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A NEW MODELLING APPROACH WHICH COMBINES ENERGY FLOWS IN MANUFACTURING WITH THOSE IN A FACTORY BUILDING

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ABSTRACT

This paper describes the development of a modelling approach which combines the energy use in industrial production, with the energy flows relating to the building. Through case studies, the effects of energy conservation measures in production on the overall thermal energy balance of a factory production area are explored.

The paper identifies three types of manufacturing processes; thermal 'air' process (oven), thermal 'fluid' process (vat) and electrical processes (motor). Product (material) flow is also discussed, accounting for product heat flux and dispersion upon the overall energy balance of the system, after leaving a process.

This paper includes both methodology and demonstrations on how building physics and manufacturing process systems may be modelled in an integrated manner, in order to improve the way that industry uses and thinks about energy at both facility and systems level.

INTRODUCTION

The conservation of energy and materials, and reduction in global carbon emissions, has become a key topic among governments, businesses, local communities and researchers. This paper focuses on an energy and material intensive sector of the global economy - manufacturing industry. Since the industrial revolution, accesses to cheap materials and fossil fuel based sources of energy have been the backbone of industry (Merchant et al., 2005). Throughout this revolution, the abundance of material and energy across industry and other sectors (i.e. domestic and non-domestic buildings, transport and services) has been largely linear: from extraction to processing, use and finally disposal in landfill or incineration (Jelinski et al., 1992). Globally, industry consumes around one third of all energy use, and accounts for almost 40% of global CO_2 emissions (IEA, 2010). Therefore, improvements in the way that industry uses energy and materials will have an effect on a global scale. This paper discusses the modelling of energy use in industrial production, and combining them with the energy flows relating to the factory building. The combination of building physics and manufacturing process systems in one integrated area of work is novel, as these two areas are usually considered separately by their designers (Herrmann and Thiede, 2009). Improvements in the way that industrial processes consume energy will likely result in energy savings at a systems level (Vijayaraghavan and Dornfeld, 2010), (Dahmus and Gutowski, 2004). But, what are the effects on energy consumption at facility level? Case study results based on simulation of an 'air' thermal process are discussed. For example, the heat flux from an industrial process into the surrounding environment may reduce space heating demand in the colder seasons. Conservation measures introduced for the thermal process might include a reduction in operation hours, resulting in an increased heating requirement for the facility. The energy balance at facility and systems level is complex and extremely difficult to evaluate at systems level alone. Through use of the integrated simulation tool, relationships and interactions between the facility environment and the manufacturing systems can be modelled, enabling the overall energy consumption of a manufacturing facility to be managed and operated in a more sustainable manner.

This paper discusses the following three areas;

Mathematical expression for the building and manufacturing process system, thermal energy flow paths.

Exploration and identification of the different energy flow paths that occur in manufacturing process systems, through a graphical representational format.

Modelling of building and manufacturing process system thermal energy flow paths, through an integrated simulation tool.

METHODOLOGY

Building physics simulation tools exist in academia and commercially (ESP-r 2011, IES 2011a). However, they do not account for heat emissions into the built environment, from industrial equipment and flowing materials. Complex manufacturing systems are sometimes analysed using 'discrete event simulation' (DES) software, which can model stochastic behaviour such as deliveries, new orders arriving or a machine or process failing, in order to minimise queuing, bottlenecks etc (Schriber and Brunner, 2007), (Michaloski1 et al., 2011). DES tools do not model energy use in manufacturing processes or thermal effects upon the surrounding environment. Nor would it be straightforward to do so, since such effects are continuous phenomena that are not suited to the DES concept. The building physics simulation within this paper is an extension of the International Building Physics Toolbox (IBPT) (Kalagasidis, 2002) developed in the Matlab/ Simulink software environment (Matlab, 2011). The framework of the simulation model uses the IBPT H-Tool, H referring to heat transfer only. The toolbox is capable of modelling one thermal zone. The mathematical expressions behind the toolbox are covered in (Kalagasidis, 2002), and therefore are not repeated here. The Simulink toolbox has been modified by the work in this paper to include the simulation of internal thermal zones within a larger surrounding thermal zone - i.e. a drying tank, surrounded by a larger thermal zone (factory). Radiation and convection interactions between the internal surfaces of the surrounding thermal zone and the outer walls of the internal thermal processes have been retained, increasing the accuracy of the model. Material flow, from and to industrial processes are also included within the physics boundary of the model. Thermal heat fluxes from the material in the form of radiation and convection to the surrounding air node and surfaces of the thermal zone and industrial thermal processes are included within the model.

