Evaluation of the Thermal Environment in Large Manufacturing Plants

By

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Dedicated to my family

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Abstract

Old “mega-factories” use significant amounts of energy to maintain an optimal production and working environment despite the mild climate of the United Kingdom. The increasing cost of energy and environmental problems put industries under pressure to reduce their energy consumption and hence the carbon footprint.

A case study was carried out at an existing large manufacturing plant, to develop a method to study thermal performance of large industrial buildings through physical measurements and numerical simulations, to profile the thermal characteristics of such a factory. Plant environment data was logged and analysed, by various systems and different techniques, to understand thermal environment that also influenced the energy usage. In addition to experimental measurements, the building including all internal components was modelled using computational fluid dynamics (CFD) to observe temperature distribution and air circulation. A validation process against collected data from multifarious sources proved the model reliability within a desired accuracy. All applied techniques of evaluating the thermal environment within the factory, experimental and simulated, were compared and outcomes suggest high potential of all utilised systems. Especially a fixed sensor system showed the advantage of continuous live sampled data that could be of instant use for temperature and humidity monitoring when required. Low priced systems such as mobile data collection systems had the advantage of detailed data acquisition at specific locations. In addition to other data presentation innovative tools such as indoor temperature distribution maps helped to evaluate the thermal environment and allowed the quantitative validation of a simulation model. A CFD model of the observed manufacturing plant showed great potential within momentary computational limitations, but even greater potential for future applications.

All these methods were engineered and tested to work towards the ultimate project aim of creating a methodology to evaluate the thermal characteristics of an industrial live environment within a large scale manufacturing plant. However, a scientific study within such a large, obsolete and complex live environment showed significant difficulties which set this project apart from investigations within smaller facilities. All applied methodologies were discussed to build new knowledge about such a task and its advantages for researchers, engineers and future projects.

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Abbreviations

$A =$ Cross section (m^{2})

$c =$ Specific heat constant (Jkg^{-1}K^{-1})

$F_j =$ Body force vector

$g_j =$ Gravitational force vector

$h =$ Heat transfer coefficient (Wm^{-2}K or Wm^{-2}C°); Enthalpy (Jkg^{-1})

$k; \lambda =$ Thermal conductivity (Wm^{-1}K^{-1} or Wm$^{-1\mathrm{o}}$C^{-1})

$l =$ Length (m)

$m =$ Mass (kg)

$n =$ Number of samples

$P =$ Static pressure (Pa)

$Q =$ Heat (J)

$s =$ Average temperature

$S_E =$ Energy source term (Wm^{-3})

$S_M =$ Mass source term (kgm^{-3})

$t =$ Time (s)

$T =$ Temperature (K or $^{\mathrm{o}}$C)

$T_a =$ Surrounding surface of emitting object (K or °C)

$T_w =$ Surface temperature (K or °C)

$u =$ Velocity (ms^{-1})

$u_{i,j} =$ Velocity vectors

$x_j =$ Direction vector

$Nu =$ Nusselt number

$\Pr =$ Prandtl number

$\mathrm{Re} =$ Reynolds number

$\varepsilon =$ Emissivity (K)

$\mu =$ Viscosity (kgm^{-1}s^{-1})

$\rho =$ Density (kgm^{-3})

$\sigma =$ Stefan-Boltzmann constant (5.67×10^{-8}Wm^{-2}K^{-4})

Chapter 1

1 Introduction

1.1 Overview

Continuously rising greenhouse gas emissions are having a detrimental effect on the climate. As a result, institutions such as the “United Nations” have committed countries around the world to lower their carbon footprint by set targets. The European Union for example obligated its member states to reduce their carbon emissions by 20% in the year 2020 compared to the 1990s levels of 3.33 billion tonnes of CO_2 emitted. Further regulations to reduce emissions by 80-95% will come into force in 2050, which will force all countries within the EU to review their energy policies, with industrial facilities the main targets. Factories emit 33% of the greenhouse gasses in the sector of non-domestic premises, with plant heating contributing up to 26% of the total energy cost in the case of the observed manufacturing plant. Intelligent cost reduction solutions can significantly reduce this energy consumption without incorporating the latest and expensive technical solutions.

1.2 Aims and Objectives

Aim: Develop a method to study thermal performance of large industrial buildings through physical measurements and numerical simulations.

Objectives:

1. Develop an effective data capture system and a standardised procedure in order to collect thermal performance data of large industrial buildings for use in developing validated simulation models
2. To build a simulation model of the plant and using a proven existing simulation tool and validate against the collected data
3. Recommendation of a standard procedure for the operational improvement of the thermal performance of similar industrial spaces based on the analysis of, both, measured and simulated data

1.3 Layout of the Thesis

This thesis is written in five main chapters which guides the reader through this study. In the second chapter the literature relevant to this research was reviewed to give background information on the latest knowledge and technologies. Third chapter shows the overall methodology of the project. The fourth chapter is a brief case study on the Dagenham Engine Plant and its thermal environment. The fifth chapter reports on the experimental techniques used, data collection, storage and treatment, presentation and analysis of measured data. Chapter six describes the simulation model and its methodology. The seventh chapter critically discusses the project its techniques and methodologies. The eighth chapter concludes this study and proposes potential future work.

Due to the size and complexity of this work; parts of the project were accomplished by a team, which was set up and managed by the Candidate. The main tasks in this work are presented by Figure 1. Ford allowed and supported the data collection within their manufacturing plant. The construction of the CAD model and the CFD simulation was made in a team with was led by the candidate. The IT department of the University of Greenwich supported the candidate with tools, which were utilised within this project.

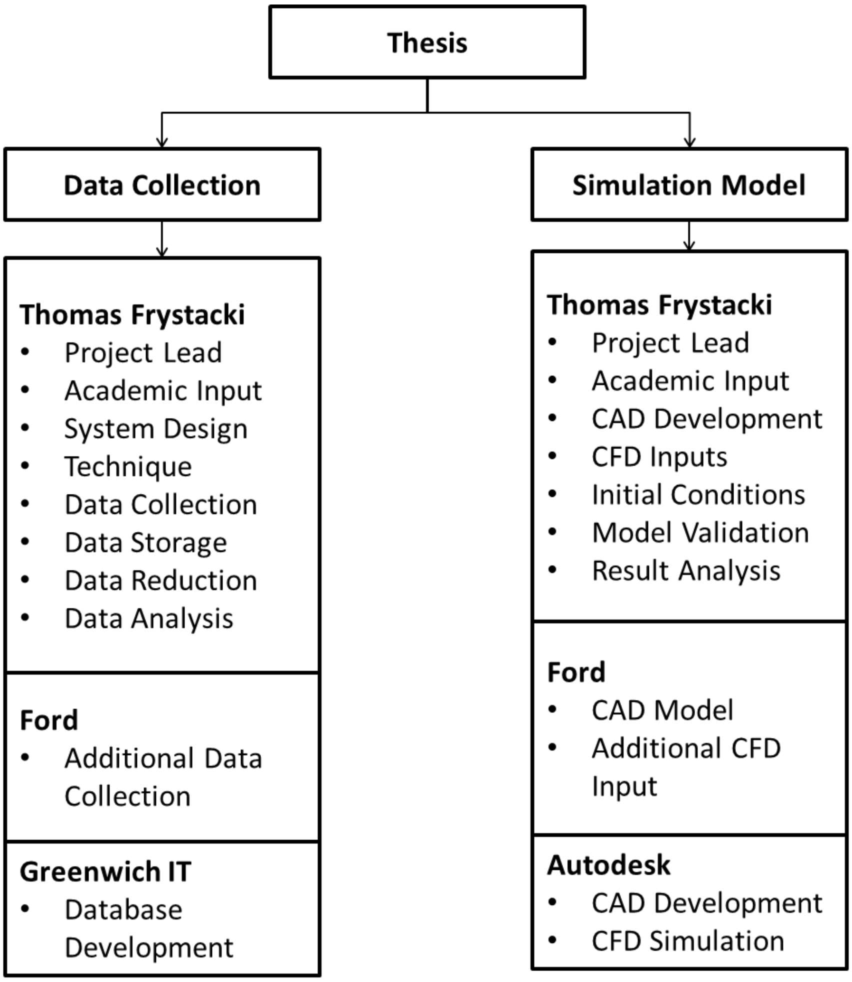


Figure 1: The project was split into three main parts data collection and simulation model. Due to the size of the project parts of the data collection and the simulation model accomplished in a team around the PhD student.

Chapter 2

2 Literature Review

2.1 Introduction

Due to government policy the value of energy saving projects have become more and more significant in recent years. This study researches and evaluates the thermal performance of large industrial buildings. In every part of this research work literature supports the understanding of existing technologies and provides the necessary background information for the development of innovative original contribution to knowledge.

2.2 Carbon Issues in the UK

2.2.1 Introduction

Industries have heavily polluted the global environment for the last 150 years which has had an undeniable impact on the climate (United Nations 2013). Continuously rising energy consumption affects the global environment in terms of climate change, global warming, ozone layer depletion (Pérez-Lombard et al. 2008) and exploitation of natural resources (Park 2010). Governments are put under pressure by members, political parties and institutions, such as the United Nations to reduce their carbon footprint. The Kyoto Protocol was enacted and signed by many countries around the world. It specifies targets for each of its member country to reduce their carbon footprint in order to improve environmental issues (United Nations 2013). Due to these inter-governmental constraints many countries around the world are under mounting pressure to explore innovative technologies to improve energy efficiencies of buildings to reduce their overall carbon dioxide (CO_2) emissions (Hamilton 2010).

2.2.2 Carbon Dioxide, Carbon Footprint and Greenhouse Emissions

Carbon dioxide (CO_2) is a chemical bond between carbon and oxygen (Stoker 2011). It has been a natural component of the atmosphere for billions of years (Ehleringer 2006). There is a natural balance between the atmospheric CO_2 and the climate, which is decisive for all life on earth (National Academy of Sciences (US) 1983). The atmospheric CO_2 is a factor for temperatures and even the ice ages were connected to this balance (Sundquist 1985). However, due to the industrialisation in recent decades the amount of CO_2 emissions increased drastically (National Research Council 2003). Any “usage” or conversion of energy obtained by fossil fuels emits CO_2 as a waste product (Aresta 2003). It is scientifically proven that this increase in carbon dioxide has a direct effect on the natural climate (National Research Council (US) 1979).

While the term “carbon footprint” is commonly used, it is a relatively new. Initially the term “Ecological Footprint” was used by William Rees in 1992 for the first time (Rees 1992). It was introduced as a measure of the total environmental impact of a product or any industrial application. After that, the ecological footprint was further developed by his student Mathis Wackernagel. However, although the term “Carbon Footprint” and its meaning were developed over time, there was not a widely accepted definition of this term. In 2007 a proposal of a definition was made by Thomas Wiedmann. "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product" (Wiedmann 2007).

Another often mentioned term is "Greenhouse Emissions". The main greenhouse gasses are CO_2, NH_4, N_2O and fluorinated gasses (Solli 2010) (Environmental Protection Agency 2013). The general composition of these gases in the United Kingdom is shown in Figure 2. The main target of the Kyoto Protocol is to globally reduce these greenhouse gasses to insure a cleaner environment.

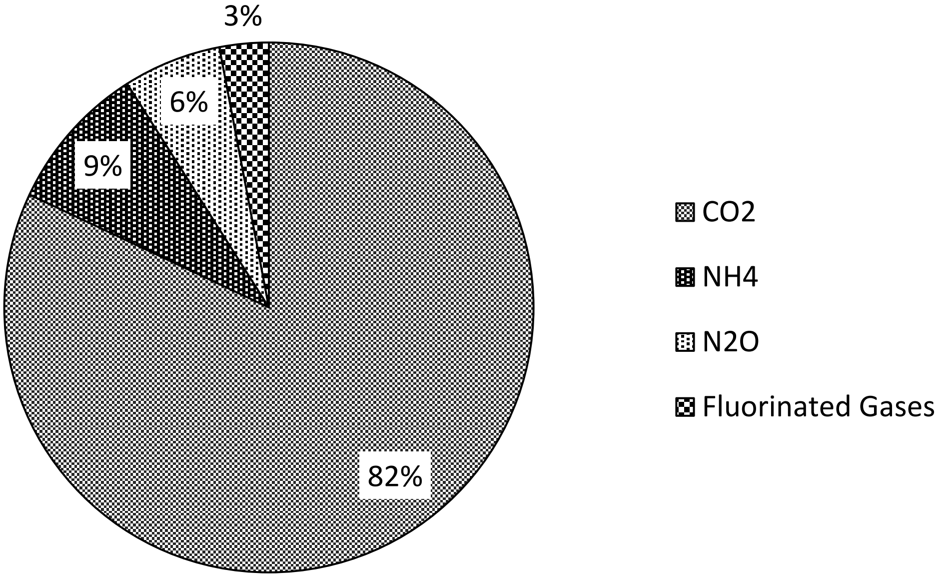


Figure 2: Greenhouse gas emissions of the UK in 2012 (%) (adapted from** Department of Energy & Climate Change 2014)**. Note most of the Greenhouse gasses are emitted in the form of CO_2.

2.2.3 Carbon Regulation and Guidelines in the UK

The Kyoto protocol is an international agreement between members of the United Nations and was set up on the 11th of December 1997. It commits nations around the world to reduce their emissions by set targets (United Nations 2013). The European Union for example, obligated its member states to reduce their carbon emissions by 20% in the year 2020 compared to the 1990s levels (European Commission 2013) of 3.33 billion tonnes of

CO_2 emitted (Olivier et al. 2013). Further targets to reduce emissions by 80-95% will come in to force in 2050 (European Commission 2013).

