/flow/flow.aspx.

DECC. (2012). "Energy consumption in the United Kingdom " [WWW] Retrieved 13/08/2012, from http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx.

DeGarmo, E., J. Black and R. Kohser (2003). Materials and Processes in Manufacturing, John Wiley and Sons.

Despeisse, M., M. R. Oates and P. D. Ball (2012). "Sustainable manufacturing tactics and cross-functional factory modelling." Journal of Cleaner Production - Under review.

Despeisse, M. I., M. R. Oates and P. D. Ball (2013). "Sustainable manufacturing tactics and cross-functional factory modelling." Journal of Cleaner Production 42(0): 31-41.

Devoldere, T., W. Dewulf, W. Deprez, B. Willems and J. Duflou (2007). Improvement Potential for Energy Consumption in Discrete Part Production Machines: 311-316.

Dietmair, A. and A. Verl (2009). "A generic energy consumption model for decision making and energy efficiency optimisation in manufacturing -- Research Article." International Journal of Sustainable Engineering 2(2): 123 - 133.

DOE. (2012). "US DOE Building Energy Software Tools Directory." [WWW] Retrieved 04/01/2012, from http://apps1.eere.energy.gov/buildings/tools_directory/alpha_list.cfm.

Dorn, C., I. Kovacic, K. Orehounig, L. Oberwinter, F. Bleicher and A. Mahdavi (2011). Energy Efficient Production – Interdisciplinary, Systemic Approach through Integrated Simulation.

Duflou, J. R., K. Kellens and W. Dewulf (2011). "Unit process impact assessment for discrete part manufacturing: A state of the art." CIRP Journal of Manufacturing Science and Technology 4(2): 129-135.

Duflou, J. R., J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild and K. Kellens (2012). "Towards energy and resource efficient manufacturing: A processes and systems approach." CIRP Annals - Manufacturing Technology 61(2): 587-609.

DUKES (2012). Digest of United Kingdom Energy Statistics 2012. DECC.

Ecology. (2012). "Earth at a glance." [WWW] Retrieved 26/08/2011, from http://www.ecology.com/2011/09/14/earth-glance/.

EIA. (2006). "Energy consumption by manufacturers." [WWW] Retrieved 04/01/2012, from http://www.eia.gov/emeu/mecs/mecs2006/2006tables.html.

El-Haggar, S. (2007). Sustainable industrial design and waste management, Elsevier Science & Technology Books.

EnergyPlus. (2012). "EnergyPlus webpage." [WWW] Retrieved 04/01/2012, from http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm.

EngineeringToolbox. (2012). "Convective Heat Transfer." [WWW] Retrieved 2012-02-23, from http://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html.

ESP-r. (2012). "ESP-r main webpage." [WWW] Retrieved 04/01/2012, from http://www.esru.strath.ac.uk/Programs/ESP-r.htm.

Evola, G., N. Papa, F. Sicurella and E. Wurtz (2011). Simulation of the behaviour of Phase Change Materials for the improvement of thermal comfort in lightweight buildings, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

Ford. (2012). "Ford River Rouge Plant." [WWW] Retrieved 04/01/2012, from http://www.hfmgv.org/rouge/index.aspx.

FSFE. (2012). "Free Software Foundation Europe main webpage." [WWW] Retrieved 04/01/2012, from http://fsfe.org/.

Gool, V. (1987). "The Value of Energy Carriers." Energy 12(6): 509-518.

Goverment, H. M. (2010a). Approved Douments L2A - Conservation of fuel and power in new buildings other than dwellings, HM Goverment.

Goverment, H. M. (2010b). Approved Douments L2B - Conservation of fuel and power in existing buildings other than dwellings, HM Goverment.

Gutowski, T. G., M. S. Branham, J. B. Dahmus, A. J. Jones, A. Thiriez and D. P. Sekulic (2009). "Thermodynamic analysis of resources used in manufacturing processes." Environmental Science and Technology 43(5): 1584-1590.

HAMlab. (2011). "HAMlab." [WWW] Retrieved 04/01/2012, from http://archbps1.campus.tue.nl/bpswiki/index.php/Hamlab.

Hammond, G. P. (2007). "Industrial energy analysis, thermodynamics and sustainability." Applied Energy 84(7-8): 675-700.

Hawken, P., A. Lovins and L. Lovins (2010). Natural Capitalism, the next industrial revolution, Earthscan.

Heinz (2010). Carbon savings in a can; Efficiencies on the production line - CTS129. Carbon Trust.

Herman-Miller. (2011). "Herman Miller." [WWW] Retrieved 04/01/2012, from http://www.hermanmiller.com/About-Us/Environmental-Advocacy/Green-Buildings.

Herman-Miller. (2012). "Herman Miller." [WWW] Retrieved 04/01/2012, from http://www.hermanmiller.com/About-Us/Environmental-Advocacy/Green-Buildings.

Herrmann, C. and S. Thiede (2009). "Process chain simulation to foster energy efficiency in manufacturing." CIRP Journal of Manufacturing Science and Technology 1(4): 221-229.

Herrmann, C., S. Thiede, S. Kara and J. Hesselbach (2011). "Energy oriented simulation of manufacturing systems - Concept and application " CIRP Annals - Manufacturing Technology 60(1): 45-48.

Hesselbach, J., C. Herrmann, R. Detzer, L. Martin, S. Thiede and B. Ludemann (2008). "Energy efficiency through optimized coordination of production and technical building services." In Proceedings 15 th CIRP International Conference on Life Cycle Engineering location:The University of New South Wales, Sydney, Australia. ISBN 1-877040-67-3: 624-628.

IBPT. (2012). "IBPT main webpage." [WWW] Retrieved 18/05/2012, from http://www.ibpt.org.

ICT (2008). ICT and energy efficiency: consultation groups sectors reports, European Commission.

IEA. (2010). "Industry." [WWW] Retrieved 01/12/2010, from http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD_ID=4157>.

IEA (2010a). World Energy Outlook 2010, IEA.

IEA (2011). Key world energy statistics, 2011, IEA.

IES (2010). ApacheView User Guide. IES Virtual Environment 6.3.

IES. (2012a). "IES main webpage " [WWW] Retrieved 04/01/2012, from http://www.iesve.com/UK-ROI.

IES. (2012b). "ApacheSim Calculation Methods." [WWW] Retrieved 04/01/2012, from http://www.iesve.com/UK-ROI

IES. (2012c). "Software verification." [WWW] Retrieved 2012-08-01, from http://www.iesve.com/software/ve-pro/analysis-tools/validation.

Incropera, F., D. DeWitt, T. Bergman and A. Lavine (2006). Fundamentals of heat and mass transfer, John Wiley & Sons.

Ingalls, R. (2002). Introduction to simulation. Proceedings of the 2002 Winter Simulation Conference.

ISO (2011). ISO 50001:2011 Energy management systems: Requirements with guidance for use. Geneva, International Organization for Standardization.

JCB (2009). Manufacturing case study CTS129. Carbon Trust.

Jelinski, L. W., T. E. Graedel, R. A. Laudise, D. W. McCall and C. K. N. Patel (1992). "Industrial ecology: Concepts and approaches." Proceedings of the National Academy of Sciences of the United States of America 89(3): 793-797.