ENERGY FLOWS

Typical built environment

Through application of building physics, the energy flow paths in a building environment can be approximated by mathematical integration (Clarke, 2001). The energy flow paths in a typical built environment, such as office, residential etc are illustrated in Figure 1. Mathematical expression for building energy flows paths are shown below (Sakulpipatsin et al, 2010);

$$\frac{dQ_{air}}{dt} = Q_{heating} - Q_{cooling} + Q_{\inf} + Q_{vent} + Q_{tran} + Q_{gain} + Q_{sol} \qquad (1)$$

The nomenclature section at the end lists the symbols used in the above expression. For clarity, these symbols represent the thermal energies from different sources that make-up the overall energy balance of a thermal zone. Q_{air} is the change in thermal energy of the air zone over time d_t. $Q_{\text{heating and cooling}}$, are heating and cooling thermal energies to the zone. Q_{inf} and Q_{vent} are infiltration and ventilation thermal energy gains. Q_{tran} is the thermal energy transmitted from the building surfaces. Q_{gain} and Q_{sol} are the thermal energies from occupants, internal gains and from diffused and direct solar gains absorbed and re-transmitted by the fabric construction of the building. The above expression does not discuss in detail the surface balance of the fabric constructions of the building. Conduction, convection and radiation occur at the construction level of a building fabric. The rate of conduction through a fabric is dependent on the number of structural layers and construction properties. Convection and radiation occur at the surface of a building construction i.e. walls, roof, glazing, floor etc. Radiation from occupant, internal gains and other sources such as solar are absorbed and re-transmitted from surfaces. Radiation does not have a direct effect on the internal air temperature of a zone. The change in air temperature of a 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), (Kalagasidis, 2002) and are not discussed further.

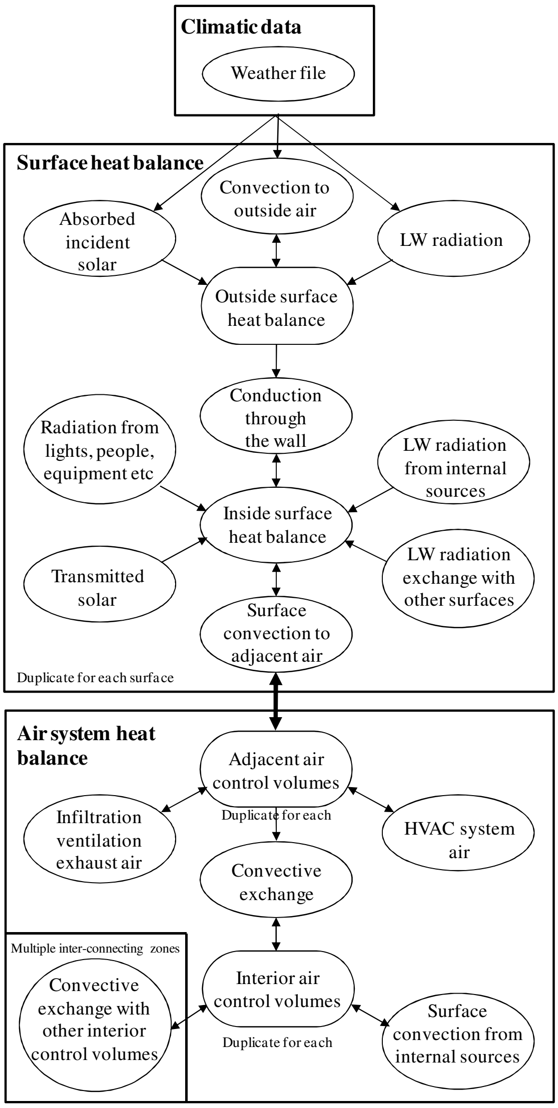

Figure 1 - Schematic of heat balance processes in a zone with air models, adapted (Griffith and Chen, 2004)