The United Kingdom aims to reduce its greenhouse gasses by 80% by 2050. Great Britain is the first country which set binding “carbon budgets” to be able to hit its ambitious target (Government Digital Service 2013). To be able to keep track of this target there is a planned “interim target” enforcing compliance of carbon reduction of 34% by 2020 (Beales 2011). This “interim target” was made legally binding by UK law in 2009. This target puts every sector, which emits greenhouse gases, shown by Figure 3, under pressure to reduce its energy consumption. The sectors within this diagram were subdivided by the governmental department of energy and climate change. It shows all of the sectors within the United Kingdom emitting greenhouse gasses, excluding LULUCF (land use, land-use change and forestry) (emissions from forestland, grassland, cropland, settlements and harvested wood products) because in 2012, when the statistic was made, it was observed that is electively is a net sink and its emissions were therefore negative. In this figure the sectors are subdivided into the following divisions (Department of Energy & Climate Change 2014):

- Energy supply (fuel combustion emissions for electricity or other energy production sources)
- Transport (emissions from railways, aviation, road transport, shipping, fishing and aircraft support vehicles)
- Business (combustion emissions in industrial and commercial sectors, industrial off-road machinery, refrigeration and air condition systems)
- Residential (emissions from combustion for heating, cooking, garden machinery and fluorinated gases released from aerosols and metered dose inhalers)
- Agriculture (emissions from agricultural soils, livestock, stationary combustion sources and off road machinery)
- Waste management (emissions from waste disposed of to landfill sites, waste water treatment and waste incineration)
- Industrial processes (emissions from industry, except for those associated with fuel combustion)
- Public (fuel combustion emissions in public sector buildings)

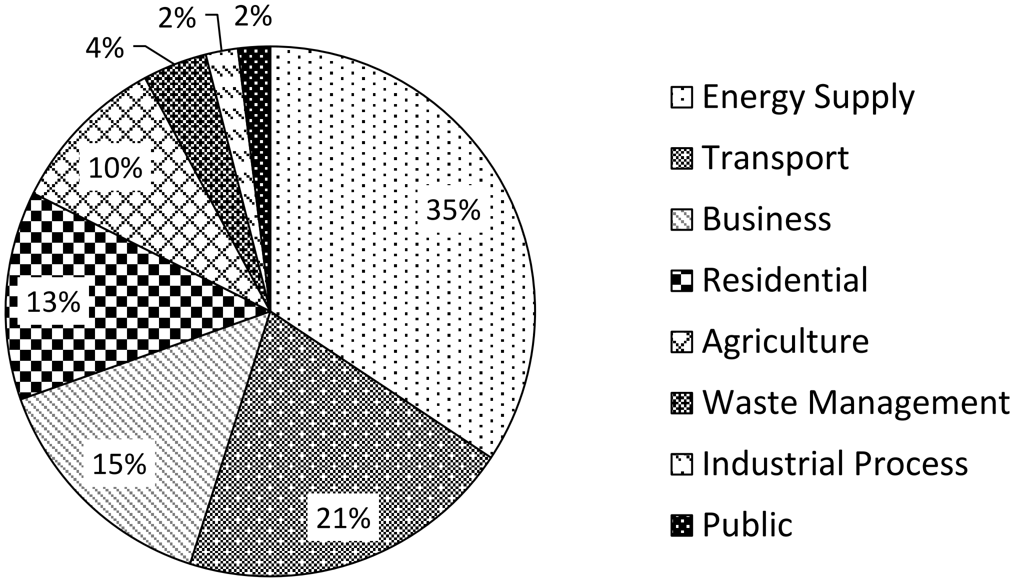


Figure 3: Greenhouse Gas Emissions by Source Sector (%) in 2012 in the UK (***adapted from*** Department of Energy & Climate Change 2014)**.**

2.2.4 Industrial Energy Consumption

Every industrial process or action of any kind “uses” energy (Office of Technology Assessment 1983). From a physics point of view energy cannot be created or destroyed, only converted (Quaschning 2010). Industrial energy usage is described as the amount of energy, which has to be converted to perform industrial processes. Such energy is commonly supplied to factories in form of electric power or fossil fuels (Office of Technology Assessment 1983). Energy converted in industrial processes enables mechanical or electrical equipment to carry out work. Once this conversion is performed, the energy is in many cases no longer available for further processing. Therefore, it is referred to as “energy usage” (Ford 2013b). In addition, such energy conversions have losses, which are set free to the environment in terms of heat (Ioinovici 2013).

Figure 4 shows the energy consumption of all the sectors in industry in the United Kingdom. Low temperature processes (processes in the chemicals sector such as distillation or heating; pressing and drying procedures in paper manufacture; washing, baking and separation processes in the food industry; or the textiles industry with scouring, dyeing and drying were included) amounted up to 32% of total energy consumption. High temperature processes (including coke ovens, blast furnaces or other furnaces, glass tanks and kilns) accounted for a further 16%. However, this project is concerned with the thermal energy consumption in industrial processes. The statistic shows 11% of the total amount of energy consumption is used for heating purposes, despite the fact that this statistic is made for all industrial processes in the UK, independent of building size and age of factory (Department of Energy & Climate Change 2013). Industrial machines are powered by electricity. Managers in the manufacturing industry are interested in statistics showing costs per component produced to be able to calculate their production figures (Ford 2013b). In addition to electricity, space heating systems consume significant amounts of energy which has to be included into this calculation.

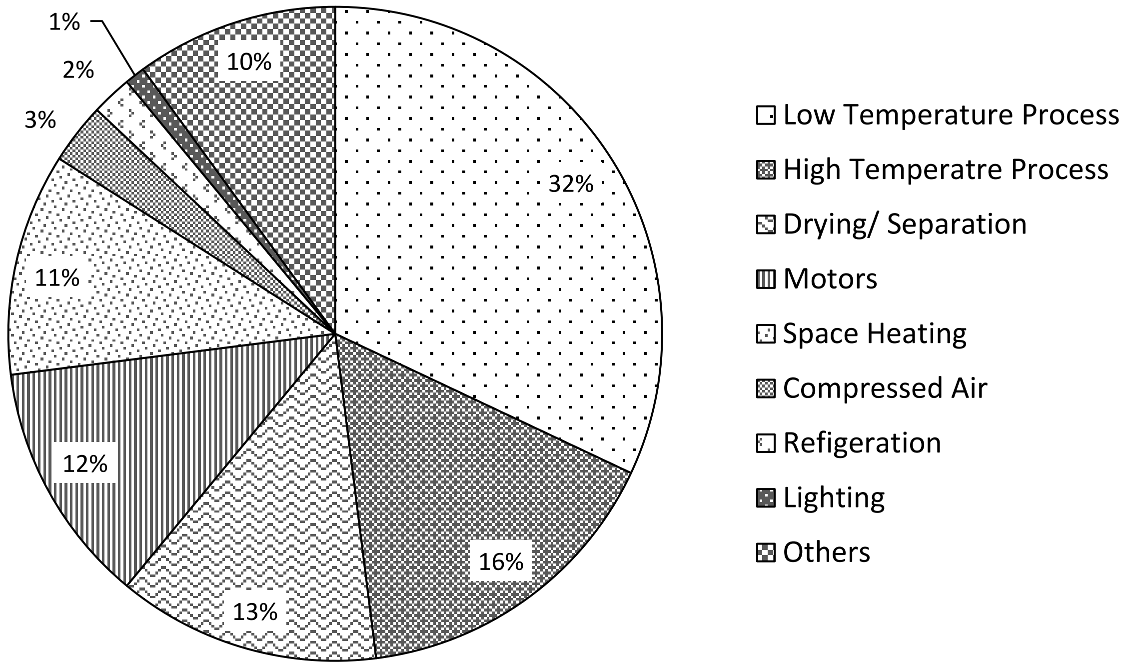


Figure 4: Energy consumption of all industrial sectors in the UK in 2011 (%) (***adapted from*** Department of Energy & Climate Change 2013)***.***

Space heating accounts for 11% of the overall industrial energy consumption in Great Britain. However, this statistic was developed by accounting for all industrial processes and areas. In old, large open plan factories the amount of heating cost can considerably higher.

Space heating alone can amount to more than 26% of the annual utility cost, see results in section 5.4. This is a significant amount of energy consumption in spite of the mild climate in the United Kingdom, see in section 2.3.5 (Weather & Climate 2013). Space heating efficiencies can be improved by new innovative but expensive technologies with government funds available to support modernisation (Hamilton 2010). However, the desire of companies to sell their new technologies and innovative products can lead to a mentality of investment without exploiting the full potential of existing technologies. In addition to expensive investment options, intelligent energy management strategies and better use of existing technologies can also support the effective reduction of carbon footprint of large sized non-domestic buildings. For example the reduction of leakages, optimisation of technology utilisation and streamlined heating strategies would have the potential to significantly reduce energy consumption.

2.2.5 Energy Consumption in Commercial Buildings

Previous statistics within this report were concerned with the total amount of emissions in the United Kingdom or referred to the total energy consumption in Great Britain in industrial processes. The energy consumption in buildings amounted to 39% of the total energy consumption of the United Kingdom in 2004 (Pérez-Lombard et al. 2008). Figure 5 shows the total energy consumption of Great Britain divided into sectors with respect to buildings, which was developed by a study of the IPF (Investment Property Forum) research programme, which is concerned with the energy consumption of commercial buildings. Such commercial buildings caused approximately 14% of total CO_2 emissions in the UK in 2003. Further emissions were caused by the transport with 33% (airports, train-stations, etc.), domestic buildings with 26%, industrial processes 22% and public or other buildings with 5% (Investment Property Forum 2012). These values convinced researchers and engineers to work out feasible solutions and energy reduction strategies in the sector of domestic and non-domestic buildings.

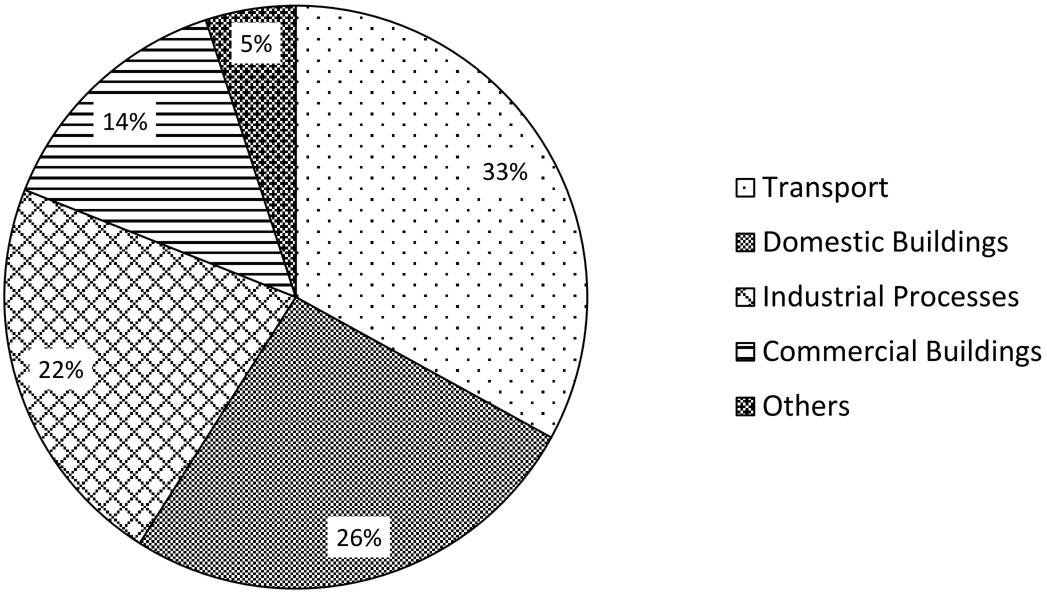


Figure 5: Total Energy Consumption of the United Kingdom in 2003 (%) divided into sectors with the respect to buildings (***adapted from*** Investment Property Forum 2012)***.***

The sector of commercial buildings can further be subdivided in specified areas of industry as shown by Figure 6. Within this subdivision factories are the largest energy consumer with 33% of the total energy consumption. All of these previous figures show reasons for the significant amount of research projects which started to investigate energy consumption in buildings, but Figure 6 points towards scientific energy studies in factories. The issue of research strategies within large complex live environments such as factories will be explained within the following chapters.

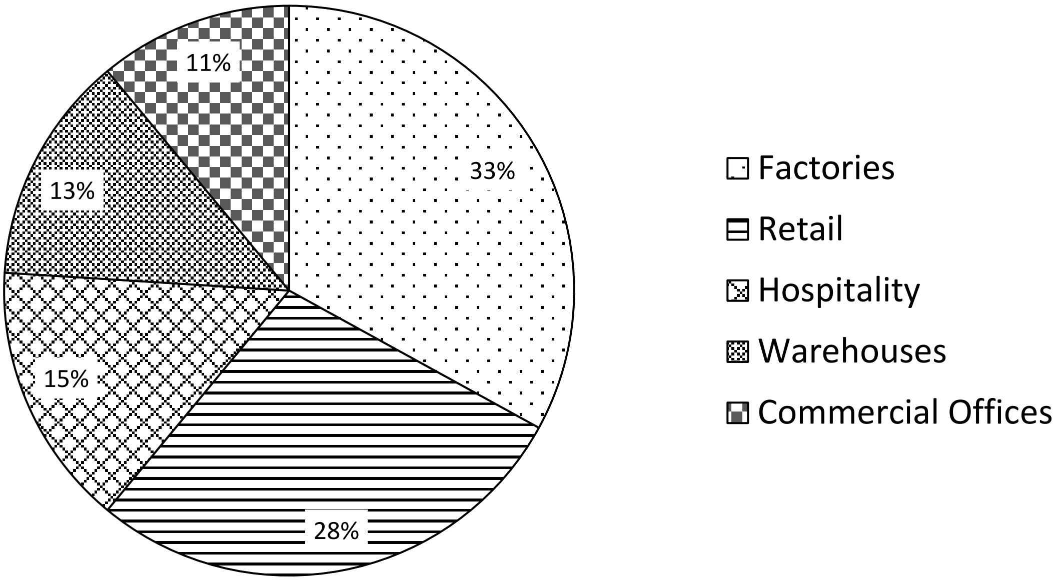


Figure 6: CO_2 emissions of commercial buildings in the UK in 2003 (%). Factories are the biggest CO_2 emitters with an amount of 33% of the total in the commercial sector (***adapted from*** Investment Property Forum 2012)**.**

2.2.6 Conclusion

Industries around the world have been heavily polluting the environment in recent decades. Due to studies, which proved a connection between greenhouse gasses and the climate, the Kyoto protocol was set up to enforce environmental awareness but also action plans. The Kyoto protocol is legally binding and commits its members to reduce greenhouse gas emissions by set targets. Due to such inter-governmental constraints member countries are under mounting pressure to explore innovative technologies to improve energy efficiencies to reduce their overall CO_2 emissions. In addition to other sectors of energy consumption governments focused on the sector of buildings as one of the key areas for energy improvements. In the subsector of commercial buildings, factories are with 33% one of the largest energy consumers within the UK, which is shown in Figure 6. In addition to electrical power consumption, energy wastage from weak HVAC system performances and insulation issues lower the energy performance of existing buildings. Figure 4 shows that space heating accounts for 11% of the overall industrial energy consumption in Great Britain. In recent times more and more energy projects in existing buildings are created to improve performances. This study is, therefore, concerned with the thermal performance of large existing factories and the research within complex live environments. There is great potential for improvement and a lack of scientific evidence in this area, which guided the project into the task of engineering research methodologies for the evaluation of the thermal performances of large and complex industrial live environments within existing buildings. The following questions arose from the research within this chapter of literature.

- What are the key issues of thermal energy consumption in factory environments?
- How can thermal energy research be implemented in complex live environments?

2.3 Factory Environment

2.3.1 Introduction

In addition to political constraints, continuously increasing energy prices are forcing industries to reduce their energy consumption to remain competitive (Kneifel 2010). For these reasons industries became more aware of thermal energy wastage within existing buildings. The thermal building environment is created by a serious of complex interactions between weather, production and control influences. The comfort of employees, but also the machinery environment must be within stable temperature limits to ensure efficient production (Ford 2013b). This section shows direct influences on the thermal environment of large manufacturing plants, but also describes optimal manufacturing conditions.

2.3.2 Manufacturing Plants and Thermal Environment

There are several factors directly influencing the thermal environment within a manufacturing plant, see Figure 7. All external influences caused by local weather conditions (external air temperatures, thermal radiation, wind, rain, snow, hail and humidity) have to be combined with energy features of the building construction, manufacturing equipment and control facilities to determine internal climate conditions. Some of these effects, such as weather conditions, are uncontrollable whereas others, for example the HV system, are controlled and are used to stabilise the temperature within the factory. This improves human comfort and generates a continuous stable machine environment, which is necessary to guarantee smooth and cost effective operation. On the other hand, factors such as insulation issues or leakages lower the effectiveness of HVAC systems. If such properties are weak the external environment has more significant influences on the internal environment and is also more difficult to control. Leakages not only exist from weak insulation, but also from transport issues within a complex manufacturing environment. Components have to be transported in and out of a manufacturing plant which is always increasing leakages by door opening. Such issues could also have a significant effect on thermal environment within a factory (Neville 2011). The thermodynamic process within and around buildings can be described using heat transfer equations which are summarised in the next chapter.