Jones, W. P. (2005). Air Conditioning Engineering, 5th Ed., Butterworth Heinemann.

Kalagasidis, A. (2002). H-Tools. International Building Physics Toolbox, Block Documentation. CTH, Report R-02:3, Chalmers University.

Kemp, I. C. (2006). Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy, Butterworth-Heinemann.

Kovacic, I., K. Orehounig, U. Renger, L. Oberwinter, C. Dorn, F. Bleicher and A. Mahdavi (2011). "A holistic model for an energy efficient production in facility." 1st international conference on sustainable intelligent manufacturing H.Bartolo et al. (Eds.) Leiria, Portugal, June 28-july 1, 2011.

Kurd, M. (2004). The Material and Energy Flow Through the Abrasive Waterjet Machining and Recycling Processes. Bachelor of science in mechanical engineering at the Massachusetts Institute of Technology.

Kusuda, T. (2001). "Building environment simulation before desk top computers in the USA through a personal memory." Energy and Buildings 33(4): 291-302.

Lehaney, B. A. and G. Vinten (1994). "Methodology: An Analysis of Its Meaning and Use." Work Study 43(3): 5-8.

Leonard, A. (2010). The Story of Stuff, Simon & Schuster.

Löfgren, B. and A. Tillman (2011). "Relating manufacturing system configuration to life-cycle environmental performance: discrete-event simulation supplemented with LCA." Journal of Cleaner Production 19: 2015 - 2024.

Malkin, S. and C. Guo (2007). "Thermal Analysis of Grinding." Annals of the CIRP 56(2): 760-782.

Maria, A. (1997). Introduction to modeling and simulation. Proceedings of the 1997 Winter Simulation Conference, IEEE.

MAS-Intimates. (2011). "Thurulie, Sri Lanka " [WWW] Retrieved 04/01/2011, from http://www.holcimfoundation.org/Portals/1/docs/Book_MAS_SriLanka.pdf.

Matlab. (2012). "Matlab product description " [WWW] Retrieved 04/01/2012, from http://www.mathworks.com/products/matlab.

McLaren. (2012). "McLaren Technology Centre." [WWW] Retrieved 04/01/2012, from http://www.mclaren.com/technologycentre/.

McMullan, R. (2007). Environmental Science in Buildings, Palgrave macmillan.

Modelica. (2012). "Modelica main webpage." [WWW] Retrieved 04/01/2012, from https://modelica.org/.

Morrisons (2010). Building a low future; from the fields to the shelves - CTS162. Carbon Trust.

Nike. (2011). "Nike, Ho Chi Minh City, Vietnam." [WWW] Retrieved 04/01/2012, from http://www.idcarchitects.com/portfolio/international/nike.asp.

Oates, M. R., M. Despeisse, P. D. Ball, S. Evans, R. M. Greenough, S. Hope, A. Levers, P. Lunt, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012). Design of Sustainable Industrial Systems by Integrated Modelling of Factory Building and Manufacturing Processes. The 10th Global Conference on Sustainable Manufacturing, Turkey, October, 2012 - Submitted.

Oates, M. R., A. Wright, R. M. Greenough and L. Shao (2011a). A new modelling approach which combines energy flows in manufacturing with those in a factory building. Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

Oates, M. R., A. Wright, R. M. Greenough and L. Shao (2011b). Understanding resource flows in a factory environment - a graphical approach. Int Conf Sustainable Intelligent Manufacturing, , Leiria, Portugal.

Office-for-National-Statistics. (2011). "UK Standard Industrial Classification 2007 (UK SIC 2007)." [WWW] Retrieved 04/01/2012, from http://www.ons.gov.uk/ons/guide-method/classifications/current-standard-classifications/standard-industrial-classification/index.html.

ONS. (2012). "Office for National Statistics - UK Standard Industrial Classification 2007 (UK SIC 2007)." [WWW] Retrieved 04/01/2012, from http://www.ons.gov.uk/ons/guide-method/classifications/current-standard-classifications/standard-industrial-classification/index.html.

Oorschot, v., R. (2010). Desicant evaporative cooling: optimnal strategy for cooling in a Dutch climate. Eindhoven University of Technololgy. Eindhoven. Masters program sustainable energy technology.

Overcash, M., J. Twomey and J. Isaacs (2009). Manufacturing unit process life cycle inventories (Uplci). Proceedings of the 9th Workshop on Performance Metrics for Intelligent Systems. Gaithersburg, Maryland, ACM.

Paton, J., Z. Khatir, H. Thompson, N. Kapur and V. Toropov (2012). "Thermal energy management in the bread baking industry using a system modelling approach." Applied Thermal Engineering(0).

Pidd, M. (2004). Computer Simulation in Management Science, John Wiley and Sons.

Pugh, S. (1990). Total design: Integrated methods for successful product engineering, Prentice Hall.

Robinson, S. (2004). Simulation: The Practice of Model Development and Use, Wiley, Chichester, UK.

Robinson, S. (2006). Conceptual modelling for simulation: issues and research requirements. Proceedings of the 2006 Winter Simulation Conference, Vols 1-5, IEEE.

Robson, C. (2011). Real world research: a resource for users of social research methods in applied settings, 3rd ed, John Wiley and Sons Ltd.

Rockwell. (2012). "Arena simulation, Rockwell Automation " [WWW] Retrieved 04/01/2012, from http://www.arenasimulation.com/Services_Webcasts.aspx.

Rode, C., C. Gudum, P. Weitzmann, R. Peuhkuri, T. R. Nielsen, A. Kalagasidis and C.-E. Hagentoft (2002). International Building Physics Toolbox. General Report, R-02:4, Chalmers University.

Sakulpipatsin, P. (2008). Exergy efficient building design. MSc in Energy Conversion and Management, University of Applied Sciences Offenburg geboren te Suphan Buri, Thailand.

Schmidt, M. (2008). "The Sankey diagram in energy and material flow management part 1 history." Journal of Industrial Ecology 12(1): 82-94.

Schonberger, R. J. (2007). "Japanese production management: An evolutionâ€"With mixed success." Journal of Operations Management 25(2): 403-419.

Schriber, T. J. and D. T. Brunner (2007). Inside discrete-event simulation software: How it works and why it matters. Proceedings of the 2007 Winter Simulation Conference

Science-Direct. (2012). "Science Direct." [WWW] Retrieved 04/01/2012, from http://www.sciencedirect.com/.

Scopus. (2012). "Scopus." [WWW] Retrieved 04/01/2012, from http://www.scopus.com.

Seow, Y. and S. Rahimifard (2011). "A framework for modelling energy consumption within manufacturing systems." CIRP Journal of Manufacturing Science and Technology 4(3): 258-264.

Simulink. (2012). "Simulink product description." [WWW] Retrieved 04/01/2012, from http://www.mathworks.com/products/simulink.

STAN. (2012). "subSTance Analysis Flow (STAN)." [WWW] Retrieved 01/04/2012, from http://www.stan2web.net/.