Factory environment

A factory building is a purpose built environment that houses large manufacturing processes and equipment, flows of material and occupants. Internal factory environmental conditions vary depending on the practice of the industry. The local weather is the driver for the flows of energy in a typical building. For the manufacturing industry, the external customer of the goods is the driver of the system, i.e. demand of the market. The manufacturing industries utilise manufacturing process machinery to change the shape, surface finish, appearance or physical properties of material in order to add value. The fundamental physical principles of many of today's manufacturing processes have not greatly changed, but the introduction of machinery and automated processes has led to an increase in productivity and quality (Degarmo et al., 2003). The process of mapping and understanding the workings of a manufacturing industrial environment can be complex i.e. numerous machinery and flows of products, time scales, quality etc. Large industrial processes and auxiliary equipment exchange large amounts of heat to the surrounding environment. The addition of moisture to the surrounding environment from processes (such as drying) is also common within manufacturing.

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 simulation modelling, Figure 1 (here, 'air control volumes' means air in thermal zones). The dynamics of the problem are similar for a container of liquid. An air thermal process is considered to resemble an oven, furnace etc. Whereas a liquid container may be a bath, tank, vat etc. Depending on the level of granularity of the model, the process may include all the energy flows illustrated in Figure 1 for a thermal zone i.e. conduction, convection and radiation. The main difference is that the external surfaces of the thermal process interact thermally with the surrounding thermal zone rather than the outside, or an adjacent zone, as would be the case with a room. The mathematical expressions for thermal 'air' or 'fluid' processes are similar to the thermal air zonal model.

Electrical manufacturing process

Energy flows from an electrical process are in the form of radiation and convection. For example, an electric motor will emit heat to its surroundings. This is mainly down to the inefficiencies of the motor, emitting radiation and convection energy flows from the outer surface of the casing of the motor. Conduction energy flows through the fabric and ground are to be ignored.

Material

Energy exchanges may also occur from the flows of materials. Materials that flow through process systems, but are not considered as energy carriers may still contain significant amounts of energy. The amount of energy absorbed or released is related to the temperature, geometry and material properties i.e. emissivity, absorption, specific heat capacity, thermal mass etc. Materials can be modelled in a similar way to a fabric element.

Overall factory energy flow paths

Figure 2 illustrates the overall energy flow paths in a factory environment. The figure couples traditional building energy flow paths with those generated in a factory environment, i.e. manufacturing process systems and material flow. Below is the mathematical expression for the rate of change of air temperature;

$$\frac{dQ_{air}}{dt} = [Q_{heating} - Q_{cooling}]_{system} + Q_{\inf} + Q_{vent} + Q_{tran} + Q_{gain} + Q_{sol} + \left[Q_{process} + Q_{material}\right] \quad (2)$$

The last two terms represent the addition of thermal energy from industrial components such as thermal and electrical processes as well as thermal energy from flowing materials.