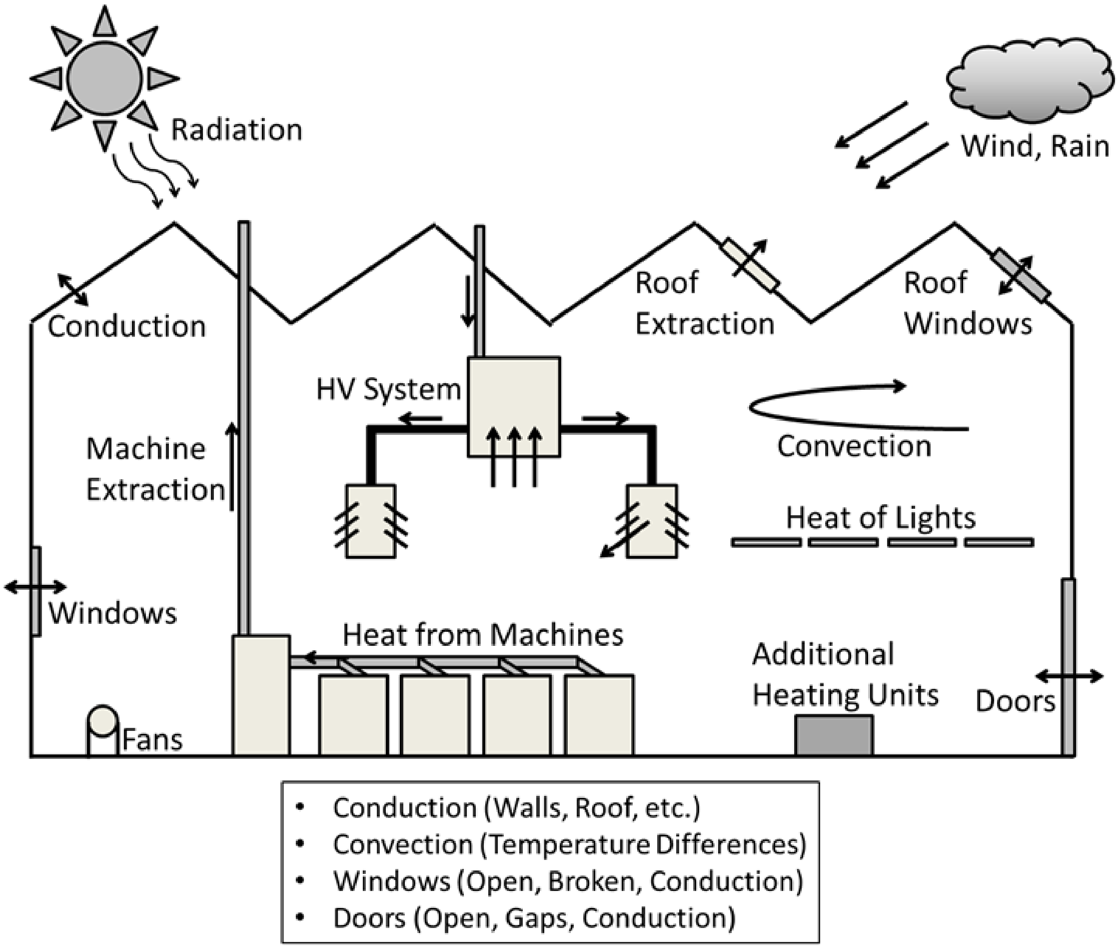


Figure 7: Environmental conditions and influences, which affect the internal thermal environment of the DEP.

2.3.3 Heat Transfer equations to calculate performances of buildings

Temperature is the measure of the internal energy of materials. Heat transfer occurs due to temperature differences between varying materials and fluids. There are two main differences, radiation transports heat by waves and diffusion through a medium to transfer heat. The two ways of diffusion are called conduction and convection. Figure 8 shows a block diagram highlighting these three forms of heat transfer.

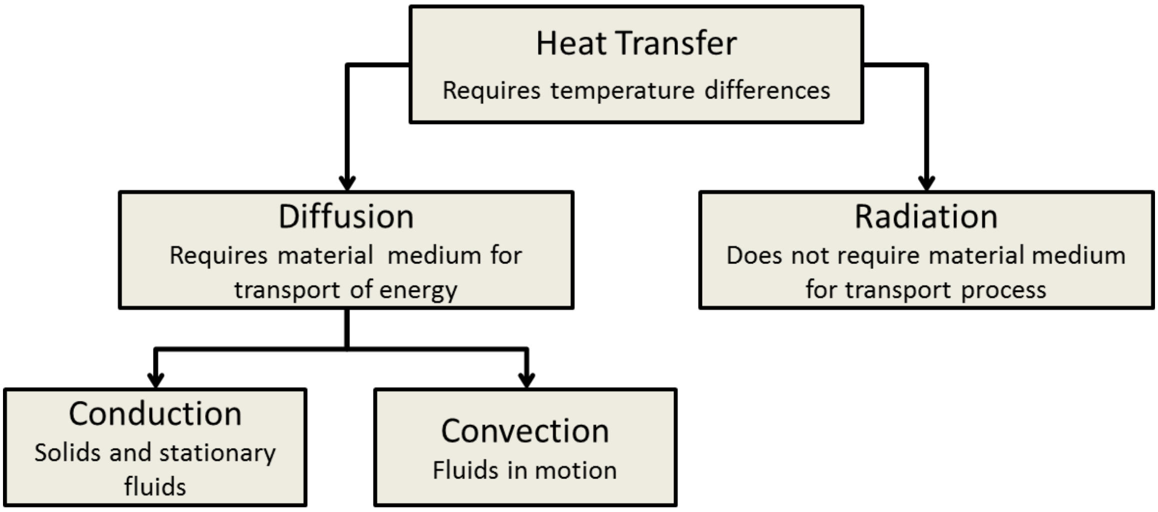


Figure 8: Block diagram defining heat transfer and its different occurrences such as conduction, convection and radiation (***adapted from*** N.V.Suryanarayana 1995)***.***

Conduction is heat transfer within solid materials and fluids without bulk motions. The motion of atoms transfers heat. To calculate conductive properties the thermal conductivity (k) of a material, its surface area (A) and thickness (L) have to be considered. Once the temperature gradient between internal and external temperature (wall surface temperatures) is known heat transfer can be expressed by the following formula (N.V.Suryanarayana 1995) (Winterton 1997):

$$Q = kA\frac{T_{in} - T_{out}}{L} \tag{1}$$

Particle movement within fluids on the other hand creates convection. Temperature gradients change the density of fluids and force molecules to move in convection currents. Considerations involve the heat transfer coefficient (h) of a gas and its surface area as well as the actual temperature gradient. In combination with the conductive heat transfer the thermal performance of buildings insulation can be calculated. However, mathematically convection can be expressed by the following formula (N.V.Suryanarayana 1995) (Winterton 1997):

$$Q = hA(T_{in} - T_1) \tag{2}$$

$$Q = hA(T_2 - T_{out}) \tag{3}$$

In this formula T_1 and T_2 (K or °C) are the respective internal and external temperatures at the boundary of the wall surface. T_{in} (K or °C) is the temperature within the building (average in the middle of the building room) and T_{out} (K or °C) is the external temperature.

Both conduction and convection need a medium to transfer energy, which is the reason for its definition as diffusion. Radiation, on the other hand, does not use a medium to transfer energy. Radiation is heat transfer in the form of waves, which emits heat even if there are no particles. The Stefan-Boltzmann constant (σ) (5,67x10^{-8}W$m^{-2}$$K^{-4}$) and the surface area of an object emitting heat waves, but also the emissivity (ε) of its material have to be taken into account. This form of heat transfer is expressed by the following formula (N.V.Suryanarayana 1995) (Winterton 1997):

$$Q = \sigma A \varepsilon \left(T_w^4 - T_a^4 \right) \tag{4}$$

In this formula T_a (K or °C) is the temperature of the surrounding surface of emitting object, whereas T_w (K or °C) is the Surface temperature of the object T_a is compared to. σ is the Stefan-Boltzmann constant (5.67×10^{-8}W$m^{-2}$$K^{-4}$), A is the area and ε is the emissivity in (k).

The next equations do not directly inform about heat transfer, but are often used to calculate thermal performances within buildings such as in table 6 in chapter 5.4. In this Table a simplified thermal building performance calculation is undertaken.

In addition to the basic principles of heat transfer, there are three parameters, which can be used to calculate heat transfer performances of buildings, the Prandtl number, the Reynolds number and the Nusselt number.

The Prandtl number couples viscosity (μ) with the specific heat constant of a material and its thermal conductivity (c) (N.V.Suryanarayana 1995) (Winterton 1997).

$$\Pr = \mu c k^{-1} \tag{5}$$

The Reynolds number characterises a flow under forced convection. The density (ρ) is related to the thickness, the velocity (u) and viscosity of the material. Its value shows whether a fluid flow is laminar or turbulent. For laminar boundary layer $Re<Re_{critical}$ ($Re_{critical}$ = ±2000), otherwise a flow is turbulent (N.V.Suryanarayana 1995).

$$\mathrm{Re} = pLu\mu^{-1} \tag{6}$$

The Nusselt number depends on the Prandtl number and also the boundary layer. It describes the ratio of conductive and convective heat transfer in the boundary layer. The Nusselt number changes depending on the condition of the boundary layer (N.V.Suryanarayana 1995).

For laminar boundary layer:

$$Nu = 0.664\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}} \tag{7}$$

For the turbulent boundary layer the relationship between Reynolds number and Prandtl number has to be adjusted, and therefore:

$$Nu = 0.03\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.6} \tag{8}$$

The heat transfer coefficient describes the intensity of heat transfer at the boundary layer. It includes the Nusselt number and therefore, all kinds of information of the earlier mentioned parameters (N.V.Suryanarayana 1995) (Winterton 1997).

$$h = NukL^{-1} \tag{9}$$

The total heat transfer coefficient can be calculated using formula (10) below. It contains the inside forced convection, insulation parameters and outside forced convection. This formula is particular helpful if the thermal performance of a building is calculated.

$$h_{total} = \frac{1}{\frac{1}{h_{inside}} + \frac{\Delta x}{k} + \frac{1}{h_{outside}}} \tag{10}$$

Heat or the total heat loss can be described with the formula below. It quantifies the heat loss considering the surface area, the temperature difference and also the heat transfer coefficient (N.V.Suryanarayana 1995) (Winterton 1997).

$$Q = -h_{total}A\Delta T \tag{11}$$

A similar formula can be applied if the energy change of a fluid is calculated if the temperature change is known (N.V.Suryanarayana 1995) (Winterton 1997). The heat energy is compared to the specific heat constant and the mass.

$$Q = cm\Delta T \tag{12}$$

All of the calculations within this report concentrate on air as a fluid, but do not necessarily relate to other gasses. In case of calculations within the building environment the air will have approximately 20°C.

The following table describes the thermal properties of air at 0°C and 20°C.

Temperature (°C)	**Viscosity ($kgm^{-1}s^{-1}$)**	**Thermal Conductivity ($Wm^{-1}K^{-1}$)**	**Specific Heat ($Jkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**
0	1.724×10^{-5}	0.02411	1002	1.292
20	1.822×10^{-5}	0.02560	1003	1.205

Table 1: Properties of air for 0°C (273K) and 20°C (293K) (***adapted from*** Winterton 1997)**.**

2.3.4 Comfort and Optimal Production Environment

Working temperatures between 18°C and 23°C are widely accepted as “comfortable” if the type of work does not involve any “physical effort” (Workplace Health Commitee 1998). In a manufacturing plant many employees work involves “physical effort”. In this case, the ideal temperature will be close to the lower value, typically set at approximately 19°C (Ford 2012). The airflow within such a factory is described as comfortable in the range of $0.1ms^{-1}$ and $0.25ms^{-1}$ (Health and Safety Executive 2000). Airflow magnitudes below $0.1ms^{-1}$ are defined as stagnant, whereas air speeds above $0.25ms^{-1}$ result in a “draught perception” (European Agency for Safety and Health at Work 2005).

On the other hand, one of the most important factors for the optimisation of machine performances is a stable environmental condition. In general, such a condition can be engineered with different temperatures. However, many manufacturing industries use accurate computer numerical control machines (CNC machines) to produce low tolerance products, such as automotive components. These types of machines are mostly constructed from metals, which expand with an increase in temperature. Even small temperature changes of less than 1°C could lead to a machine internal adjustment process to maintain low tolerances. This process costs time and money by interrupting production runs but can be improved by maintaining a stable thermal environment. Such CNC machines cannot simply be segregated from each other to reduce the environmental issues because of the interconnection between them. Each machine is part of a production line and has to be open to instant access for possible faults and maintenance work. Furthermore, heavy parts and components are constantly transferred from CNC machine to CNC machine along the machining line. Each machine processes the components further before they are transferred to the next machine. A simple segregation of machines could also cause overheating issues which again would cost time and energy for potential machine internal cooling cycles. Therefore, machine segregation would not be economically or technically feasible; hence energy issues within the machinery environment have to be treated for entire production lines or even production areas in case of older factories (Ford Dagenham Layout Team 2014).

2.3.5 Climate and Weather Conditions of the United Kingdom

There are only few studies about the immediate effects of weather on buildings. The main research was conducted into the long-term effects like the wear of buildings over time. This study was less concerned about the wear than the immediate effects of weather. External temperatures and wind, affect the thermal environment within a building and therefore, its HVAC system is designed to compensate such weather influences (Faye C. McQuiston, Jerald D. Paker 2005).

The climate in the United Kingdom is considered as “mild”. Great Britain is an island and its climate is stabilised by the Gulf Stream (Weather & Climate 2013). Table 2 shows the average temperatures in the UK over a period of 30 years. The lowest average minimum temperature in winter is marked red and has a value of 0.7°C. On the other hand, the highest maximum value in average which is also marked red can be seen in July and has a magnitude of 19.4°C. It can be observed that the difference between these temperatures, minimum and maximum, is lower than 20 degrees; hence the external temperature effects on buildings are lower in the United Kingdom than in other countries, which have a larger temperature variation. However, these are the conditions for the entire United Kingdom. Conditions often change around big cities such as London (Met Office 2010). Table 3 shows average temperatures at Greenwich Park in London close to the Dagenham Engine Plant. The distance between Greenwich Park and the DEP are approximately 11 km (Google 2013). The difference of the lowest minimal temperature in February and the highest maximal temperature in July is again approximately 20°C. Both of these temperatures, minimal and maximal, are marked in bold in Table 2 and Table 3. The climate in London seems to be two to three degrees warmer than the average of the UK.