Stournaras, A. (2009). "An investigation of quality in CO2 laser cutting of aluminium." CIRP Journal of Manufacturing Science and Technology 2: 61-69.

Sugimori, Y., K. Kusunoki, F. Cho and S. Uchikawa (1977). "Toyota production system and Kanban system Materialization of just-in-time and respect-for-human system." International Journal of Production Research 15(6): 553-564.

Tedngai. (2012). "Psychrometrics with Matlab." [WWW] Retrieved 2012-08-01, from http://www.tedngai.net/teaching/psychrometrics-with-matlab.html.

THERM. (2012). "about THERM." [WWW] Retrieved 04/01/2012, from http://www.therm-project.org/?page_id=2.

Thiede, S., C. Herrmann and S. Kara (2011). "State of Research and an innovative Approach for simulating Energy Flows of Manufacturing Systems." Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International 335 Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011,.

Thiriez, A. and T. Gutowski (2006). An Environmental Analysis of Injection Molding. Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on.

Toyota, (2011). "Toyota Tsutsumi." [WWW] Retrieved 04/01/2012, from http://www.toyota.co.jp/en/tech/hybrid/plant/index.html.

Turner, C., A. Dave, M. R. Oates, V. Murray and P. D. Ball (2012). Modelling energy in buildings and production systems: The impact of model granularity and quality on output. Proceedings of the 10th International Conference on Manufacturing Research ICMR 2012 - Submitted.

Vanguard-Packaging, (2012). "Vanguard Packaging, Kansas City." [WWW] Retrieved 04/01/2012, from http://www.vanguardpkg.com/home.aspx>www.vanguardpkg.com/home.aspx.

Vijayaraghavan, A. and D. Dornfeld (2010). "Automated energy monitoring of machine tools." CIRP Annals - Manufacturing Technology 59(1): 21-24.

Waters, J. R. and A. J. Wright (1985). "Criteria for the distribution of nodes in multilayer walls in finite-difference thermal modelling." Building and Environment 20(3): 151-162.

Web-of-knowledge. (2012). "Web of knowledge." [WWW] Retrieved 04/01/2012, from http://apps.isiknowledge.com.

Wetter, M., Z. Wangda and T. Nouidui (2011). "Modelling of heat transfer in rooms in the Modelica 'buildings' library." Proceedings of Building Simulation 2011; 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November: 1096-1103.

Wright, A., M. R. Oates and R. M. Greenough (2012). Concepts for dynamic modelling of energy-related flows in manufacturing. International Conference on Applied Energy ICAE, Suzhou, China, Jul 5-8, 2012, .

Wright, A. J., M. R. Oates and R. Greenough "Concepts for dynamic modelling of energy-related flows in manufacturing." Applied Energy(0)

Wright, J. A. and V. I. Hanby (1988). IEA Annex 10 - Systems Simulation. Fans, University of Liège, Belgium, report AN10 881020-RF, 1988, 90pp

Yildiz, A. and A. Gungor (2009). "Energy and exergy analyses of space heating in buildings." Applied Energy 86(10): 1939-1948.

Yin, R. K. (2009). Case study research: design and methods, 4th ed. Applied social research methods v.5.

Zetoc. (2012). "Zetoc." [WWW] Retrieved 04/01/2012, from http://zetoc.mimas.ac.uk/.

List of publications

Journal

- Wright, A. J., M. R. Oates and R. Greenough "Concepts for dynamic modelling of energy-related flows in manufacturing." Applied Energy(0)

- Despeisse, M. I., M. R. Oates and P. D. Ball (2013). Sustainable manufacturing tactics and cross-functional factory modelling. Journal of Cleaner Production 42(0): 31-41.

- Hughes, B. R. and M. Oates (2011). Performance investigation of a passive solar-assisted kiln in the United Kingdom. Solar Energy 85(7): 1488-1498.

Conference

- Oates, M. R., M. Despeisse, P. D. Ball, S. Evans, R. M. Greenough, S. Hope, A. Levers, P. Lunt, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012). Design of Sustainable Industrial Systems by Integrated Modelling of Factory Building and Manufacturing Processes. The 10th Global Conference on Sustainable Manufacturing, Turkey, October, 2012

- Turner, C., A. Dave, M. R. Oates, V. Murray and P. D. Ball (2012). Modelling energy in buildings and production systems: The impact of model granularity and quality on output. Proceedings of the 10th International Conference on Manufacturing Research ICMR 2012

- Ball, P. D., M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, Oates, M. R., R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012a). Factory modelling: combining energy modelling for buildings and production systems. International Conference on Advances in Production Management Systems APMS Greece, September 2012

- Wright, A., M. R. Oates and R. M. Greenough (2012). Concepts for dynamic modelling of energy-related flows in manufacturing. International Conference on Applied Energy ICAE, Suzhou, China, Jul 5-8, 2012.

- Parker, J., M. R. Oates, P. Cropper and L. Shao (2012). Comparison of EPC, DEC and dynamic thermal simulation results at Birmingham Airport. Building Simulation and Optimization (BSO), 10-11 September, Loughborough, UK

- Ball, P. D., M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, Oates, M. R., R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2012b). Modelling buildings, facilities and manufacturing operations to reduce energy consumption. Proceedings of the Production and Operations Management Society (POMS) international conference, Chicago, USA, April 2012.

- Oates, M. R., A. Wright, R. M. Greenough and L. Shao (2011a). A new modelling approach which combines energy flows in manufacturing with those in a factory building. Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

- Oates, M. R., A. Wright, R. M. Greenough and L. Shao (2011b). Understanding resource flows in a factory environment - a graphical approach. Int Conf Sustainable Intelligent Manufacturing, , Leiria, Portugal.

- Ball P. D, M. Despeisse, S. Evans, R. M. Greenough, S. Hope, R. Kerrigan, A. Levers, P. Lunt, M. R. Oates, R. Quincey, L. Shao, T. Waltniel, C. Wheatley and A. Wright (2011). Modelling energy flows across buildings, facilities and manufacturing operations. IMC 28, Manufacturing Sustainability,, Dublin City University, August 2011.

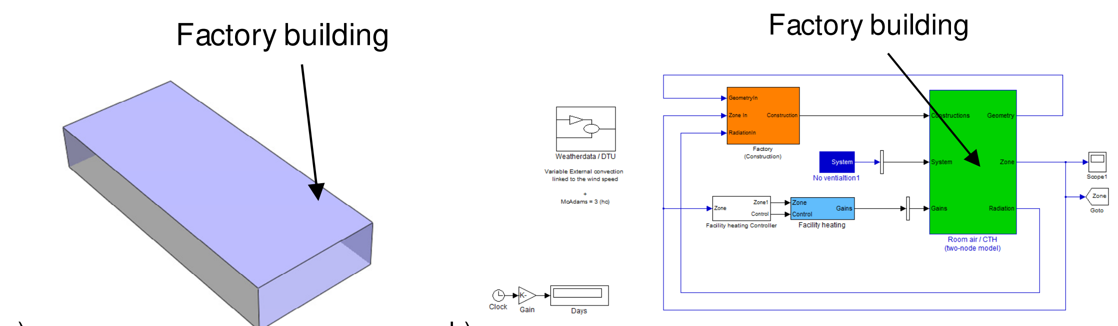
Appendix A - Tool verification

The following tool verification scenarios related to Sections 5.3.5

A.1 - Single zone (dynamic - mixed material, mean ground temperature)

The initial scenarios compare results for a factory building controlled by a temperature driven external climatic zone. The fictitious zone blocked the effects of solar radiation on the outer surface of the factory building. The thermal response of the building was based on air temperature differentials.