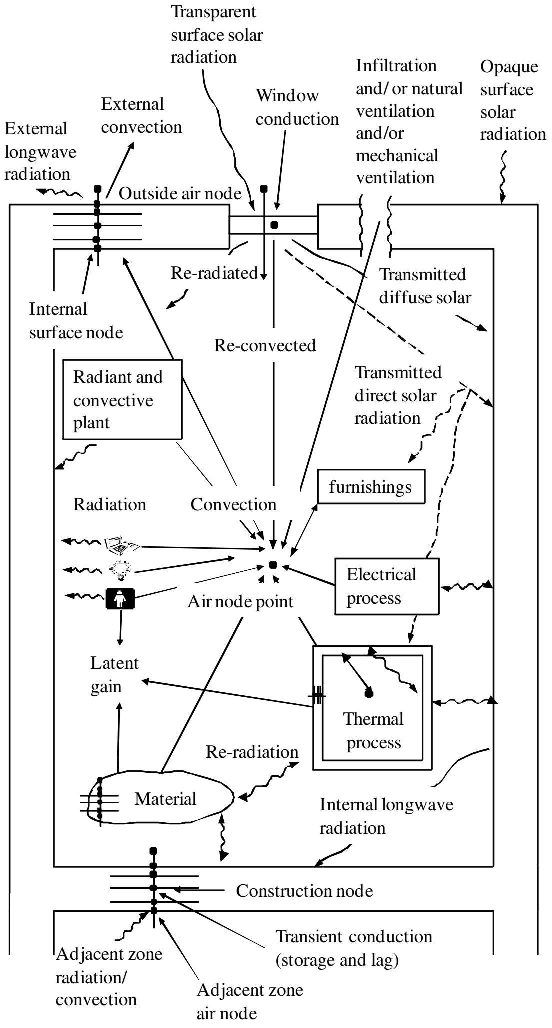

Figure 2 - Schematic of the overall energy flow paths of a factory environment, adapted from (Clarke, 2001)

GRAPHICAL REPRESENTATION

The coupling of thermal heat fluxes from industrial processes, equipment and materials with the energy flow paths of the built environment is complex. A generic graphical representation of the interactions of energy and material flows into and out of a manufacturing process and their equipment is proposed, Figure 3.

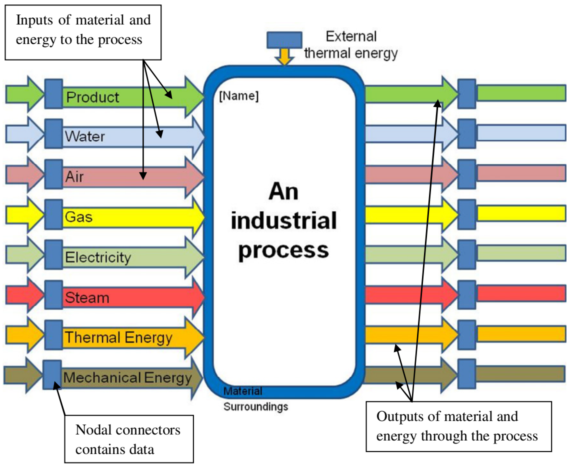

Figure 3 - Energy and material flows into and out of a process

These flows consist of product, and the main forms of energy used by the manufacturing industry. The list of energy sources and energy carriers is not exhaustive, but the most common are included. Further sources could be added. It is conceptually difficult to distinguish between a mass of substance and that of a mass carrying/containing energy. In thermodynamic terms, a mass leaving a control value carrying energy, is termed as, advection energy (Incropera, et al., 2007). This may be applicable to any form of mass that carries energy e.g. a piece of material that leaves a process hotter than when it first entered the process. For the purpose of this work, a product (material) that enters and leaves a process, whose sole purpose is not to transfer energy, is deemed a product. However, energy carriers such as water, steam and air, 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 another source, e.g. electricity. Thermal energy may be the result of a chemical reaction, transfer of heat flux energy from surfaces, etc. An example of the flow of material from one process to another, and on, is shown in Figure 4. Data referring to a product flow (material), is collated at nodal points before and after each process. The initial condition state defines the properties of the material i.e. mass, density, specific heat capacity etc. Data can be input as predefined set point values, or the material may inherit these values from another material source point within the model. The material flows through a process and its properties are recorded at the outputs, indentified as blue blocks in Figure 3 and Figure 4.

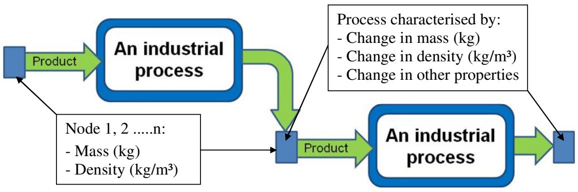

Figure 4 – Nodal network of energy and material flow through a system

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 model of a simple or complex system. Note; the thickness of the flow lines do not signify quantity (as they would in a Sankey diagram); they merely demonstrate flows of product and energy through the system. An interaction with the environment that surrounds the process, its equipment and material flow is another important feature of the model. By defining properties and locations, thermal interactions and effects on their surroundings are possible.