	Max Temp	Min Temp	Days of Air Frost	Sunshine	Rainfall	Days of Rainfall ≥ 1mm
Month	**[°C]**	**[°C]**	**[days]**	**[hours]**	**[mm]**	**[days]**
Jan	6.4	0.9	11.3	47.2	121.7	15.5
Feb	6.6	**0.7**	11.3	69.8	88.6	12.3
Mar	8.9	2.1	7.6	101.8	95.1	13.9
Apr	11.4	3.4	4.5	148.1	72.7	11.7
May	14.7	6.0	1.2	185.9	70.0	11.2
Jun	17.3	8.8	0.1	169.5	73.4	11.0
Jul	**19.4**	10.9	0.0	172.4	78.1	11.4
Aug	19.1	10.8	0.0	163.0	89.5	12.0
Sep	16.5	8.8	0.2	124.7	96.4	12.1
Oct	12.8	6.2	1.8	92.5	127.1	15.0
Nov	9.1	3.3	5.6	57.2	121.2	15.2
Dec	6.7	1.1	11.0	40.8	120.2	14.7
Year	12.4	5.3	54.6	1372.8	1154.0	156.2

Table 2: Average Weather Conditions between 1981-2010 in the UK (***adapted from*** Met Office 2010)***. Minimal and maximal temperature values are marked bold.***

	Max Temp	Min Temp	Days of Air Frost	Sunshine	Rainfall	Days of Rainfall ≥ 1mm	Wind at 10 m
Month	**[°C]**	**[°C]**	**[days]**	**[hours]**	**[mm]**	**[days]**	**[knots]**
Jan	8.3	2.6	6.6	49.9	51.6	10.8	N/A
Feb	8.5	**2.4**	7.6	71.4	38.2	8.5	N/A
Mar	11.4	4.1	2.8	107.1	40.5	9.6	N/A
Apr	14.2	5.4	0.8	159.8	45	9.4	N/A
May	17.7	8.4	0.1	181.2	46.5	9	N/A
Jun	20.7	11.5	0	181	47.3	8.3	N/A
Jul	**23.2**	13.9	0	192.1	41.1	8	N/A
Aug	22.9	13.7	0	195.1	51.6	7.6	N/A
Sep	19.7	11.2	0	138.9	50.4	8.5	N/A
Oct	15.6	8.3	0.4	108.1	68.8	10.7	N/A
Nov	11.4	5.1	2.7	58.5	58	10.1	N/A
Dec	8.6	2.8	7.6	37.4	53	9.9	N/A
Year	15.2	7.5	28.6	1480.5	591.8	110.1	N/A

Table 3: Average Weather conditions between 1981-2010 at Greenwich Park (***adapted from*** Met Office 2010)***. This is the closeted weather data logging location to the Dagenham Engine Plant examined by the Met Office. Minimal and maximal temperature values are marked bold.***

2.3.6 Conclusion

The thermal environment within a manufacturing plant is influenced by various internal and external factors. The effects of uncontrollable influences such as the climate around a factory, heat of production and lighting during production are balanced by HVAC systems. Thermodynamic weaknesses such as insulation issues or leakages could lower the effectiveness of HVAC units by a significant amount. All thermodynamic processes, such as physical temperature changes and natural airflow currents, occur due to heat transfer. Temperatures of approximately 19°C as well as airflow between $0.1ms^{-1}$ and $0.25ms^{-1}$ are optimal for employees but also for the machinery environment and production. The climate in the United Kingdom is considered as mild, compared to most other countries around the world. Considering all these facts the following questions were asked:

- What is the most effective method of obtaining temperatures in large and complex industrial live environments?
- What scientific techniques can be applied to manufacturing plants to understand their thermal environments?

2.4 Modelling of Thermal FD Behaviour of Industrial Estate

2.4.1 Introduction

Data collection was carried out to determine thermal properties of a large existing manufacturing plant. For this purpose, existing studies relating to building observations concerning temperature measurements, airflow measurements, humidity measurements, measurement errors, data logging, data storage and weather conditions were reviewed. For the understanding of such an environment collected data is used to specify quantities of all observed physical properties (B.S.Massey 1989) and enables the creation of numerical mathematical models (Patankar 1980). Different aspects of measurement equipment and properties of the environment are decisive to obtain the most suited instrumentation. Apart from accuracies and measuring ranges (B.S.Massey 1989) also project budgets and model validation methods were considered for choosing instrumentation.

2.4.2 Temperature

In this study temperatures within and around a building were measured. The expected temperature range for such measurements is between 35°C and -5°C in the UK see weather conditions in section 2.3.5. There are mainly three kinds of temperature measurement instruments, which are considered to obtain data within such a temperature range, thermocouples, resistance thermometers and thermal cameras. The advantages of thermocouples are the low cost, quick response times, availability, ease of use, accuracy and a wide temperature range. The disadvantage of a thermocouple is that it is not as accurate as a resistance thermometer (TC Ltd 2001) (Farnell 2013) (RS Components 2013). On the other hand, advantages of resistive thermometers are high accuracy, ease of use and response time (Michalski et al. 2001) (Morris & Langari 2012). However, compared to thermocouples resistance thermometers are expensive (Farnell 2013) (RS Components 2013). Thermocouples and resistance thermometers both can be connected to data loggers. These data loggers log temperatures and connect to a storage medium, as explained in section 2.4.7.

Another instrument, which is used to obtain temperature data in buildings, is the thermal camera. Whereas thermocouples and resistive thermometers are known for their ease of use, thermography has to be understood and carefully applied. Thermal cameras capture emitted radiation to visualise temperatures of objects or other types of heat transfer such as conduction and convection. However, heat is reflected differently on surfaces and causes inaccuracies. When thermography is applied, correct adjustments are necessary for correct temperature capture.

First "T-reflect", which is an error adjustment related to the reflected temperature of the surrounding of the thermal camera, is entered in such devices. Usually a piece of crumpled and reflective aluminium foil is used as a reflector to measure T-reflect. In addition to that the emissivity of the measured material has to be known in order to measure correct temperatures (TCL 2014). Emissivity is a physical property that specifies the amount of radiation any measurement object emits. A mirror would have a very low emissivity factor close to 0, whereas black tar for example would have an emissivity factor close to 1. An emissivity factor of 96% would be considered as reasonable and accurate for most kinds of materials except shiny metals (FLIR 2009). Table 4 shows typical materials and their emissivity, however, a surface thermometer can be utilised to compare thermo-graphical images with measured values to gain confidence in thermal measurements.

Material	Emissivity (%)
Asphalt	0.96
Brick	0.75
Concrete	0.97
Leather	0.98
Water	0.96
Wood	0.85
Rubber	0.95

Table 4: General emissivity values of different materials for the use of thermal imaging cameras (adapted from FLIR 2009).

2.4.3 Thermal Investigations in Buildings

Many studies are taking place to investigate techniques and materials for the construction of new modern energy efficient buildings such as "passive houses" (Badescu & Sicre 2003). A significant amount of research for domestic or smaller non-domestic premises was carried out (Bell & Lowe 2000) (Bell 2004) (D B Belzer 2009) (Department for Communities and Local Government 2006) (Pickles et al. 2011). There are well understood solutions for improving efficiencies of new and existing houses investigated by Malcom Bell (Bell 2004) in 2004. In his studies, more effective building energy regulations were reviewed. Malcom Bell (Bell & Lowe 2000) also led a case study in 2000, which reviewed the "York Energy

Demonstration Project". Infiltration at doors, windows, ceiling and walls were improved on some of the buildings and then compared to the still unmodified ones. Additional different heating systems were tested for comparison. Continuously logged internal temperatures were gathered to check for differences. In many cases small and cost effective adjustments of construction and modern heating strategies could increase efficiencies by more than 50%.

Hiroko Masuda (Masuda & Claridge 2014) used thermal energy data for the investigation of commercial buildings. He obtained thermal energy data to be able to statistically create mathematical models to optimise the energy balance load within such facilities. Such models can be useful but a large scale temperature map analysis to exactly prove building weaknesses was not made. On the other hand, Yen-Wei Chang (Jiang 2011) developed a wireless sensor network to monitor temperatures within a plant factory. His studies were successful and its technique could be applied to mega factories. However, his analysis was made to optimise the environment of plants and not to improve building performance.

David Pickles (Pickles et al. 2011) investigated energy efficiencies of historic buildings in 2011. In his report, government's guidelines for the modernisation of existing buildings were reviewed. The use of thermal cameras or surface temperature data loggers was recommended to obtain moisture and insulation efficiency issues within old buildings. Mainly heating strategies and insulation materials were improved in order to increase efficiencies. These methods are perfectly relevant in small or medium sized buildings. In large industrial open space buildings, on the other hand, insulation improvements are not necessarily feasible due to slow payback periods, which was investigated in a study by Nick Olson in 2012 (Olson 2012).

Many recent studies observed energy inefficiencies in new and existing, small and medium sized dwellings. Literature on the thermal energy reduction of old Mega-factories on the other hand is scarce. There is a lack of published scientific investigations on actual temperature distribution in large open space factories. There are many energy investigations within dwellings or smaller industrial buildings, but as far as the author is aware, structured scientific investigations of large and complex manufacturing plants to the scale investigated in this work are not in the public domain. Additionally temperature distribution maps are currently only used for monitoring simulated data such as for example weather or temperature distribution in buildings. Most industrial efforts on improvements are achieved by the use of HVAC system, BMS (Building Management System) and insulation upgrades with new expensive technologies to be able to reduce CO_2 emission and save energy. This study addresses a gap in the knowledge by showing how continuous monitoring of internal temperature maps can help in the adjustment of the plant's internal environment and therefore, adjust energy usage accordingly. It is also part of this investigation to understand large complex internal live environments and recommend techniques and methods of analysing thermodynamic properties to discover unknown issues within large scale manufacturing plants. In the following chapters' suitable instrumentation, error consideration and appropriate data storage methodologies are explained.

2.4.4 Airflow Measurement

Rotating anemometers, hot-wire anemometers and ultrasonic anemometers measure airflow in a variety of environments. The advantages of rotating anemometers are low cost, robustness, ease of use and accuracy in stable environments. Disadvantages are the inertia of the rotor, which is unable to inert in quick changing environments, and relatively high lower ranges (Environmental Protection Agency 2000). Rotating anemometers may meter airflow as low as $0.25 ms^{-1}$, but these devices are relatively inaccurate for the utilisation of low fluid flow (Kimo Instruments 2012). Such instruments are often used to measure wind speeds at weather stations. However, in an internal environment air speeds are generally too low for those instruments.

On the other hand, hot-wire anemometers, are designed to measure airflows as low as $0.1 ms^{-1}$ accurately (Dantec Dynamics 2012). Further advantages of such systems are the large range and high accuracies. Disadvantages are high cost systems, especially for scientific use, and the sensor fragility. However, there are a variety of different anemometers such as hand-held hot-wire anemometers especially designed for the utilisation in a factory environment. Dirt, oil and dust particles in the air would affect most other fragile hot-wire sensors. More robust sensors and lower cost making such industrial hot-wire anemometers an ideal tool for internal airflow measurements (CFM 2012).

Other devices such as ultrasonic systems are highly accurate, but too expensive for the short-term use in industrial applications.

2.4.5 Humidity Measurement

As mentioned before the relative humidity is the amount of water vapour in the air. There are two main instruments which accurately measure the relative humidity, hair hygrometer and humistor hygrometer (Nakra & Chaudhry 2006).

A hair hygrometer uses certain materials such as human hair, animal membranes, wood or paper to indicate relative humidity. These materials absorb moisture from the atmosphere and expand with higher humidity levels or shorten with lower humidity levels in a linear manner (Nakra & Chaudhry 2006). Human hair hygrometer are especially accurate (±3% relative humidity) and easily calibrated (Fischer 2006).

A "humistor" hygrometer, on the other hand, changes its resistance with moisture to indicate the relative humidity. Humistors are made from humidity sensitive resistors. These resistors are only able to cover a small range (11% relative humidity), but if a device consists of many of these resistors, it would be able to cover the whole humidity range with a high accuracy (±1% relative humidity). The disadvantage of these instruments is the difficult calibration and high prices (Nakra & Chaudhry 2006).

2.4.6 Measurement Errors

All measurements have errors, which need consideration in any scientific data analysis. In general, bias and precision errors appear, but due to overlaps, a straight classification is not possible. However, measurement errors were classified as follows (Beckwith et al. 1993).

1. Bias or systematic errors
    a. Limitations of system resolution
    b. Calibration errors
    c. Consistent recurring human errors
    d. Errors caused by defective equipment
    e. Loading errors (caused by loading times of programmes)
2. Precision or random errors
    a. Human errors
    b. Disturbances caused by equipment
    c. Fluctuating experimental condition
    d. Insufficient sensitivity of measurement system
3. Illegitimate errors
    a. Mistakes during experimental data collection
    b. Computational errors after the experiment
    c. Variable procedures or definition in experimental studies

The standard statistical error (SE) is calculated by the following formula, where s = average value of measurement and n = number of measurements:

$$SE = \frac{s}{\sqrt{n}} \tag{13}$$

All these errors have to be considered before analysing collected data. All measurements within this study are mostly made to gain a general understanding of thermal building environments and do not necessarily require high accuracies, but the knowledge of potential errors has to be taken into account in any data collection. However, depending on the measurements, the required accuracies and the specific tasks of research some of these errors are more important than others; hence if the limit of permitted accuracy ranges allows, a lot of these errors can in fact be neglected, even though it is important to consider them before instrument choice and actual implementation. Therefore, it is not possible to generally define the overall uncertainty of measurement, since it varies depending on the design of the experiment.

2.4.7 Data Logging Systems and Storage Methodology

From the simplest process of data logging, pen and paper, to modern automatic data logging methods, which enable continuous logging over long time periods, lots of systems are available (Brower 2012). In recent times the quickest method of data logging are computers with pre-designed software. Many measurement systems directly connect to a computer or provide adaptors for such a connections (Tinytag 2012a). Computers are often relatively large and might not be the best solution for every data logging process. A lot of different smaller and embedded systems were developed. Most of these systems are designed for short-term storage and their information can then be transferred to PC's for long-term storage and analysis. Some systems are connected by cable whereas others have wireless connections (telemetric systems). However, all these systems enable continuous logging of large amounts of data, which makes them a useful tool for any kind of data collection.

Lots of programs, which allow any users to input data, are on the market. Data stored in certain formats enlighten accessibility for predefined users for further processing. In recent times most data collected by modern instrumentation is stored electronically, within database systems. A database has a variety of advantages over older methods of data storage. The ease of quick inputs of large sets of data is a definite advantage to older storage mediums such as books or even text files. Not only input advantages, but also systematic access of data sets within a large database is more manageable and can be automated. The access of data bits within a database is called "query" (Jennings 2011). This makes a database a useful tool for handling large amounts of data.

2.4.8 Conclusion

In this study the thermal background of a large existing manufacturing plant is researched. Past studies about internal temperature environments were investigated to understand existing methodologies used to obtain strategies of gathering thermal energy data within buildings. The research of past studies outlined a gap of knowledge within the momentary energy research within large factories. There is no existing data collection and presentation method suitable for computer simulation and validation of simulated results in large manufacturing spaces. Scientific methods of gathering and analysing data within such manufacturing buildings is not sufficiently enough discovered and innovative techniques such as internal temperature mapping could lead to a cost effective tool for the better understanding and analysis of such difficult environments. Instrumental data collection is undertaken to obtain quantities of physical properties to be able to perform analysis and support the understanding of potential findings and new correlations. However, instruments must carefully be chosen to measure the desired physical properties within required ranges and accuracies, but also within the limits of budgets. Such a procedure could be able to support mathematically described models. In this chapter the following questions emerged:

- What are the differences between data collection methodologies in small buildings compared to the research techniques of in large sized complex manufacturing plants?
- Can exiting data collection methods be improved and presented to suit mathematical / computer modelling?
- How can temperature distribution maps be useful in predicting internal environment in large open spaces?
- How could such temperature distribution maps be designed to become a suitable tool for energy reduction in buildings?

2.5 Simulation Model

2.5.1 Introduction

There are several methods to design a valuable simulation model predicting temperature distribution and airflows within indoor spaces. In 2009 Qingyan Chen reviewed different methods for the airflow and temperature prediction of indoor environments. Analytical and empirical models seem to rarely been used nowadays, because of their dependency on a particular case. The development of these systems does not seem as promising as other simulation techniques. Small and full scale experimental models are mainly used as a source of data for the validation of numerical results (Chen 2009). Especially in large scale buildings experimental models can be demanding and expensive (Patankar 1980). Zonal and multi-zonal models are improving and could be used for the prediction of large scale ventilation systems within entire buildings, but their graphical representation of results could be more attractive. In addition to that, such models still have long simulation times. Models of large scale manufacturing plants require effective simulation performances. For these reasons, the simulation method which is chosen most frequently is “Computational Fluid Dynamics” (CFD) (Chen 2009).