The following scenarios are considered dynamic, driven by weather input files and do not require an outer controlled environmental zone, Figure A-1. This model includes solar radiation and wind speed affects upon the outer surface of the building. There are no supplementary internal gains inside of the building. As discussed in section 5.2.2, the IBPT has been modified to calculate a variable external surface convective heat transfer coefficient that is linked to the external wind speed from the attached weather file.



a) b)

Figure A-1 - Factory building only, a) IES VE and b) IBPT

The building is of mixed materials, same as section 5.4.2. The soil temperature in contact with the ground floor material has been simulated in both tools at a constant 11.76°C. This value has been derived from the weather file based upon the annual average external dry bulb air temperature. The ground floor is modelled in the same way as a wall construction with the exception of convective heat transfer between the surfaces of the soil and floor.

A.1.1. Results

Factory building dry bulb air temperature results for January and July are shown in Figure A-2 and Figure A-3 respectively. The IBPT model has a RMSE of 1.13°C against IES VE result.

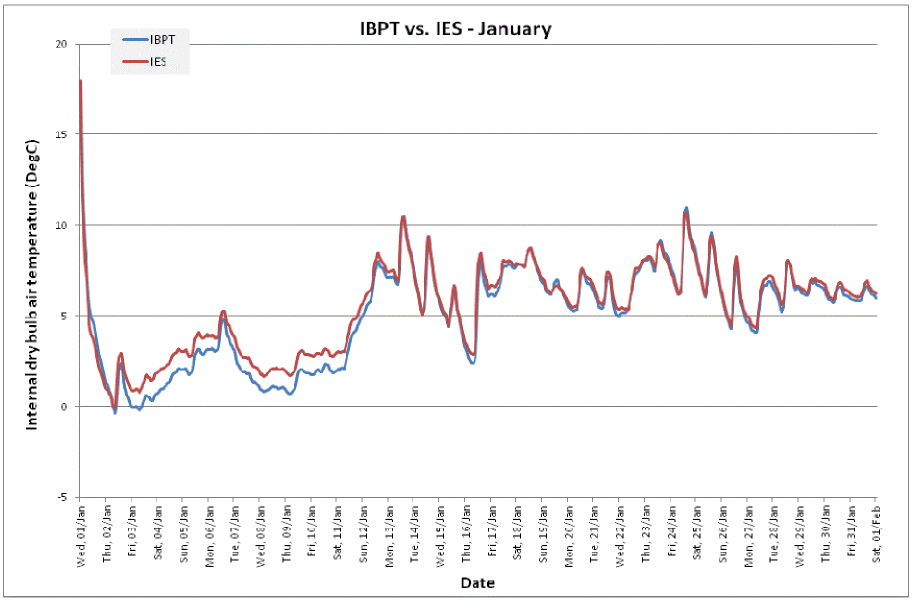


Figure A-2 - Factory air temperature - IBPT vs. IES VE – mixed construction and mean soil temperature (January)

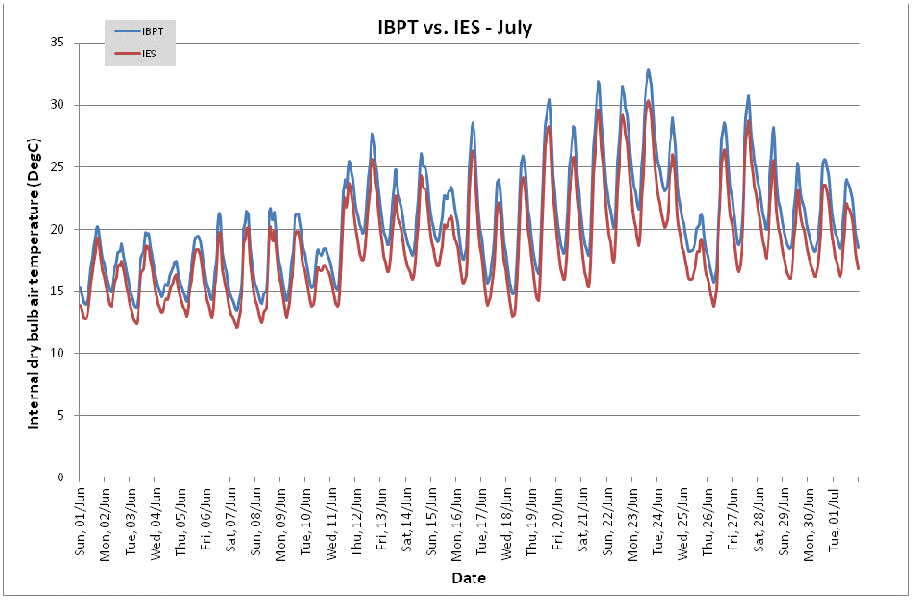


Figure A-3 - Factory air temperature - IBPT vs. IES VE – mixed construction and mean soil temperature (July)

A.1.2. Summary

The results for January show a close correlation between the two modelling tools. However, the correlation begins to diverge during the remaining 11 months of the year. This can be seen more clearly in July's results shown in Figure A-3.

A.2 - Single zone (dynamic - mixed material, ground adiabatic and windows)

The below scenario is the same as described in Appendix A.1, with the inclusion of windows. Surface areas and positioning of windows are based on a 10% area weighting to all vertical surfaces (i.e. 4No. walls), Figure A-5.

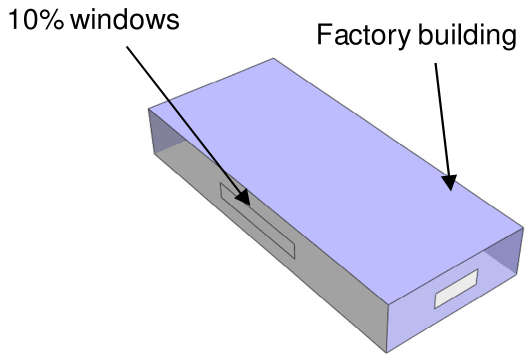


Figure A-4 - Factory building with windows

A.2.1. Results

Factory building dry bulb air temperature results for January and July are shown in Figure A-5 and Figure A-6 respectively. The IBPT model has a RMSE of 0.78°C against IES VE result.