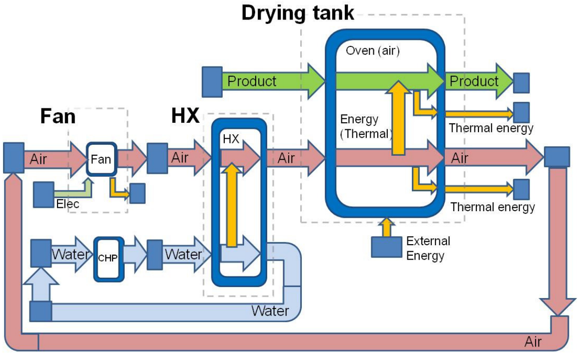

Figure 5 – Graphical representation of a drying tank and its subsequent equipment

Figure 5 is an example of an industrial process drying tank and its subsequent equipment. The block flow diagram connects graphical models of a drying tank, a fan and a heat exchanger (HX). Material (product) passes through the drying tank. Sourced air is drawn through the fan. The air picks up heat from the fan and the heat exchanger before entering the drying tank. The product is dried, and the process is repeated. A proportion of the air from the drying tank is recirculated back into the incoming air stream. For clarity reasons only, the properties of the materials and energy have not been included within the graphical representation. Energy carriers such as air and water in the figure, will be assigned properties e.g. temperature, volumetric flow rate, humidity ratio (air), enthalpy, mass etc. The same would apply for the product flowing through the drying tank.

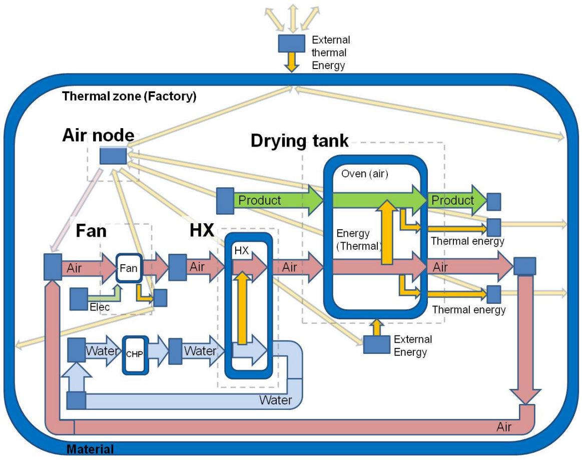

Figure 6 – Graphical representation of a drying tank and its subsequent equipment defined by its location (thermal zone)

Figure 6 expands the graphical representation by linking the drying tank model to its surroundings. From Figure 6, the interactions of energy flows from the building fabric (convection and radiation), inefficiencies of the fan and generated heat flux from the fabric construction of the wall of the drying tank are linked together.

SIMULATION MODEL OF A DRYING TANK

The Simulink simulation model (Figure 8) follows on from the manufacturing process system graphically represented in Figure 6, a drying tank. The model includes the following features:

- A large enclosure (i.e. the factory room)
- A thermal "air" drying tank (internal thermal process zone)
- Auxiliary equipment i.e. a fan, heat exchanger coil.