Due to the complexity of the plant any modelling approach is complex and tedious, especially analytical approaches. CFD offers the best simulation approach to be completed within the existing constraints. The modelling tools in modern pre-processors can model the very fine details of such a complex environment and the impressive post processing tools make it easier to handle, visualise and interpret data. Other modelling approaches were not considered because of the overall complexity of the model. CFD is not only able to simulate such buildings in detail, but it is also one of the best existing tools for the visualisation of a thermal environment.

Computational Fluid Dynamics (CFD) was developed to simulate and predict fluid flows and thermal properties of a model. The techniques provide innovative opportunities to comprehensively evaluate the thermal performances of a building (Zhai 2006). Due to a variety of consideration and boundary conditions the application of CFD in building is challenging, but its utilisation is an effective tool which can help to save energy and improve comfort of indoor spaces (Zhang & Chen 2000). This study presents a CFD simulation model of a large manufacturing plant to analyse its internal thermal environment and find unnecessary energy wastage. For this reason the building including all its internal components was modelled. This chapter presents literature, which concentrates on past studies, to provide guidance for the development of such a simulation model.

2.5.2 General Comparison between Experimental Research and CFD

Experimental investigation can capture thermodynamic processes as mentioned previously. Such investigations are mostly time consuming and expensive, but it is the only method of obtaining actual data of physical problems. Due to well established data collection techniques and procedures and the knowledge of their limitations, it is the most reliable form of information which can be obtained. The main issue comes with the limited ability of capturing a full scale environment (Patankar 1980). Usually experimental methods focus on the most important aspects of an internal environment, such as only internal temperatures (Bell 2004), but the grid coarseness of collected data points across the entire building do not allow to show all effects of thermal behaviour within a building. It is often difficult to collect data in inaccessible locations between machines and vehicle traffic, but it is also expensive to get enough data across the large scale of manufacturing plants. The other limitation with experimental studies comes with the issue of capturing environments in changing conditions. It is also not always possible to test buildings for every climate (maximal and minimal temperatures) because such conditions might only exist for a short period not long enough for the collection of a full set of data. Additionally, it is not possible to test potential environmental improvements in advance before implementation. These facts show the potential for simulation models, which are able to cover some of these issues (Patankar 1980).

Simulation models, on the other hand, process theoretical calculations to acquire consequences of mathematical influences. Within the limits of their complexity all simulation models try to predict physical processes as accurately as possible, but will never be as reliable as measured properties. Any simulation model is only as valuable as the combination of model design, construction, applied methodologies, validation and model analysis. Low cost and quick processing times are the main advantages of simulation models compared to experimental investigations. One of the biggest advantages comes with the mostly complete information with all required details (temperature, airflow, pressure) of every node within a CFD model. In a CFD model there are no issues with inaccessible locations; data can be acquired from all area without limitations. It is also possible to test potential improvements in advance which can reduces design cost significantly (Patankar 1980) (Chen 2009). Simulation can additionally be made for realistic and ideal condition, which can improve the analysis of such a model. Especially in building simulations it is possible to test the model for minimal and maximal external temperatures or other climate conditions such as wind factors for example (Patankar 1980). However, in simulations of large and complex manufacturing plants, model size, simulation features, simulation time and accuracy reach their restrictions because of current computational limits. Especially if the model involves a large number of components such as machines and HVAC units, the complexity of such a model increases significantly. With current computational limits simplifications are necessary to be able to simulate complex models (Neville 2011). Such simplification are restrictions of CFD which is another disadvantage compared to experimental methods. All in all both methods have their advantage and disadvantages, but a combination of both could be advantageous because a model could not only be validated, but results could directly be compared.

2.5.3 Computer-Aided Design Models

The CAD model (Computer-Aided Design Model), which is the physical model construction, can be built on existing templates, if such models were used in the past. In case of this study the entire Dagenham Engine Plant building including its contents are represented in 2D AutoCAD 2013 formatted layouts and schematics. Any additional facilities, new production lines or modifications to existing manufacturing processes are developed and engineered to an optimum level before installation. Numerous engineering principles are considered and included during this process to optimise resources, time, space and financial restrictions (Ford Dagenham Layout Team 2014).

The plant layout team used various measuring equipment such as plumb lines, tape measures and a laser measurement instrument. The majority of initial information is obtained from supplier CAD information and drawings, which contain the technical details the layout team utilise as the base outline of a program or modification. Historical data can also be used in the form of original hand-drawn acetate drawings or layouts when required. Modern measurement techniques using instruments such as scanning robots and measuring cameras are being considered, but this is expensive and complex. These techniques create a large amount of data, which the layout team has to manipulate in a timely manner on a daily basis on a continuously changing environment (Ford Dagenham Layout Team 2014).

There are different types of three-dimensional drawing techniques within CAD programs, namely; wireframe, surface and solid models. To be able to perform a CFD simulation its CAD model only includes surfaces and solid blocks. At every surface, boundary conditions are defined which is not possible in a wireframe model. Due to time advantages, most companies use two-dimensional CAD drawings to layout their offices or manufacturing plants. However, two-dimensional layouts support the production of three-dimensional layouts. Length, width and positions of building components are taken from these two dimensional layouts (Ford Dagenham Layout Team 2014).

2.5.4 CFD Models and Application in Buildings

In the past, environmental airflow and thermal properties of buildings were measured and problems resolved by “trial and error”, which is time consuming, expensive and in many cases ineffective. Advances in technology allowed the benefit of investigating changes before the actual implementation, leading to improvements in a more cost effective way (Patankar 1980). There are several methods available to simulate and predict temperature distribution and airflow within indoor spaces. Due to their complexity, analytical solutions are not favoured. Experimental investigations are costly, especially when dealing with large models. CFD on the other hand has gained popularity in recent years due to its low cost, relative simplicity and speed (Chen 2009). It is a powerful tool, which can simulate, predict and visualise fluid flow and thermal distribution of internal rooms or buildings. The flow transport equations with the appropriate boundary conditions and a turbulence model are solved over the flow domain for specific quantities. Figure 9 shows an internal environment, which is meshed to solve such transfer equations from node to node. The effects of airflow movement and heated components can be calculated and then be visualised by CFD software. Conduction through walls or any other boundaries within such a model are simulated.

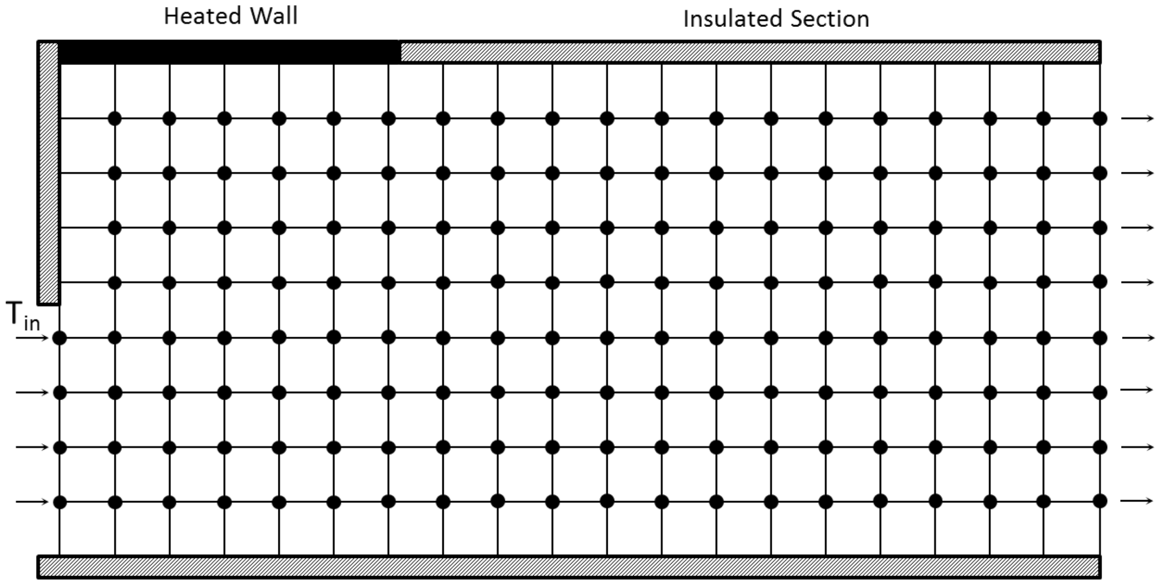


Figure 9: Grid layout for obtaining numerical solutions of a temperature and airflow field (***adapted from*** Patankar 1980)***. With initial condition applied the environmental behaviour of every node can be numerically calculated.***

The following "full Navier-Stroke" transfer equations calculate laminar fluid flow at every node of the CFD model. In these equations ρ = density (kgm^{-3}), $u_{j,i}$ = velocity vectors, x_j = direction vector, S_M = mass source term (kgm^{-3}), S_E = energy source term (Wm^{-3}), λ = thermal conductivity (Wm^{-1}K^{-1}), H = thermal enthalpy (Jkg^{-3}), c_p = specific heat capacity (Jkg^{-1}K^{-1}), P = static pressure (Pa), T = temperature (K), τ = stress tensor, g_j = gravitational force vector and F_j = body force vector (Gowreesunker & Tassou 2013).

Mass Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = S_M \tag{14}$$

Energy Equation:

$$\frac{\partial}{\partial t}(\rho H) = -\frac{\partial}{\partial x_j}(\rho u_j c_p T) + \frac{\partial}{\partial x_j}\left[\lambda \frac{\partial T}{\partial x_j}\right] + S_E \tag{15}$$

Momentum Equation:

$$\frac{\partial}{\partial t}\left(\rho u_j\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial}{\partial x_j}(P)+\frac{\partial}{\partial x_j}(\tau)+\rho g_j+F_j \tag{16}$$

Next to laminar flow there is also turbulent flow which can be calculated by various models which use more complex formulas, however, this study applied CFD as a tool to better understand the thermal performance of a building and does not improve CFD software, but it is significant to be able to apply such software correctly. For this purpose simulation techniques are reviewed.

Turbulence models perform differently depending on the type of flow under investigation (Kim et al. 2001) (Posner & Buchanan 2003) (Chow et al. 2006) (Wu et al. 2012) (Gowreesunker & Tassou 2013) and the standard k-ε is one of the most versatile turbulence models and was used satisfactorily to investigate internal environments with heating and cooling chambers (Kim et al. 2001). The RNG (Re-Normalisation Group) k-ε model, which does not need the introduction of wall functions, proved to be more accurate when simulating small internal rooms (Posner & Buchanan 2003) (Sun & Wang 2010). In the simulation of heating and ventilation systems (HVAC systems) where high velocities are present the "Reynolds Stress Model" was found to perform better (Wu et al. 2012), while in the simulation of large indoor spaces the standard k-ε and the RNG k-ε are more commonly used with the k-ε slightly favoured (Gowreesunker & Tassou 2013).

Usually building models are not reduced in size, because it would not reduce the complexity of the simulation. However, due to computing constraints, computational grids are often limited in size and non-uniform grids are a way forward to partially overcome the problem and deploy computing power in areas of interest (Hajdukiewicz et al. 2013). Assumptions are also made to reduce the complexity of the problem and keep within computational limits. For example pressure losses to account for flow obstacles are deployed to simplify the model (Lee et al. 2011). In this study all flow obstacles are actually simulated and only simplified in shape, which enabled more realistic simulation outcomes. Simplifications to the geometry were also made in the simulation of the library by Hajdukiewicz. Whitin all the rooms human ocupants, desks, chairs and PCs were also simplified to blocks, which she validated as resonable accurate (Hajdukiewicz et al. 2013). In Lee's study of the power plant all important components such as boilers and other heated parts were also simplified to blocks which seemed to perform reasonable well, if the entire power plant is observed (Lee et al. 2011). In all larger simulations the geometry of complex components were simplified, but the validated simulation outcomes proved such simplification as feasible and reasonable accurate. Furthermore, most large scale CFD simulations are limited to steady state applications and models need to be validated within certain accuracies to gain confidence. This is mostly done against field measurement data (Rohdin & Moshfegh 2007). In this investigation, data was collected by mapping the space using a mobile data collection system and fixed sensors.

Lot of models for small scale spaces exist in current literature, however, these cannot be simply extended to a significantly larger spaces, because there would be a lack of experimental data for validation and detailed machine heat load for industrial buildings. Furthermore, large spaces tend to have larger temperature gradients and there is a significant change in heat capacity due to cubic law.

One of the largest CFD simulations in open literature, a library with 800m^2, was performed by Magdalena in 2013 (Hajdukiewicz et al. 2013). The building model within this thesis is 183,243m^2; hence it is 229 times larger than the library. Furthermore, the building was naturally ventilated although radiators, natural ventilation and additional heat sources such as lights, computers and human occupants were considered. However, the complexity required to simulate an entire manufacturing plant is considerably higher.

Such large buildings have not been investigated in the past due to computational limits. Furthermore, scientific observations of such a large scale buildings are expensive and it is also not easy to get enough access in an industrial live environment to perform such detailed studies. For these reasons it was the first study in open literature to observe the thermal environment of such a complex manufacturing plant.

2.5.5 Conclusion

Experimental research is the most accurate method to obtain thermal data within a building, but its application is limited in certain aspects. It would be too time consuming and in many cases it would be not possible to carry out a full scale investigation of an entire manufacturing plant. In most cases limitations lead to coarse grids between data points and also not all physical properties such as pressure and exact airflow can always be gathered. It is also difficult to obtain data for extreme conditions and it is not easy to predict potential improvements upfront.

CFD on the other hand is able to overcome such issues and is also able to obtain data in a more comprehensive manner. Recent advancements in computer technology and the deployment of advanced numerical methods have allowed the simulation of relatively complex problems with acceptable accuracies. In large manufacturing plants machine tools, auxiliary equipment, HVAC systems, extraction systems, leakages and lighting can make it complex model to simulate. In addition, components interact with each other and can influence the internal environment. Individual components can, however, be simulated with ease and to the author's knowledge a simulation that combines all systems in a large plant such as the one investigated in the study is still to be performed. A full scale simulation would be 229 times larger than one of the largest simulations carried out to date, but it is not only size but also the complexity.

In most large scale simulations heat sources and airflow inputs are either neglected or fewer sources were apparent. Hence, this study attempts to enlarge research opportunities for the future use and also compares both, experimental and simulated data and guides the reader along their challenges. In this project a large open space factory is simulated and this report explains innovative methodologies and guides the reader along the difficult task of performing such complex simulations and its analysis. Due to the investigation of past CFD simulations published in open literature the following questions arose:

- Where are the biggest challenges of creating such a complex model?
- What issues arise with the computational limits of current times?
- How can such a large scale simulation be validated?
- What type of data is required for the validation of such a model?
- What types of boundary conditions are required to build such a model?

2.6 Conclusion

In this second main chapter all issues of energy consumption, its effect on the environment and governmental constraints were reviewed. Carbon Footprint, Greenhouse Gasses and the Kyoto Protocol were linked to thermodynamic issues of existing large scale manufacturing plants to explain the relevance and the importance of this study in current times. Intergovernmental constraints put pressure on the industry to improve their energy effectiveness. Manufacturing plants consume a significant amount of energy which created original research opportunities. In this study the thermal performance of such a manufacturing plant was evaluated and analysed. Existing literature was reviewed to guide this study along the newest technologies and simulation strategies to fill missing gaps of energy research within large existing manufacturing plants. To the author's knowledge, it was the first time in open literature, that it was attempted to evaluate the thermal energy performants of such a complex live environment within a large manufacturing plant due to computational, budget, access and time constraints of scientific work. Due to this complex task the project was split into the following three main areas:

- Instrumental investigation to understand and analyse the plant's internal environmental issues.
- A simulation model to further analyse the theoretical building performance
- The comparison of experimental and simulation investigation methods and the benefits to have both

This study will guide the reader through innovative methodologies and techniques of obtaining and analysing data for the better understanding of thermal issues in existing large scale manufacturing plants.