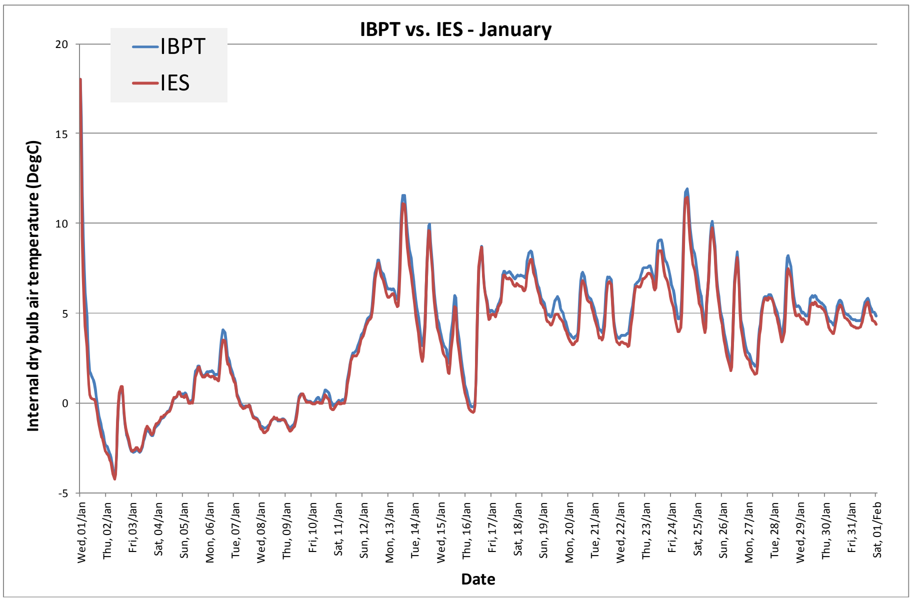


Figure A-5 - Factory air temperature - IBPT vs. IES VE – mixed construction, adiabatic ground material and 10% percent windows to all vertical walls (January)

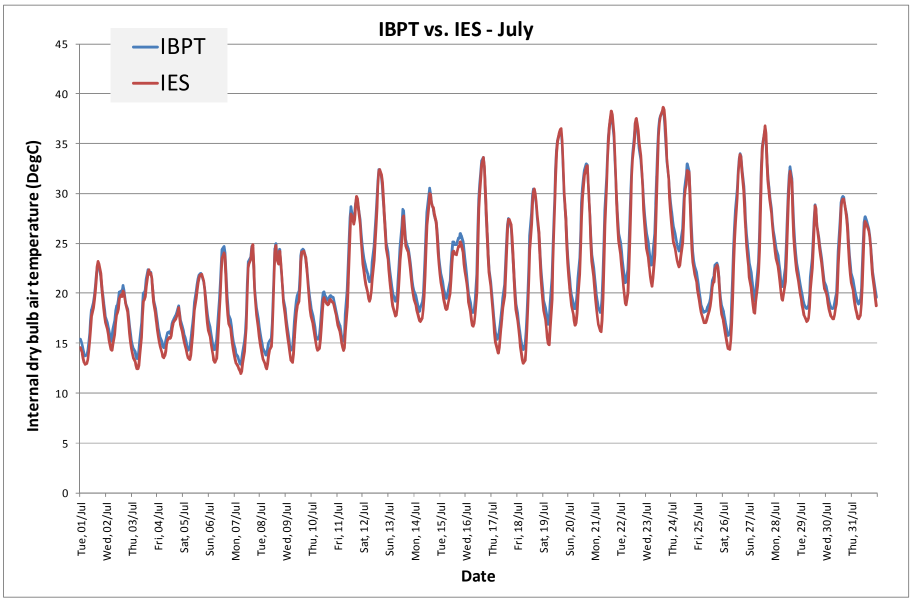


Figure A-6 - Factory air temperature - IBPT vs. IES VE – mixed construction, adiabatic ground material and 10% percent windows to all vertical walls (July)

A.2.2. Summary

The addition of windows to the model maintains a good correlation between results for both building modelling tools.

The following tool verification scenarios relate to Section 5.5

A.3 - Single internal zone (controlled – one material)

The below scenario uses the same approach as discussed in section 5.4.1, with the exception to modelling an internal thermal zone (i.e. tank) inside a larger zone (factory building), Figure A-7. The factory building is encapsulated by a surrounding zone that is controlled by a temperature driven profile (i.e. 18℃ Monday to Friday (9am - 5pm), 12℃ during all other times), as discussed in section 5.4.1. The thermal response of the building is based on air temperature differentials. The scenario models 1No. air based tank as an internal zone, dimensions (H/L/W) 5m, 35m and 2m. The factory building and tank have no internal gains. The factory building is constructed from 0.2m concrete.

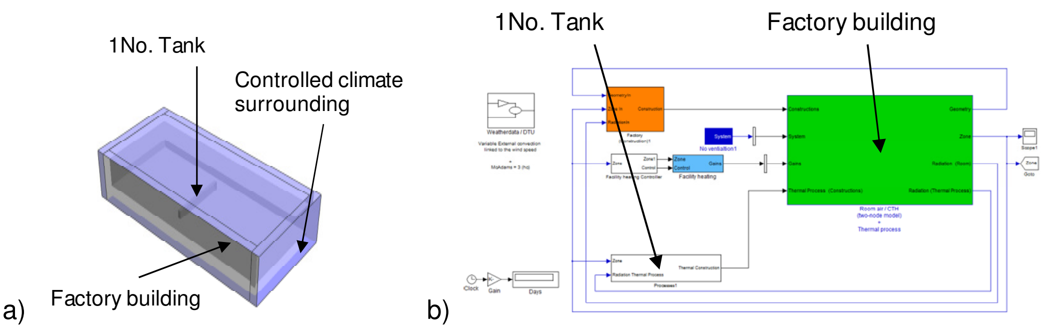


Figure A-7 - Factory building and internal zone with climate controlled surrounding zone, a) IES VE, b) IBPT

A.3.1. Results

Factory building dry bulb air temperature results for January are shown in Figure A-8 and for the internal air tank in Figure A-9. The IBPT model has a RMSE of 0.36°C and 0.38°C against IES VE result for the factory building and the air tank.

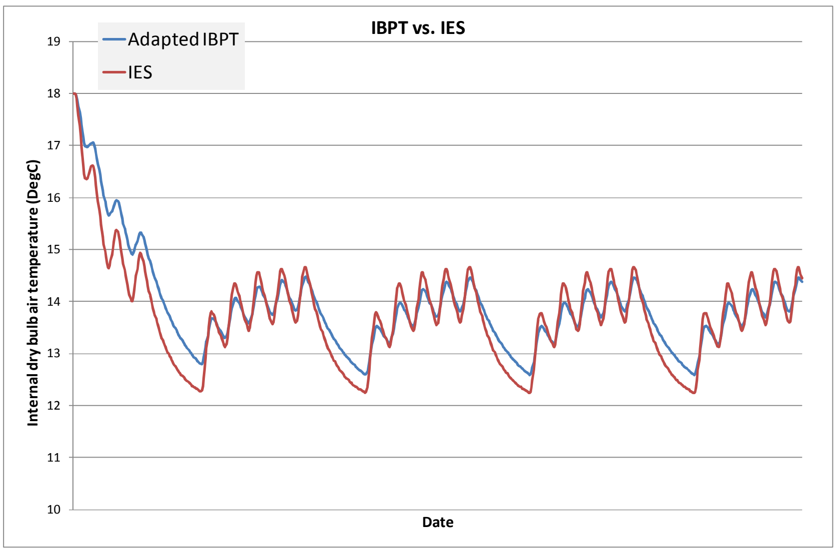


Figure A-8 - Factory air temperature - Adapted IBPT vs. IES VE – 0.2m thick concrete (31 days)