Model description

The drying tank is represented within the simulation model as a 3m x 3m x 3m box, 0.01m thick steel construction. The steel material properties are; density 7800kg/m^3, thermal conductivity 50W/m.K, heat capacity 480J/kg.K, absorptivity 0.7 and emissivity 0.9. The surrounding thermal zone i.e. factory room, is three times larger than the drying tank. The construction of the external walls are concrete, 0.2m thick. The concrete properties are; density 2400kg/m^3, thermal conductivity 1.5W/m.K, heat capacity 800J/kg.K, absorptivity 0.65 and emissivity 0.9. The roof is 0.01m thick steel, same properties used for the drying tank. Block flow models have been created for a fan, HX, mixing box and air splitter within the Simulink software. Air at a volumetric flow rate of 6.3m^3/s from the surrounding thermal zone 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, 0.7 effective, which increases the temperature of the air to the design temperature of the drying tank, 40°C. Air from the drying tank is recirculated at a rate of 5.3m^3/s into the incoming air stream of the fan. Ductwork losses have not been included. Material flowing from the surrounding thermal zone, into the process and back out into the surrounding zone is also included within the model. The material is a sheet of steel, 2.5m^2. Profiles within the Simulink tool 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. Weekly profiles are described in the validation and results section. The Simulink model uses the London Heathrow weather file 96-97 extracted from the IES software.

Validation

Future models are planned to be based on real life data obtained from the industrial partners of the THERM project. Prior to this, initial simulation results have been validated against the commercial building physics software IES v6.3.0.1. A model has been created within IES based on similar data input into the Simulink simulation model. The difference between the models is in the implementation of the drying tank components, i.e. fan, HX, mixing box and air splitter. The thermal efficiency losses 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 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 additional alterations to the fan and temperature profiles. It is possible to represent a simple model of the drying tank within the IES software 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 into the surrounding environment have been input independently from the operational profile of the drying tank. In the event of future models including an extensive network of varying processes, this could lead to increase risk of errors within the model. The flow of material within the IES software is not included, as IES is not capable of modelling decaying heat fluxes from flowing material in and out of processes. Therefore, results in Table 1 do not include thermal energy interactions from material flow. Table 1 compares results taken from IES and the adapted IBPT Simulink model, based on the energy required to heat the surrounding thermal zone to a temperature profile i.e. facility energy. For scenarios 1 to 3, the drying tank process is maintained at a constant 40°C, all year round. Scenario 1, the surrounding thermal zone (i.e. factory) is heated to a minimum of 19°C at all times. Scenario 2, the surrounding thermal zone is heated from 9am till 5pm, to a minimum of 19°C, Sunday to Sunday and at all other times heated to a minimum of 12°C. Scenario 3, the surrounding thermal zone is heated from 9am till 5pm, to a minimum of 19°C, Monday to Friday and at all other times heated to a minimum of 12°C. Scenario 4, is the same as scenario 3 except the drying tank is heated to 40°C, from 9am till 5pm, Monday to Friday only. All models use an annual simulation. Table 1 indicates that the results from the Simulink model are within 15% of the results obtained from the IES software, facility energy consumption only. The root mean square error (RMSE) has also been performed on the internal air temperature of the factory. The results in Table 1 further establish that the two models are in good correlation which each other.

Table 1 – Facility heating energy consumption results for scenarios 1 to 4 (IES and Simulink)

- Thermal zone - Drying tank	IES (MWh/yr)	Simulink (MWh/yr)	diff (%)	RMSE (%)
Scenario 1 (constant 19) (constant 40)	49.38	44.50	-9.88	0.39
Scenario 2 (Sun-Sun, 9-5) (constant 40)	24.11	22.85	-5.23	1.10
Scenario 3 (Mon-Fri, 9-5) (constant 40)	20.17	19.12	-5.21	0.96
Scenario 4 (Mon-Fri, 9-5) (Mon-Fri, 9-5)	32.19	27.52	-14.51	1.16

As discussed, the results in Table 1 do not include heat fluxes to its surroundings from material flowing in and out of the drying tank. Table 2 results are based on simulation model outcomes from the adapted IBPT Simulink model, including material flow.