Studies in such large scale facilities have mainly focused on simulation albeit with a lack of experimental evidence to validate simulated results. There is a need to understand effective data collection and reduction methods to develop and validate simulation models. Lot of models for small scale spaces, less than 800m^2, exist in current literature, however, these cannot be simply extended to a significantly larger spaces due to:

- Lack of comprehensive experimental data for validation
- Lack of detailed machine heat load for industrial buildings
- Larger temperature gradients in large buildings
- Significant change in heat capacity due to cubic law

The most demanding part of this project will be the combinational task of acquiring both, experimental and simulated methodologies of energy research for an existing mega factory which was opened in 1931. In this large open space factory, without any partitioning, performances and technologies are obsolete which increased the importance of this study. All scientific research was made in a live environment and resources, budget, time and computational power were limited. New methods of analysis had to be developed to fill research gaps around the thermal energy environment of large and complex industrial estate.

Chapter 3

3 Methodology

3.1 Introduction

This chapter overviews general methods and technique which were used in this study of thermal energy research within large and complex industrial buildings. All mentioned methods are specifically chosen for the task of thermal energy research in large existing buildings and may not necessarily be applicable for other research areas. In this chapter advantages and disadvantages of various methods are briefly discussed and linked to the actual methodologies performed in this research work.

3.2 Methodologies

To initiate this work, after the acquirement of background knowledge, a general methodology was made, to be able to plan the study along the objectives. First of all a problem was defined, before a methodology is put in place. There are several methods of defining such a problem.

3.2.1 Visual Inspection

A visual inspection could be made, to get the first impression of the research task. The advantage of a visual inspection is that the magnitude of the task and first research ideas cannot only be obtained in a quick manner, but a researcher acquires first impressions on the matter of the research problem. The disadvantage of such a method is that it could initially be misleading and all acquired information could be vague (Newby 2014).

3.2.2 Usage of Existing Data

Another method which could be applied, is the research of existing data. In a manufacturing plant for example production data, utility cost, data of previous studies or even collected data sets may exist and can be evaluated. This approach could significantly support the work and reduce the actual task of data collection (Ford 2013b). The issue with this method is, that existing data may be unreliable because data collection methods and errors are unknown.

3.2.3 Case Studies

A case study is also a method with could combine or include a visual inspection and the research of existing data. It can also help to obtain the roots of a problem, which can help to develop implementation strategies, once problem areas are defined. Another advantage of case studies is that such a task can be researched in detail, without the need of acquiring information of similar problems in the area. In case of this project, the manufacturing plant was researched, but access to only one manufacturing plant was required. The disadvantage of such a technique is that any engineered methodology may only be valid for the case of the study (Newby 2014) (Woodside 2010). However, a case study could be combined with literature review, which is another method of approaching such a research problem. Other people within the same discipline could have developed a useful methodology or solved similar research problems.

3.2.4 Review of existing literature

The literature review is a basic concept within science, because it will not only guide the researcher in the correct direction, but it also identifies research gaps. There are a variety of different sources such as for example research papers, books, web-sites or interviews. Sources have to be carefully chosen, because not all data sources may present information in a scientific manner. In general, a literature review alone may present knowledge about the area of research, but it would not bring new data on a particular task (Newby 2014).

3.2.5 Multiple Case Study

Instead of a single case study approach, more studies could be undertaken to create a comprehensive methodology of the research task. The advantage is that such a methodology could be engineered to be applied more universally. On the other hand, it would take a lot of time, budget, other resources and cooperation to undertake such a project. Furthermore, such a method could miss details which a case study may support.

3.2.6 Interviews

Another technique of deriving initial data could be achieved by interviews. Especially in a thermal energy study in industry, existing knowledge of employees could obtain valuable information. Such a technique could create complications with ethic guidelines (Woodside 2010). Furthermore, acquired information could be too subjectively, and not necessarily rely on evidence. Interviews could be an informal support of such a project, but it would rather be difficult for an engineering project, to actually acquire reliable data sets.

3.2.7 Preferred Methods

There are methods which can be chosen to research a problem, but all methods mentioned have advantages and disadvantages. In this work a combination of literature review and case study was undertaken to acquire knowledge about the thermal performance of a manufacturing plant. For more information on the literature review, see chapter 2.

Once the research task is defined, there are different techniques of obtaining data within a clarified area of research. Data can be obtained experimental or via simulation. Advantages and disadvantages of both methods are discussed in section 2.5.2. Within this project a combination of both methods was engineered, to be able to create a comprehensive analysis of the thermal environment of a manufacturing plant, to test the most relevant methods and build knowledge for future engineers.

3.3 Experimental Methodology

For the creation of a standard procedure around the thermal data collection of a manufacturing plant model, a case study in one of the largest existing manufacturing plants within the United Kingdom was planned and undertaken. It started with a visual inspection of the plant, including all its facilities, to build an initial understanding of the task. Once the plant became more familiar, two independent data collection systems were developed. Both systems had to pass a safety inspection before they were tested within the plant. When both systems became a clear, a methodology around the data collection had to be developed, see section 5.2. In addition to these data collection systems, data from external sources, such as plant internal production data and weather data from a public website, was collected in parallel. Once data was collected it had to be stored and analysed. Lots of data was going to be collected, which enforced the design of a custom built database, see section 5.3. The database was used as the base of the project because it was able to not only support the analysis of the all collected data, but also it could prepare data for the potential analysis of a simulation model.

3.4 Simulation Model Methodology

There are varies of methods of creating a simulation model, see section 2.5.1. In in case of this project, a CFD model was developed to obtain more information on the thermal environment of the observed manufacturing plant. All existing resources, such as CAD models or old drawings, were used to create a three dimensional building model of the plant. Once the model was built, it was simplified and various test simulation runs of single building components and the entire model were made before simulating the overall model. When the model was simulated it had to be validated against the collected data, before it was improved and simulated again for various times. Once the model showed a close enough match within reasonable predefined limits the model was analysed to increase the understanding of the thermal environment of the manufacturing plant.

The methodology of creating a CFD model including all difficulties of such a large and complex simulation approach are explained in section 6.3 and section 6.4. Data was analysed and results of both, experimental and simulation, were presented within this report. To finalise the work standard produces for the operational improvement of the thermal performance of manufacturing plants was worked out and presented in chapter 7.

3.5 Conclusion

There are many methods which can be utilised to evaluate the thermal environment of a large and complex manufacturing plant. First of all literature was reviewed to be able to identify research gaps within the area of this study. In this project a case study is made to test the most effective methods of evaluating the thermal energy performance of an industrial live environment within an obsolete, large and complex manufacturing plant. A visual inspection and the analysis of existing data were the foundation of initiating this study. Afterwards methods such as experimental research and the utilisation of a simulation model were tested to evaluate advantages and disadvantages of each technique and the benefit which a combination of both methods would bring. All methodologies of the tasks are explained in Chapter 5 and Chapter 6.

Chapter 4

4 Case Study

4.1 Introduction

In the 1920s Ford, an American automobile company, planned to open their first manufacturing plant in Europe. In 1931 the "Dagenham Plant" opened in Britain and was the largest manufacturing plant in Europe at the time. Initially complete automobiles were designed and manufactured at the plant. Over time, as production increased this manufacturing plant turned into an engine plant. Currently the "Dagenham Engine Plant (DEP)" is one of the largest diesel engine manufacturing plants in Europe. It was designed as an open space factory and due to changes in building construction and operation, significant energy problems occurred.

4.2 The Dagenham Engine Plant

When first built the Dagenham Plant was 124,490m^2 (1,340,000ft^2) with a length of 304.80m (1,000ft) and a height reaching up to 25m as shown in Figure 10. To be able to independently produce automobiles this factory even had its own power station to insure electric power supply. The “Dagenham Plant” did not require heating systems. A hot metal building and a foundry heated the plant all seasons of the year. Health and safety rules were not applied or even known. Comfort problems were also neglected which caused a significant amount of accidents. To be able to move heavy machines and components, internal crane constructions reached heights of more than 20m. A factory owned train and a shipping dock enabled the transport of machines, components and automobiles (Ford 1968).

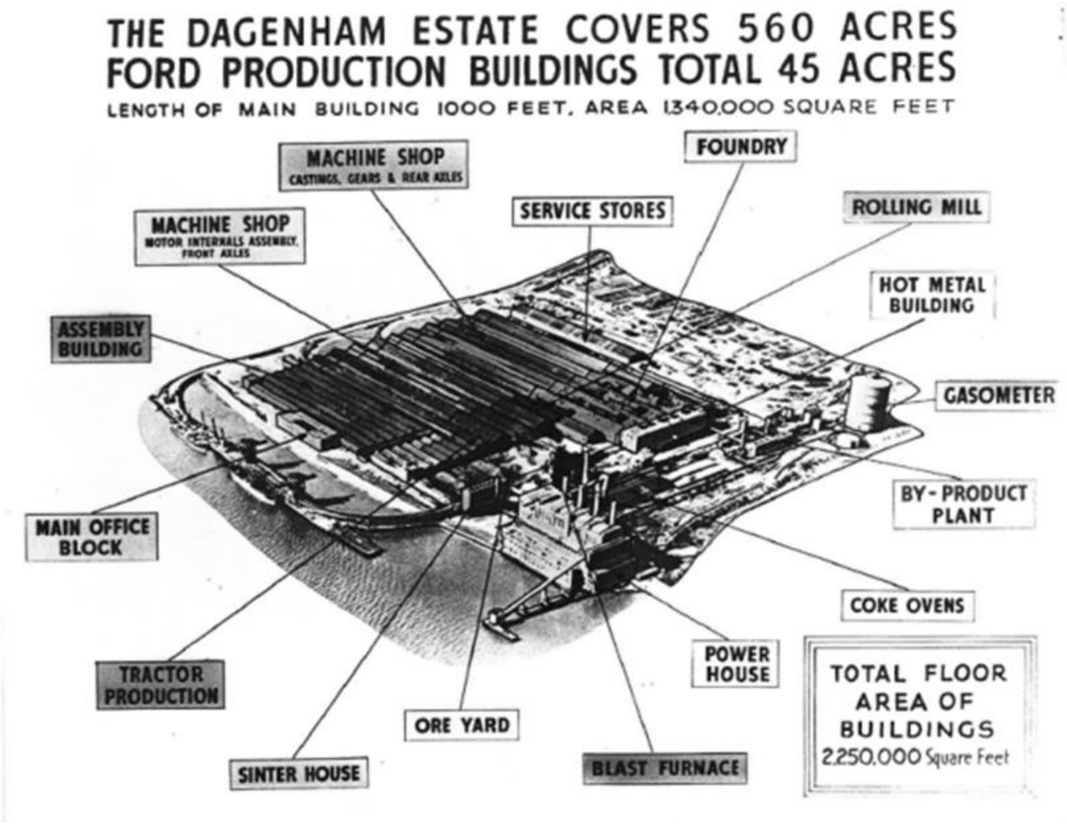


Figure 10: The Dagenham Engine Plant and its initial setup at the opening in 1931 (Ford 1968)***.***

Due to rising production cost, the “Dagenham Plant” transformed into one of the largest engine plants in Europe. Nowadays, the entire machinery environment is built on the ground floor leaving a lot of factory space unused. The Manufacturing plant also increased up to a size of 183,243m^2 with a length of 528m and a width of 468m including all building attachments. Today the “Dagenham Plant” is known as the DEP and produces approximately 1,000,000 engines a year (Ford 2013a). The DEP and all its production lines are shown in Figure 11.

It is operating 24-hours from Monday to Saturday to manufacture the “Tiger”, the “Lion” and the “Puma” engines (in case of the “Tiger” engine 24/7). The production of the “Lynx” engine stopped in July 2013 and will now be replaced by a new engine manufacturing programme called “Panther”.

Obsolete building technology, design issues and several expansion projects caused many thermal problems within the internal environment of this manufacturing plant. In the early seventies a heating and ventilation system (HV system) was installed due to health and safety and comfort regulations in Great Britain (Ford 2013b). However, over the years, holes in the walls, broken windows and roof leakages occurred. Antiquated designed insulation causes crucial energy problems within the factory space. In general, the DEP suffers a lack of maintenance and restoration works. Nowadays transport of engines, components and machines is performed by vehicle usage which additionally creates leakages through door openings. Besides that, negative pressure within the plant is created by machine extraction, which potentially sucks external air uncontrolled via gaps in the building walls. Modern HV systems counteract to achieve a positive pressure within the plant, but due to an aged design and poor maintenance negative pressure is maintained (Olson 2012). Temperature and pressure differences do cause undesired airflows. Due to all these complications the plant internal thermal environment is described as its own “micro environment” (Ford 2013b).

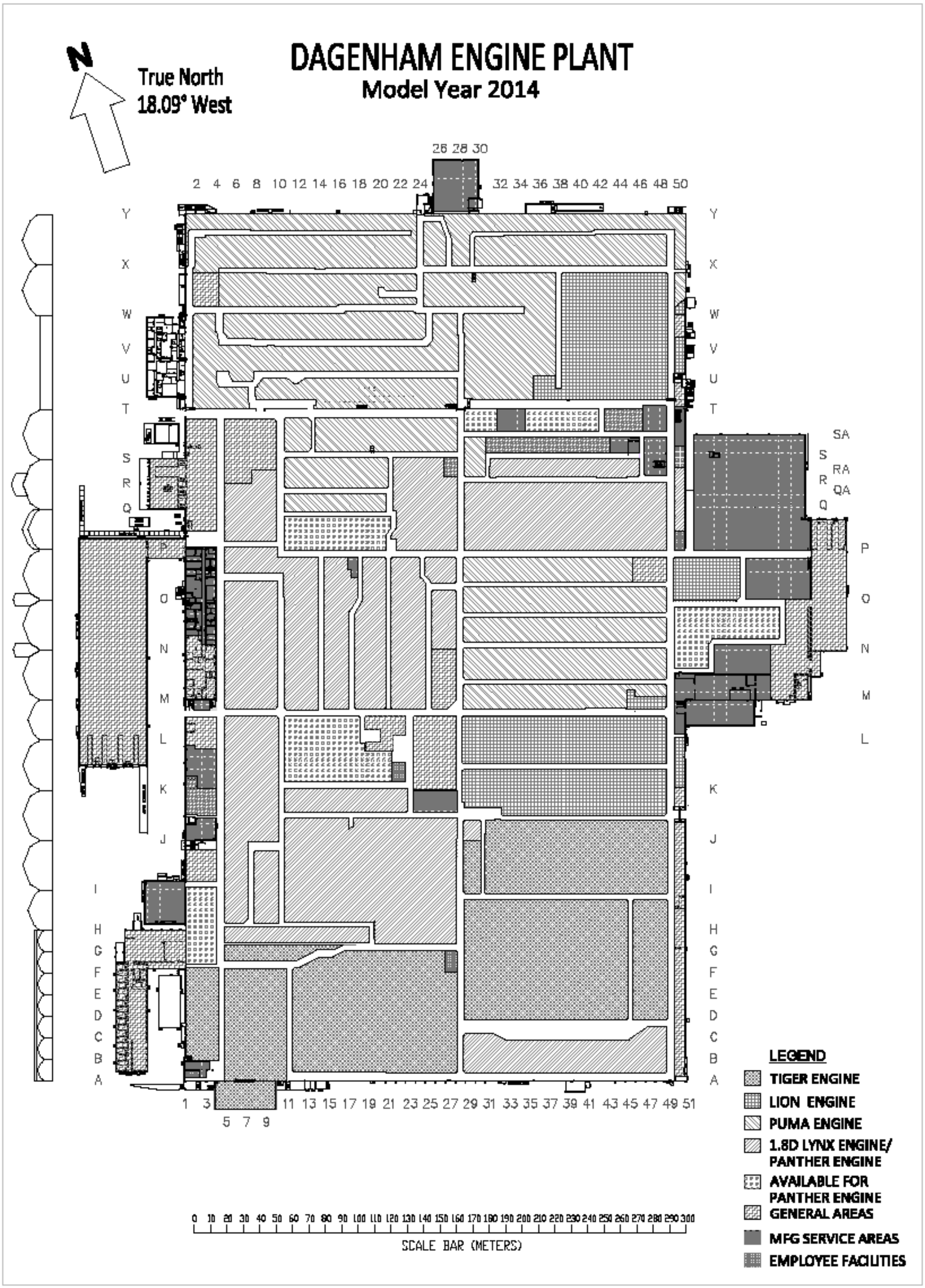


Figure 11: Operational block diagram of the Dagenham Engine Plant in 2014. All engine lines including the Tiger engine line, the Lion engine line and the Puma engine line are shown. Additional provisional layouts of the incoming Panther line are shown (Ford Dagenham Layout Team 2014)***.***

4.3 Heating Ventilation System in the DEP

Figure 12 shows a typical plant room of the HV system utilised in the DEP. Airflows get forced through the return from the plant where it is mixed with fresh air. After this mixing process air is heated by heating coils before it is filtered. Then the air is forced through ducts to the diffusors by fans.