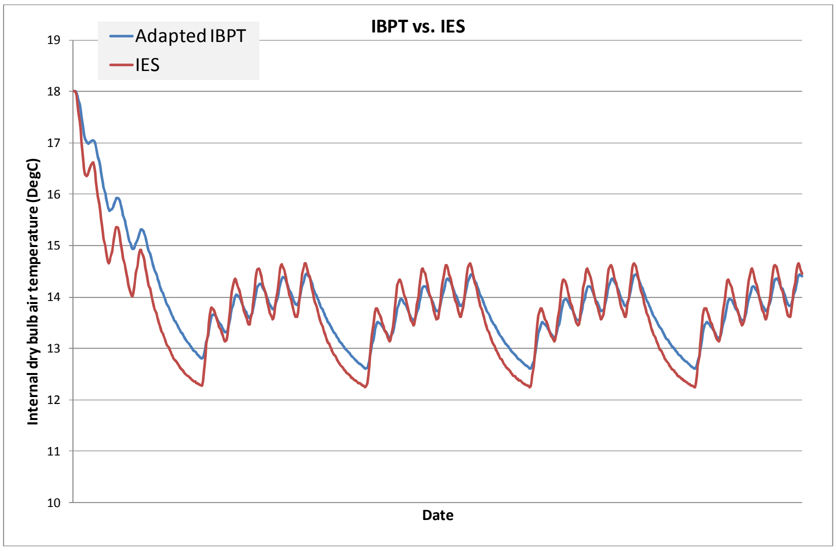


Figure A-9 – 1No. tank air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (31 days)

A.3.2. Summary

Results shown in Figure A-8 are comparable to Figure 5-5 (i.e. factory building only). This is expected as the scenario is the same with the exception of an internal thermal zone. This demonstrates that changes made to the model have not affected the mathematical approach of the tool. The results for the tank are also as expected, as the air temperature of the tank closely matches that of its surroundings, due to the thin steel structure of the tank.

A.4 - Single internal zone (controlled – mixed material)

The below scenario uses the same approach as discussed in section 5.4.2, with the exception of modelling an internal thermal zone inside a larger zone (factory building). The factory building is constructed from 0.2m thick concrete for all vertical wall and ground floor constructions. The roof is constructed of 0.01m thick steel. The factory building is encapsulated by a surrounding climate controlled zone. The thermal response of the building is based on air temperature differentials. The factory building and tank have no internal gains.

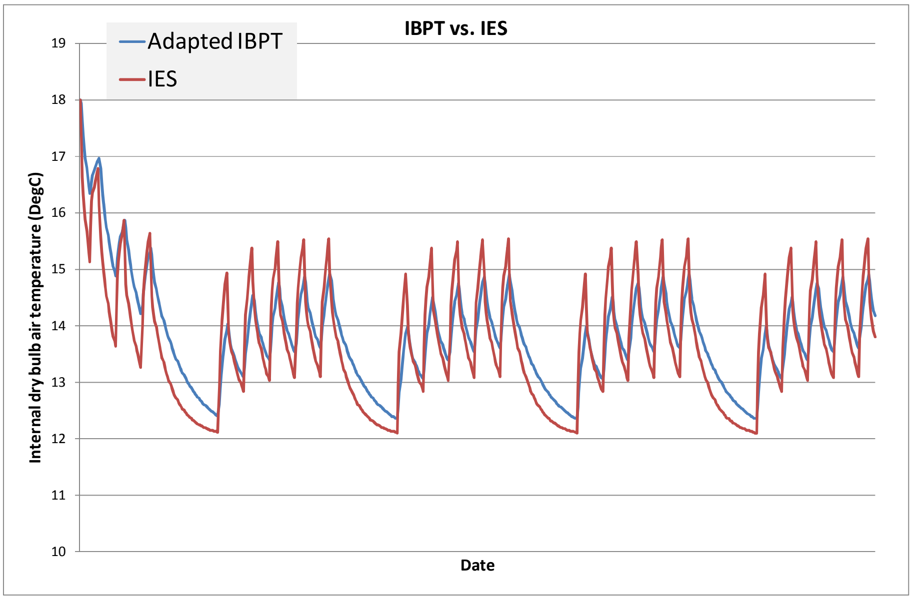


Figure A-10 - Factory air temperature - Adapted IBPT vs. IES VE – mixed construction, 0.01m thick steel roof, all other surfaces 0.2m thick concrete (31 days)

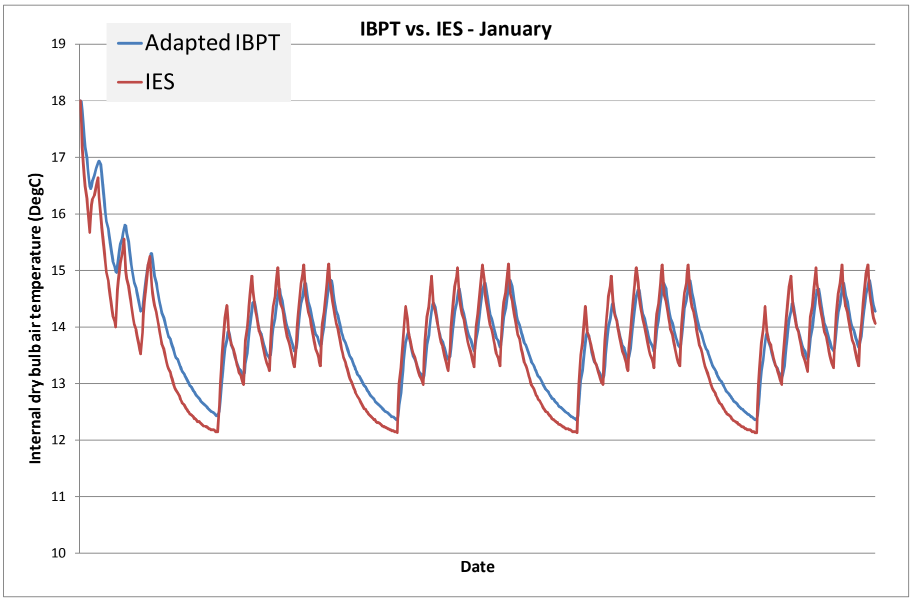


Figure A-11 - 1No. tank air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (31 days)

A.4.1. Results

Factory building dry bulb air temperature results for January are shown in Figure A-10 and for the internal air tank, Figure A-11. The IBPT model has a RMSE of 0.53°C and 0.36°C against IES VE result for the factory building and the air tank.

A.4.2. Summary

Results shown in Figure A-10 are comparable to Figure 5-7 (i.e. factory building only). The results for the tank (Figure A-11) are also as expected, as the air temperature of the tank closely matches that of its surroundings, due to the thin steel structure of the tank.