Table 2 – Process/Facility energy consumption results for scenarios 5 to 6 (adapted IBPT Simulink)

- Thermal zone - Drying tank	Process energy (MWh/yr)	Facility energy (MWh/yr)	Total (MWh/yr)
Scenario 5 (Mon – Fri, 9-5) (constant 40)	298.37	18.4	316.77
Scenario 6 (Mon – Fri, 9-5) (Mon – Fri, 9-5)	78.46	26.62	105.08
diff (MWh/yr)	+219.91	-8.22	+211.69
		diff (%)	66.83%

Table 2 also includes the energy required to treat the air flowing into the drying tank i.e. fan and HX process energy consumption. For scenarios 5 and 6, the flow of material is considered to be located in the drying tank during the hours 10am till 2pm, and at all other times located in the surrounding room. Scenario 5, is the same as Scenario 3 except for the inclusion of material flow. Scenario 6 is the same as scenario 5 except that the drying tank is only operated during the hours 9am till 5pm, Monday to Friday, and is off at all other times.

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 decrease the energy usage of the drying tank by one hour before and after the material is schedule to enter and leave the drying tank, Table 3.

Table 3 – Process/Facility energy consumption results for scenarios 6 to 7 (adapted IBPT Simulink)

- Thermal zone - Drying tank	Process energy (MWh/yr)	Facility energy (MWh/yr)	Total (MWh/yr)
Scenario 6 (Mon – Fri, 9-5) (Mon – Fri, 9-5)	78.46	26.62	105.08
Scenario 7 (Mon – Fri, 9-5) (Mon – Fri, 9-3)	62.92	27.38	90.3
diff (MWh/yr)	+15.54	-0.76	+14.78
		diff (%)	13.59%

Results summary

The initial validation results in Table 1 use the commercially available IES software as a benchmark to test the accuracy of Simulink model. The adapted IBPT Simulink model is within an accuracy of 15%, of the IES simulation results. The discrepancy is subject to the variations in the mathematical modelling of the building physics tools. The IES software uses a combination of the finite difference explicit and implicit time-stepping method (i.e. hopscotch method) (IES, 2011b). The Simulink model uses the explicit finite difference method only.

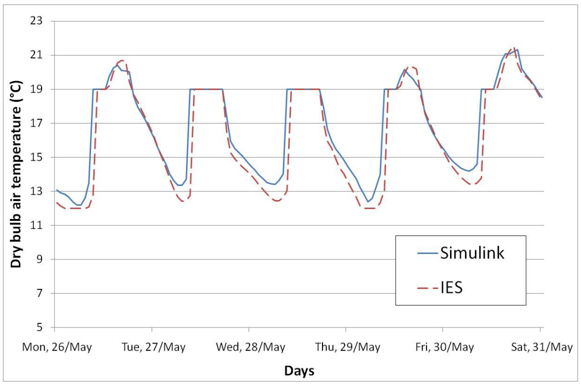

Figure 7 – An example, comparing the internal air temperature of the factory, IES and Simulink models