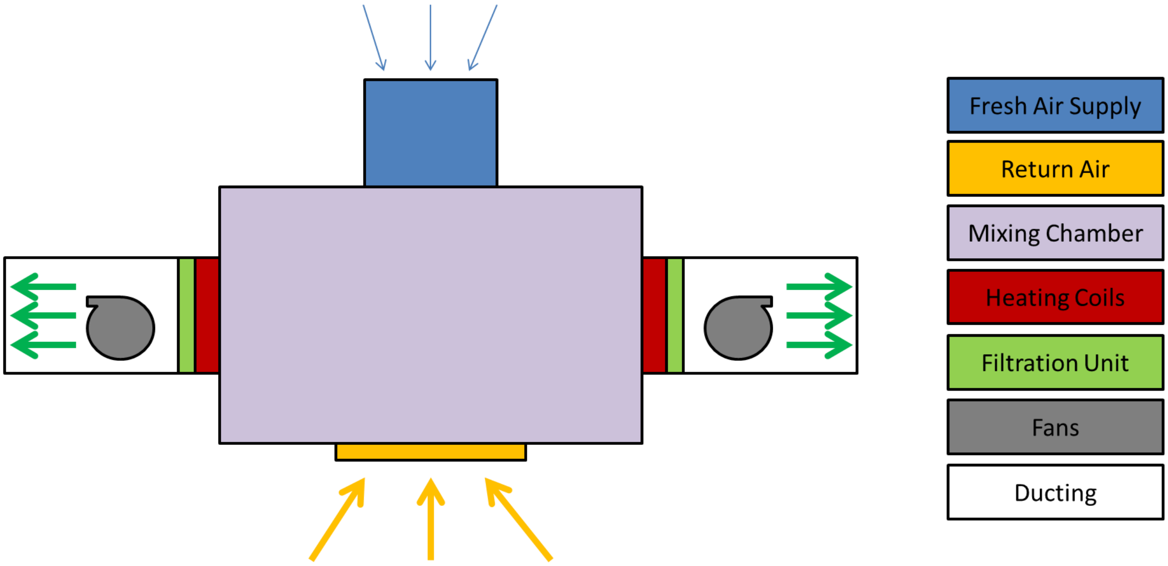


Figure 12: Typical industrial plant rooms of the heating and ventilation system used in the Dagenham Engine Plant.

The HV system, largely installed in the seventies, is still under constant use in winter conditions and is shown in Figure 13. All plant rooms from one to 18 are steam operated. A boiler house next to the plant building supplies all of these plant rooms with hot steam to operate their heating coils if required. The plant rooms one to eight are controlling the main HV system over duct-runs orientated from north to south. Plant room nine is supporting the main units in a storage area at the eastern part of the plant. In the southern part three units from 10 to 12 are operating smaller ducts operated in an east to west direction. Plant rooms 13 to 16 control ducts of smaller HV units at the northern part of the plant. The plant rooms 17 and 18 are supplying offices and are not considered within this study. The plant room from 20 to 26 are operated by gas but are not under use in currently.

Different types of diffusors are supplying air into the plant. Two of those types are shown in Appendix A. However, the main strategy suggests the supply air out of diffusors travels back to the plant rooms, where it is remixed, filtered, heated (if required) and resupplied over the heating ducts. The heating ducts are non-insulated which lowers its performance. In addition, a lot of diffusor heads are damaged which affects their efficiency. Moreover, the actual plant rooms are hardly maintained and refurbished since their installation. Filters are polluted and fresh air inlet vent adjustments are often damaged. Initially the HV system was designed with an automatic control system which broke down and is not currently used. In recent years this system was controlled manually which is not the most effective way of controlling airflow within the manufacturing plant. In general, obsolete and hardly maintained technologies lower the efficiency of the HV system in this plant.

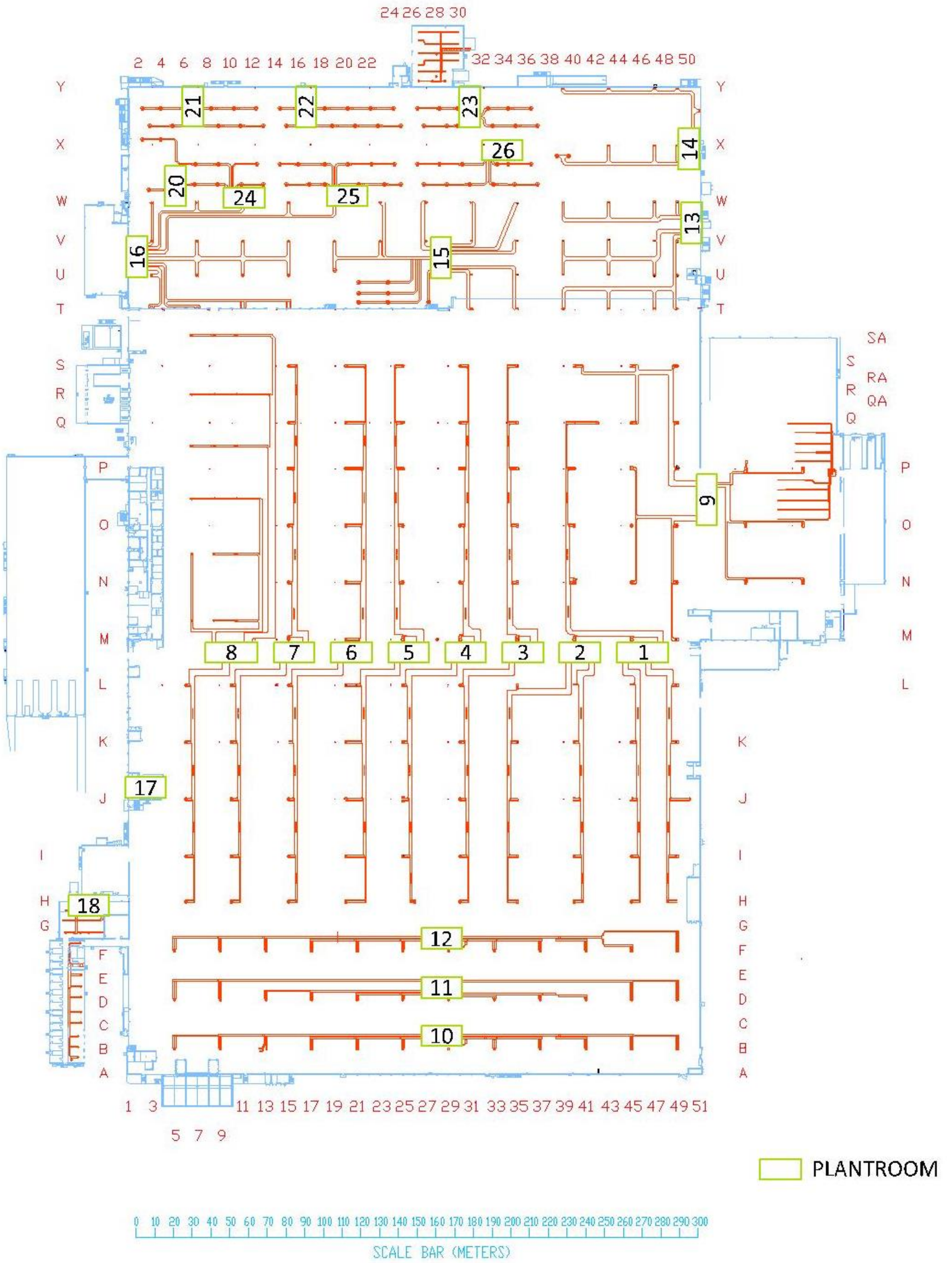


Figure 13: HV layout of the DEP. All duct runs and diffusers are red and the corresponding plant rooms from 1 to 26 are green (Ford Dagenham Layout Team 2014)**.**

4.4 Conclusion

Since the opening in 1931 the “Dagenham Engine Plant” changed its production and management focus various times. Due to external and internal circumstances, issues of the thermal environment within the manufacturing plant have caused many energy efficiency problems. Factors such as poor insulation, leakages, pressure problems, building construction and an aged HV system increasing the “carbon footprint” of the DEP. Due to external machine extraction systems a negative pressure is created within the plant. That forces external air through leakages into the plant. Modern HVAC systems are able to abolish such issues by increasing the internal pressure, however, due to the large obsolete HVAC system in the DEP this negative pressure cannot be equalised which strongly reduces the energy performance of the plant. In addition to energy consumption, the employees comfort and a widely unstable stable machinery environment caused lower production efficiencies which created opportunities for such energy saving project with a large potential for improvements. Out of this case study the following question emerged: How can a scientific study take place at such a large and complex live environment? The following chapters will explain the difficulties but also give answers on how such issues could be overcome.

Chapter 5

5 Data Collection, Storage and Reduction Methods

5.1 Introduction

Extensive research was carried out at a large, old manufacturing plant to investigate multifarious solutions of low cost energy saving methods. Environmental plant data was obtained and analysed to understand thermal characteristics of the factory space. A database was designed to store, reduce and analyse relevant information about thermal properties of the internal and external plant environment. This section presents all the methods and results of an experimental investigation of such a factory.

5.2 Data Collection Methodology

5.2.1 Mobile Data Collection System - Design and Construction

Due to the complex thermal characteristics of the DEP, a comprehensive data collection programme was designed and carried out to understand the temperature distribution and airflow. Various sensors for temperature, humidity, air velocity and direction were used in order to collect data. A complete suite of instruments was specifically developed for this purpose.

To be able to collect data at any accessible location within the plant, a "Mobile Data Collection System", shown in Figure 14 was designed and built. All components used for manufacturing the measurement rig were investigated and tested for accuracies before assembly to reduce the possibilities of unwanted system faults. A set of test measurements in a known environment was made to confirm specified accuracies of all components in the system (accuracies of all sensors were later in this section).

Once the system was assembled it was able to measure and record temperatures at five levels of height simultaneously. Various levels were chosen to be able to understand thermal behaviour within a building in three dimensions. One sensor was designed to collect as close to the ground as feasible, but a rough factory environment was considered which determined a lowest sensor height of 15cm. Ideally the highest sensor would be as close to the roof as possible, but in such a large and complex industrial environment with a building reaching up to 25m in height such measurements were not feasible. The highest sensor was adjusted to be 450cm due to reasons of practicality. Most pipe work, truss bars, labelling, lights and other obstacles limited the height at which measurements can be taken. It would be possible to readjust, but due to the large plant size such height adjustments would cost too much time and would not be feasible. Furthermore, the rig would have to be adjusted for every measurement for comparison purposes, but there are parts of the building which do not reach in greater heights. Additionally, most important factors of production are below 450cm. Most diffusors, machines and the workforce are below that height within the tested manufacturing plant which finally decided the highest position of measurement.

Another important measurement height would be at the height of human bodies. Two of the sensors at T_2 and T_3 were placed at 135cm and 130cm due to the human presence within this region. Humans sensibly “feel” temperatures around there upper bodies which was the reason for choosing such a height. The sensor at 130cm was hidden under the top plate of the test rack to be able to compare temperatures without influences of radiation. An additional sensor was placed between the highest at 450cm and the sensor at 135cm at 300cm to get data between those heights. Also most of the diffusors are fixed at a height of 300cm which made it an interesting sensor for capturing data at diffusor level.

Sensors had to be low priced, accurate and quick and easy to install. Sensors also had to be robust and exchangeable due to a dirty oily environment. The range of the sensors was between -5°C and 35°C, which was slightly wider, then the plant external temperature minimum and maximum over the last 20 years. The actual accuracy of the sensor was considered optimal between ±1.5°C, because it was enough to observe an average temperature pattern within the plant. Hence, first class “J-type” thermocouples from Labfacility (Labfacility 2012) were connected to a data logging system to efficiently handle large quantities of collected temperature samples.

Temperatures were considered the most important physical property within this project, since temperatures are not measured in vectors such as velocity for example; hence averages are valuable results and can easily be used for analysis. Also temperatures are the main factor for heating cost and production issues.

Additionally, the system uses airflow indicators at three levels of height to show internal airflow directions. Once airflow directions were known, magnitudes could be measured with a hand held hot-wire anemometer (AVM 8880 (Range 0.1-25m/s; Accuracy ±5%)) (CFM 2012). The heights of the airflow indicators were mainly chosen due to practical reasons. Airflow indicators were fixed to the pole within reasonable distances between the temperature sensors at 70cm, 220cm and 400cm of height. The acquisition of temperatures was prioritised and the airflow measurements were mainly taken to build an understanding of the low level airflow movements, its direction and magnitude.

Humidity was collected manually with a hair hygrometer (Fischer Präzisions-Haarhygrometer (Accuracy ±3%)) (Fischer 2006). The “Mobile Data Collection System” was used to collect thermal data at discrete locations across the entire DEP.

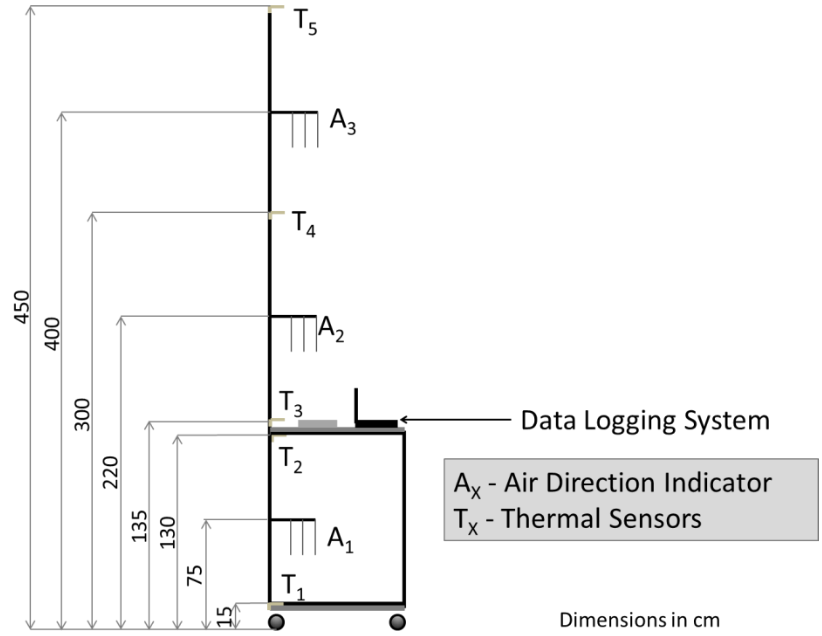


Figure 14: The Mobile Data Collection System reads and records temperatures, airflow and humidity samples across large buildings.