A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows)

The below scenario uses the same approach as discussed in section 5.4.3, with the exception of modelling an internal thermal zone inside a larger zone (factory building). The model is weather file driven. The factory building is of mixed materials, adiabatic ground floor and windows of 10% area to all vertical surfaces, Figure A-12. The internal thermal zone is constructed from 0.01m thick steel. The factory building and tank have no internal gains.

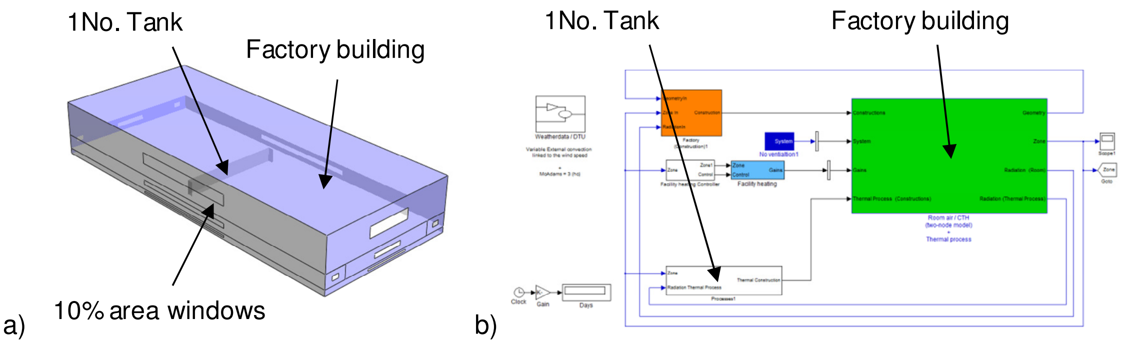


Figure A-12 - Factory building and 1No. internal tank, a) IES VE and b) IBPT

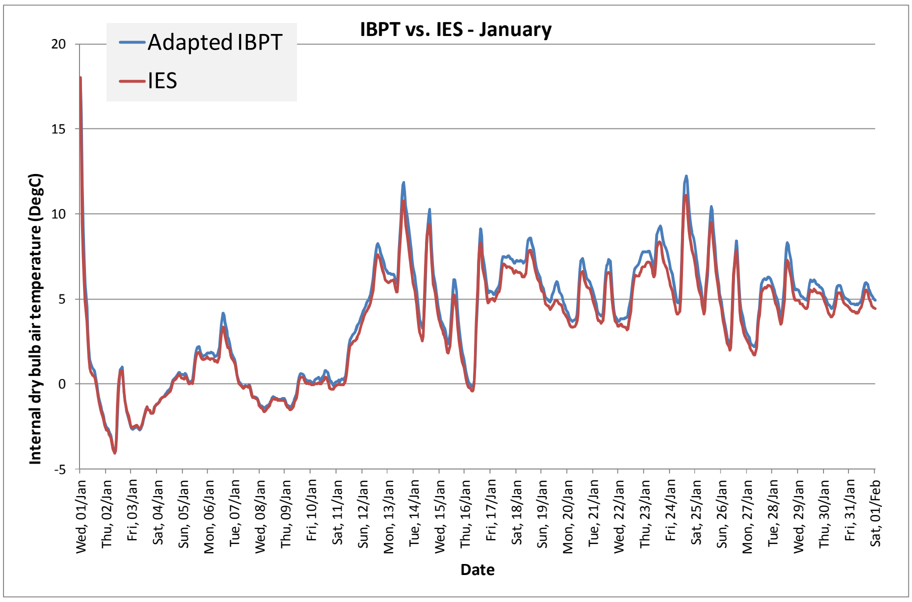


Figure A-13 - Factory air temperature - Adapted IBPT vs. IES VE – mixed construction, adiabatic ground material and windows (January)

A.5.1. Results

The factory building dry bulb air temperature results for January are shown in Figure A-13 and for the internal air tank, Figure A-14. The IBPT model has a RMSE of 0.45°C and 0.56°C against IES VE result for the factory building and the air tank

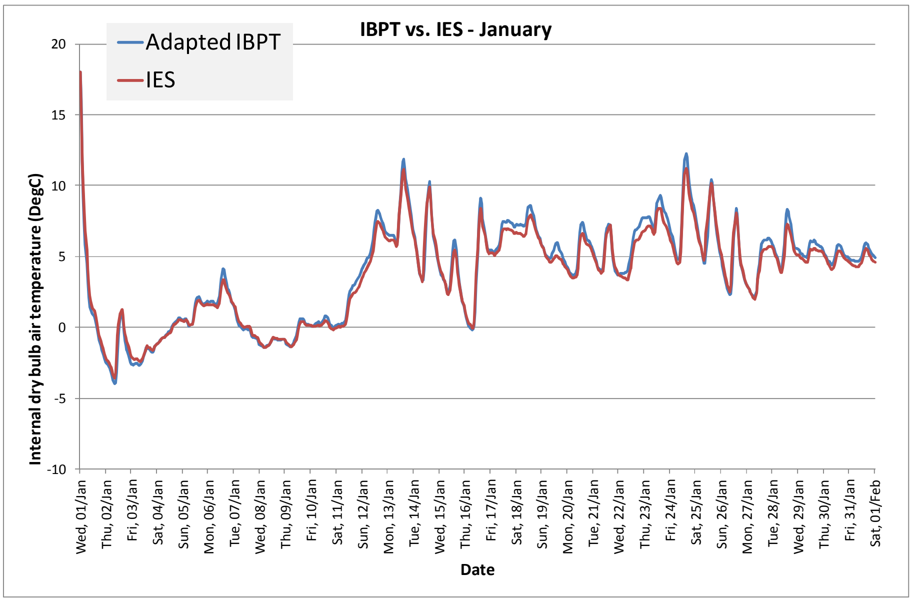


Figure A-14 - 1No. tank air temperature - Adapted IBPT vs. IES VE – 0.01m thick steel (January)

A.5.2. Summary

Results shown in Figure A-13 are comparable to Figure A-5 (i.e. factory building only). The windows based scenario is important, as the two simulation approaches model long wave radiation differently. IES VE calculates long wave radiation heat transfer based on view factors, where as the IBPT model uses area weighting averages. This may have greater affects when modelling more than one internal thermal zone, discussed in section 5.6.

Appendix B – Drying tank (plant components)

Below are mathematical equations used in the development of Simulink models representative of the manufacturing plant (fan, HX and circulation ductwork including air splitter and mixing box) as part of the drying tank in the case study discussed in section 6.2. Simulink models of the manufacturing plant can be found in Appendix D (material provided on a CD).

B.1 – Fan

Depending on whether the motor of the fan is in line with the incoming air, the energy transferred from the motor to the air is in two parts; the energy that is consumed by the air to overcome the pressure drop and losses from the motor (Oorschot 2010). Neglecting changes in kinetic energy of the air, all of the losses will appear as heat, resulting in a temperature rise of the passing air flow if the fan is in line with the motor (Wright et al. 1988).

$$q_e = \frac{\Delta p \times \dot{V}}{\mu_{motor}}$$

Equation B-1

Where, q_e is the power consumption of the motor (W), Δp is the pressure drop (Pa), $\dot{V}$ is the volumetric flow rate of air (m^3/s) and μ_{motor} is the efficiency of the motor between 0 and 1 (1=100% efficient) (Oorschot 2010).