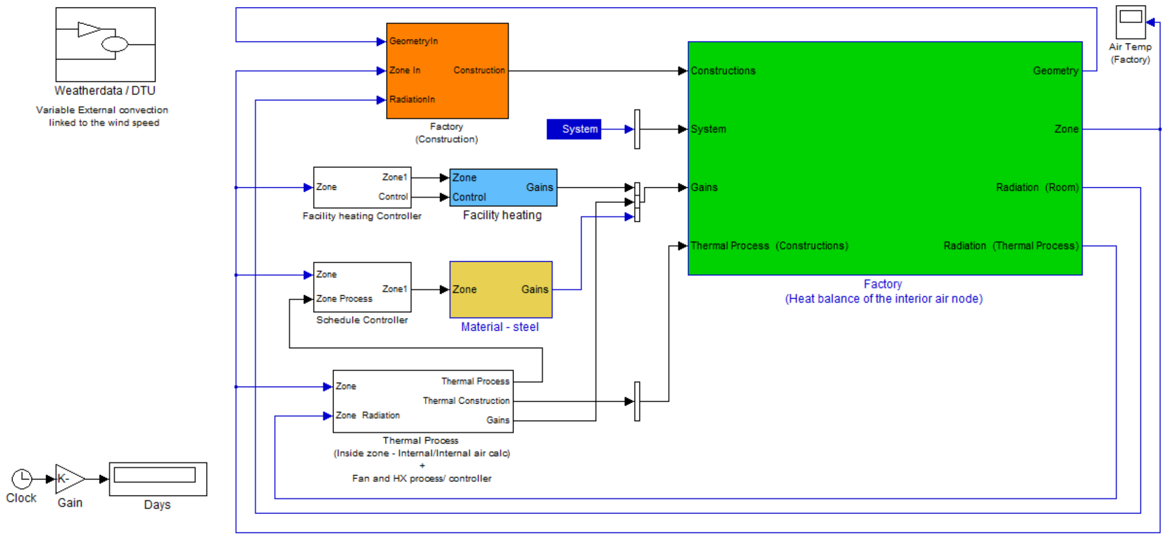

Figure 8 – Extract taken from the adapted IBPT Simulink simulation model

Figure 7 shows a typical graph comparing the internal air temperature of the factory during a weekly cycle, for periods of heating and none, for both simulation methods. There is a strong correlation between the graphical shapes of the results, providing additional confidence that the Simulink model is modelling the physics of the building in a similar manner to the IES software. In general, the air temperature results for the factory zone show that the Simulink results are slightly higher than the IES results. This explains why the energy consumed to heat the factory building (facility energy) using the adapted IBPT Simulink model is lower than the results obtained from the IES simulation.

The simulated results in Table 1, show how changes to the heating profile of the factory environment and changes to the operational usage of the drying tank begin to effect the energy consumption of the facility heating system. From Table 1, Scenario's 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. The results indicate that the energy required to heat the factory facility has risen from 19.12MWh/yr to 27.52MWh/yr, respectively. This is a 30.52% annual increase in the energy consumed by the heating system. These results are unsurprising, as a loss of heat from the drying tank would require an input of energy from elsewhere, in circumstance when tight temperature controls are implemented. The addition of heat flux from material flowing into and out of the drying tank, also makes a difference to the facility energy consumption. These differences can be seen when comparing results from Table 1 with Table 2; scenario's 3 and 5 (0.72MWh/yr) and scenario's 4 and 6 (0.90MWh/yr). High-energy savings of 219.91MWh/yr are shown in Table 2, when comparing an inefficiently constantly ran process to one that is operated between normal shift hours. Table 3 also indicates further process energy savings through further reduction of the operational hours of the drying tank. These energy savings are at a manufacturing process systems level, and do not reflect the overall energy balance of the system. Results from Table 2 and Table 3 demonstrate that there is an increase in facility energy, for each conservation improvement made to the drying tank process. It is therefore important to understand the overall energy balance between facility and process systems when reporting energy savings in a manufacturing production environment.

CONCLUSION

Most current building simulation models are inadequate for simulating the energy flows within manufacturing, particularly where product flows and processes are important. This paper presents a methodology for modelling both building physics and manufacturing process systems in one integrated tool. Energy flow paths in a factory environment through both mathematical expressions and use of a graphical representation have been explored. The graphical representations begin to form a structure for the detailing of industrial processes and their equipment in simulation form. The validation of the thermal simulation model gives excellent agreement. 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 analysed. The simulated results shown in Tables 1-3, 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 system, and not just at systems level. Through use of an integrated simulation tool, energy managers can assess energy used at both facility and system level with a view to using energy in a more sustainable manner.

Future work

Future works are intended to include validation of the simulation work against real life factory processes using monitored data from the industrial collaborators of the THERM project, and to extend the model further to include latent heat effects.

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NOMENLCATURE

$\frac{dQ_{air}}{dt}$ = thermal energy of the zonal air (W)

$Q_{heating}; Q_{cooling}$ = thermal energy supplied by heating and cooling equipment (W)

$Q_{\inf}; Q_{vent}$ = infiltration and ventilation thermal energy gains (W)

Q_{tran} = radiation exchange between inner surfaces (W)

Q_{gain} = internal thermal energy gains (radiation and convection) (W)

Q_{sol} = solar thermal energy (short and longwave radiation) (W)

$Q_{process}$ = thermal energy from thermal and electrical processes (radiation and convection) (W)

$Q_{material}$ = thermal energy from processed material (radiation and convection) (W)

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