The total amount of energy transferred to the air q_{air} (W) from the motor can be calculated from the below equation (Oorschot 2010);

$$q_{air} = (\mu_{motor} + (1 - \mu_{motor}) \times f_{motorless}) \times q_e$$

Equation B-2

Where, $f_{motorless}$ is the transfer of loses from the motor to the passing air (1 or 0). $f_{motorless}$ is equal to 1 if the motor is line and 0 if not.

If the motor is in line with the passing air, the inlet air condition will increase in sensible gain at a constant humidity ratio (W) (g of moisture/kg of dry air). From known values of the air condition pre fan, the change in condition of the air can be derived from the change in enthalpy (Oorschot 2010).

$$h_{out} = h_{in} + \frac{q_{air}}{\dot{m}_{air}}$$

Equation B-3

Where, h_{in} and h_{out} are the enthalpy condition of the air at pre and post fan (KJ/Kg) and $\dot{m}_{air}$ is the mass flow rate of the air (kg/s).

B.2 – Heat exchanger (HX)

Figure B-1 is a classic representation of a counter flow heat exchanger (ASHRAE 1999).

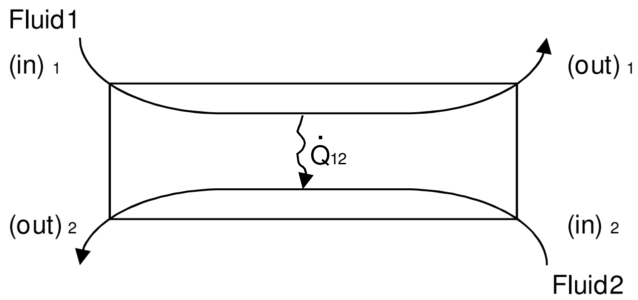


Figure B-1 – Classical schematic of a heat exchanger

$$\dot{Q} = \dot{Q}_{12} = \dot{C}_1(T_{in} - T_{out})_1 = \dot{C}_2(T_{in} - T_{out})_2$$

Equation B-4

Where, $\dot{Q}_{12}$ is the heat transfer rate from fluid 1 to fluid 2 (W), $\dot{C} = \dot{m}c_p$ is the heat capacity flow rate (W/K) where $\dot{m}$ is the mass flow rate (kg/s) and c_p specific heat capacity at a constant pressure (J/Kg.K). T is the temperature of the fluid (K) entering (in) and leaving (out) the heat exchanger.

The above equation equates to:

$$\dot{Q} = \in \dot{C}_{min}(T_{in1} - T_{in2})$$

Equation B-5

Where, $\in = f(NTU, \dot{C})$ is the heat exchanger effectiveness, where $NTU = \frac{UA}{\dot{C}_{min}}$, UA is the heat transfer coefficient-area product (W/K) and $\dot{C}_{min} = \dot{C} \times \dot{C}_{MAX}$, where $\dot{C}_{min} = min(\dot{C}_1, \dot{C}_2)$ and $\dot{C}_{max} = max(\dot{C}_1, \dot{C}_2)$.

B.3 – Mixing box

The adiabatic mixing of two moist airstreams is governed by the equation (ASHRAE 2001):

$$\frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1} = \frac{\dot{m_{da1}}}{\dot{m_{da2}}}$$

Equation B-6

Where, $h_{1\ to\ 3}$ are the enthalpies of the air condition at three state points (KJ/Kg), $W_{1\ to\ 3}$ are the humidity ratios at three state points (g of moisture/kg of dry air) and $\dot{m}$ is the mass flow rate of air at state points 1 and 2 (kg/s). State point 3 is determined from the mixing of states 1 and 2, resulting in a mixture (state 3) that lies on a straight line between the two states if expressed on a psychrometric chart.

B.4 – Splitter

The splitter separates the volumetric flow rate of one air stream into two streams of air. This is simply expressed as a percentage ratio.

$$\dot{v}_1 = \dot{v}_2 + \dot{v}_3$$

$$\dot{v}_2 = \dot{v}_1 \times \%_{ratio}$$

$$\dot{v}_3 = \dot{v}_1 - \dot{v}_2$$

Equation B-7

Where, $\dot{v}_{1\ to\ 3}$ are the volumetric flow rate of the incoming air stream and the two air streams after the splitter (m^3/s) and $\%_{ratio}$ is the percentage ratio of stream 2 in relation to stream 1.

Appendix C – Adapted IBPT tool and manual

Below is a list of contents submitted on a compact disc (CD). The below numbering relates to the subsequent chapters of the work.

5.2_Adapted IBPT tool

- Adapted_IBPT_inc_Material
- Model information (i.e. weather files, material construction etc)
- Adapted H-Tools Manual

Appendix D – Simulated models and results

Below is a list of contents submitted on a compact disc (CD). The below numbering relates to the subsequent chapters of the work.

D.1 – Verification models and results

- 5.4 IBPT (single thermal zone)
  - 5.4.1 Single zone (controlled – one material)
    - IBPT model
    - Results
  - 5.4.2. Single zone (controlled – mixed material)
    - IBPT model
    - Results
  - 5.4.3. Single zone (dynamic - mixed material, adiabatic ground)
    - IBPT model
    - Results
  - 5.4.4. Single zone (dynamic - mixed material, ground adiabatic, windows and heating)
    - IBPT model
    - Results
  - Appendix A.1 - Single zone (dynamic - mixed material, mean grd temperature)
    - IBPT model
    - Results
  - Appendix A.2 - Single zone (dynamic - mixed material, ground adiabatic and windows)
    - IBPT model
    - Results
- 0_With exception to the scenario modelled in section 5.4.1 (including space heating), the accuracy and the ability of the IBPT to model comparable building energy flow paths when compared with IES VE, makes the tool suitable for future use by the research. Future scenarios shall explore this issue further. Though one solution could be to increase the radiant heating fraction of the heating system within the IBPT from 20% to 40%, where required.
- Adapted IBPT (zone inside a zone)
  - 5.5.1. Single internal zone (dynamic - mixed material, ground adiabatic, windows and heating)
    - IBPT model
    - Results
  - A.3 - Single internal zone (controlled – one material)

    - IBPT model
    - Results

  - A.4 - Single internal zone (controlled – mixed material)
    - IBPT model
    - Results

  - A.5 - Single internal zone (dynamic - mixed material, grd adiabatic, windows)
    - IBPT model
    - Results

- 5.6_Adapted IBPT (several zones inside a zone)
  - 5.6.1. Six internal zones (dynamic – mixed material, adiabatic ground and windows)
    - IBPT model
    - Results
  - 5.6.2. Six internal zones (dynamic – mixed material, adiabatic ground, windows and heating)
    - IBPT model
    - Results

D.2 – Case study models and results

6.2_Industrial drying tank

- Scenarios 1 to 7
  - IBPT model
  - Results

6.3_Industrial treatments process

- Scenarios 1 and 2
  - IBPT model
  - Results

6.4_Air supply house

- Macro and micro Simulink model
  - Data not included to maintain confidentially of the industrial partner data