5.2.2 Mobile Data Collection System - Methodology

This system was used to collect data over the seasons of a year from the warmest day in summer until the coldest day in winter. Due to health and safety reasons (only license to operate daytime) and daily operational data was collected 3 days a week from approximately 9am to 3pm. The days in the week were selected based on weather forecasts. For instance, if the weather forecast predicted a particular warm or cold period, such periods were preferred whenever possible.

In general, the acquisition of an entire data set across the entire manufacturing plant was time consuming. Discrete locations were chosen with respect to time and size of the area of measurement. Measurements were always taken close to standard grid locations in the plant, within a 2m radius, for the purpose of referring to a time and location for the duration of a measurement. A complete set of data through the entire manufacturing plant was collected within 3 days. In such complex plants fixed measurement paths were not possible due to varying plant operational practices. At the beginning of a set an area was investigated (Which areas are required? What areas are accessible? Are paths blocked? Are machines in the area running?). Once an area was defined measurements were made at an adjusted logical path, which allowed to optimally observe areas of interest within the time frame of a working day. Due to unforeseen plant operational disruptions, such as for example blockages, heavy vehicle traffic, repair or restoration works, paths had to be adjusted if necessary. The distance between measuring points depended on the plant internal grid which is shown in Figure 15, but also on plant operational practice. This grid differs throughout the building so reasonable measurement distances had to be set. Plant grid distances measure approximately 6.1m in east-west direction and varied from 13.1m to approximately 31m in north-south direction. Depending on these distances one, two or three column steps were taken after a set of measurements.

At every discrete location within the plant 500 samples were taken, to account for environmental short term changes such as an open door for instance. Every second a sample was taken and after a full set of 500 samples the test cart progressed to another grid location. During the time when the temperature readings were made, airflow and humidity measurements were obtained. For airflow measurements the indicators to show the airflow direction were used. In height of the indicator, the direction was known and the magnitude of the airflow was measured by the handheld anemometer. While all 500 temperatures were logged automatically, airflow measurements had to be logged manually on a sheet of paper. Hence, for every measurement location three airflow measurements were made and logged, before the mobile data collection system was moved to the next location. Equally the humidity was logged at once at every location. These measurements were written down manually before they were typed in an Excel sheet. During the progression towards further grid location or even between data sets, external conditions could have changed, which was the reason for the installation of a second system.

5.2.3 Fixed Sensor System – Design, Construction and Methodology

Due to changing environmental conditions between varying discrete locations at different times, reference values were required and collected by a set of permanently fixed and continuously recording temperature sensors. These fixed sensors need to operate within the same range as the mobile data collection system of -5°C to 35°C. Machine internal adjustment processes slow down machines, if temperature changes of approximately 0.5°C occurred, which is the reason that sensors with an accuracy better than ±0.25°C were chosen (Tinytag Ultra TGU 0050 (Range -30 to 50°C; Accuracy ±0.2°C)) (Tinytag 2002) (Tinytag Radio (Range -40 to 125°C; Accuracy between 0 to 70°C better than 0.25°C)) (Tinytag 2012a) (Tinytag 2012b). In total 37 temperature sensors, shown in Figure 15, were installed in fixed locations across the factory at the height of approximately 1.7m. The number of sensors was assigned with respect to the size of the manufacturing plant and budget constraints. In some cases probes with additional humidity sensors were used to obtain further information. Three probes were also fixed at truss height (height of steel beam construction supporting the roof) to read temperatures at the maximum height.

All sensors were set to collect one sample every 10 minutes simultaneously. This collection process was automated, to be able to collected data at day and night times, on working and on holidays. With this methodology data was acquired at all times at all fixed locations. All measured data was logged by the system and then stored in a computer. This information was transferred wirelessly in an automatic manner. Once the data was stored it was input into a custom build database for further analysis (see section 5.3).

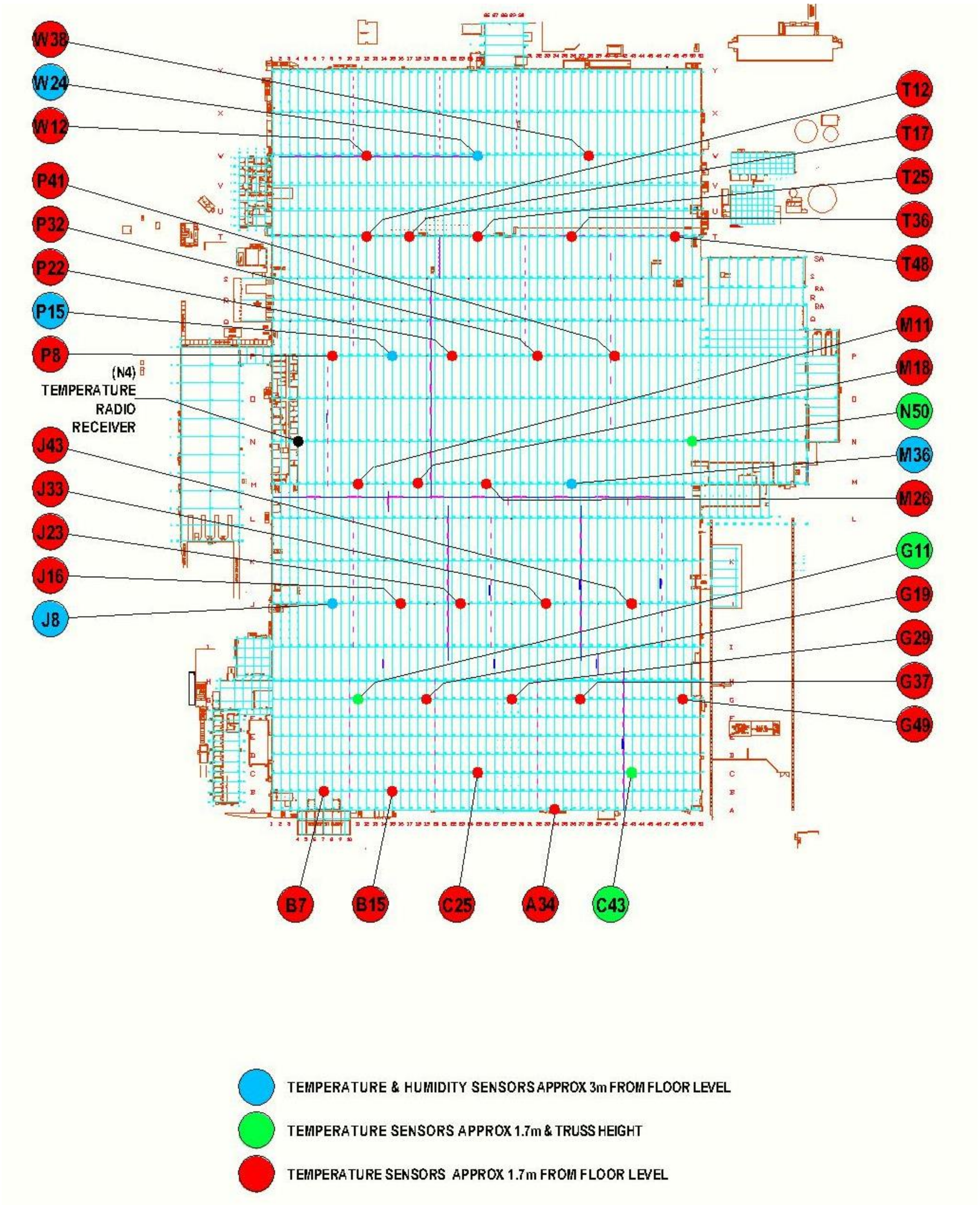


Figure 15: Fixed sensor locations in the manufacturing plant, blue for additional humidity sensors at 3m of height, green at 1.7m of height with an additional sensor under the roof and red for the standard sensor at 1.7m of height.

5.2.4 Other Data Sources

In addition to all collected data, environmentally relevant information was obtained from external sources. Local climate data was obtained from a weather logging web-site (Weather Underground 2013) as a source of reference. All-important data of energy usage and utilities was collected from factory internal sources. This data is particularly important to relate any conclusion with business cost relevance, substantiating meaningful implementations or management awareness. Production characteristics are connected to temperatures within the plant and vice-versa. All obtained data was stored in a custom build database for further analysis, which is explained in the following section.

5.3 Data Storage

A database was developed to store and process information. Data from sensors and other sources was linked to derive and differentiate trends and dependencies. Once this data was organised within different tables in a database, it was treated and then analysed to understand all observed effects and to obtain new correlations. Figure 16 shows a block diagram of all project facets for the elaboration of a custom-built database. The database is the central block within this project. Data from all the previously explained sources is stored and prepared for further analysis. Data will then become meaningful, if it is reduced or queried in adequate measures, to be able to present it in visible and understandable ways, which is the main advantage of a well-designed database compared to other storage methodologies.

A further advantage comes with the ability of transforming data for validation purposes. All collected data can be used to validate a simulation model, which would allow further analysis of the collected data if required. Figure 17 shows the actual tables within the database which were created to include collected data from all sources. More information about the database, the tables within the database and the coding are shown in Appendix B. All measured variables are indicated in boxes on the upper left hand side whereas collected data from other sources is summarised in boxes on the upper right hand side. The database is used to analyse data and set to feed a simulation model. It can be used to validate simulated results.

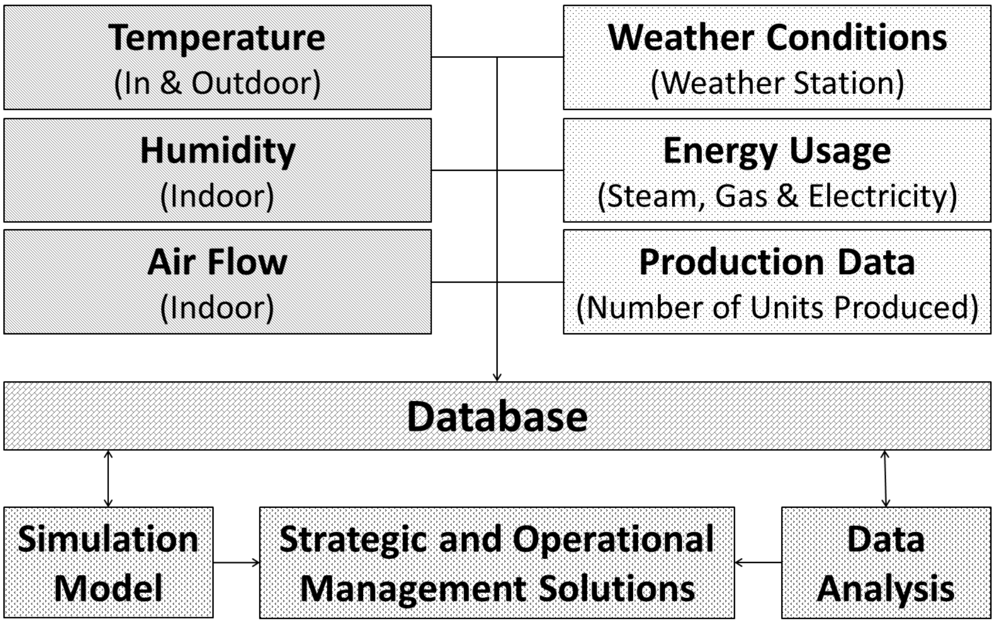
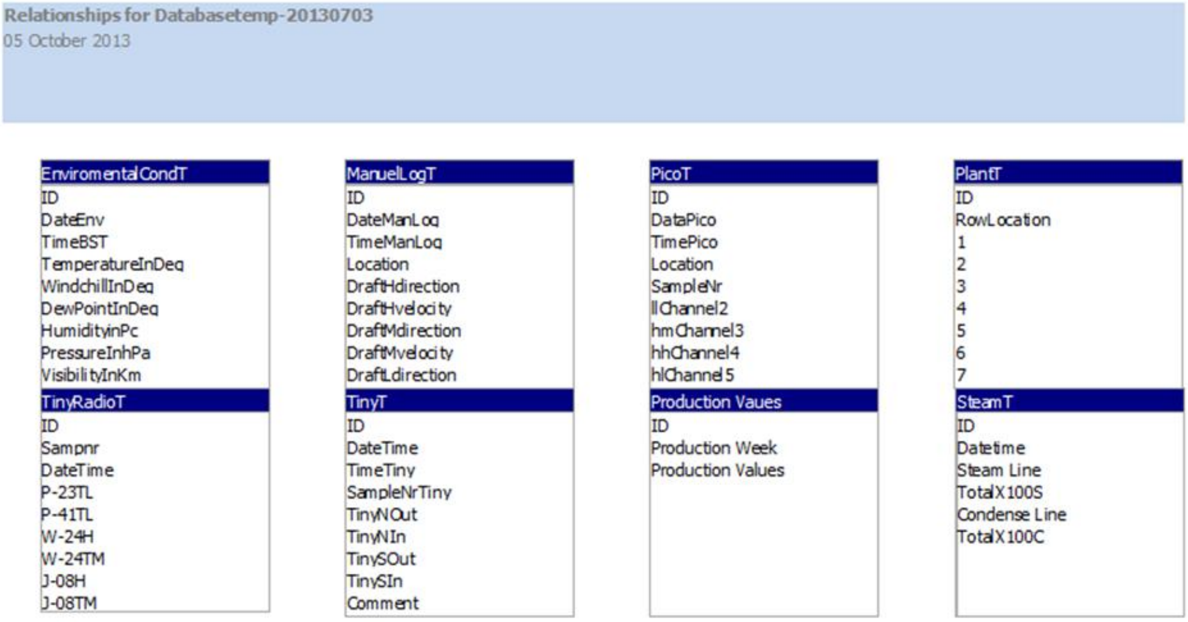


Figure 16: Block diagram to visualise database operations. Measured data is shown in boxes on the upper left hand side and data from external sources in boxes on the upper right hand side.



Relationships for Databasetemp-20130703
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P-23TL
P-41TL
W-24H
W-24TM
J-08H
J-08TM

ManuelLogT
ID
DateManLog
TimeManLog
Location
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DraftMdirection
DraftMvelocity
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SampleNr
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hmChannel3
hhChannel4
hlChannel5

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Production Values

PlantT
ID
RowLocation
1
2
3
4
5
6
7

SteamT
ID
Datetime
Steam Line
TotalX100S
Condense Line
TotalX100C

Figure 17: Shows all tables within the database and some of their columns. Different tables within the database were connected by the time and the DEP column locations.

5.4 Data Collection Methods and Procedures

For industry cost related results are particularly valuable. It is important to underline the impact of energy saving projects to potentially enforce cost effective implementations. Figure 18 shows the utility and energy cost of the DEP in 2012. The biggest cost impact is caused by electric power cost, certainly not unexpectedly due to the large number of high power consuming machines. However, it can be seen that the heating cost alone adds up to 26% of the utility bill over the entire year despite the fact that heating is not required in the summer. In winter, the heating cost can exceed GBP 500,000 per month due to the large size of such a mega-factory. This magnitude of heating expenses is representative for the United Kingdom. In colder East European countries with continental climate, such as Russia, the heating cost is exorbitant. But even in the UK the energy consumption overview justifies the importance of energy saving projects such as this.

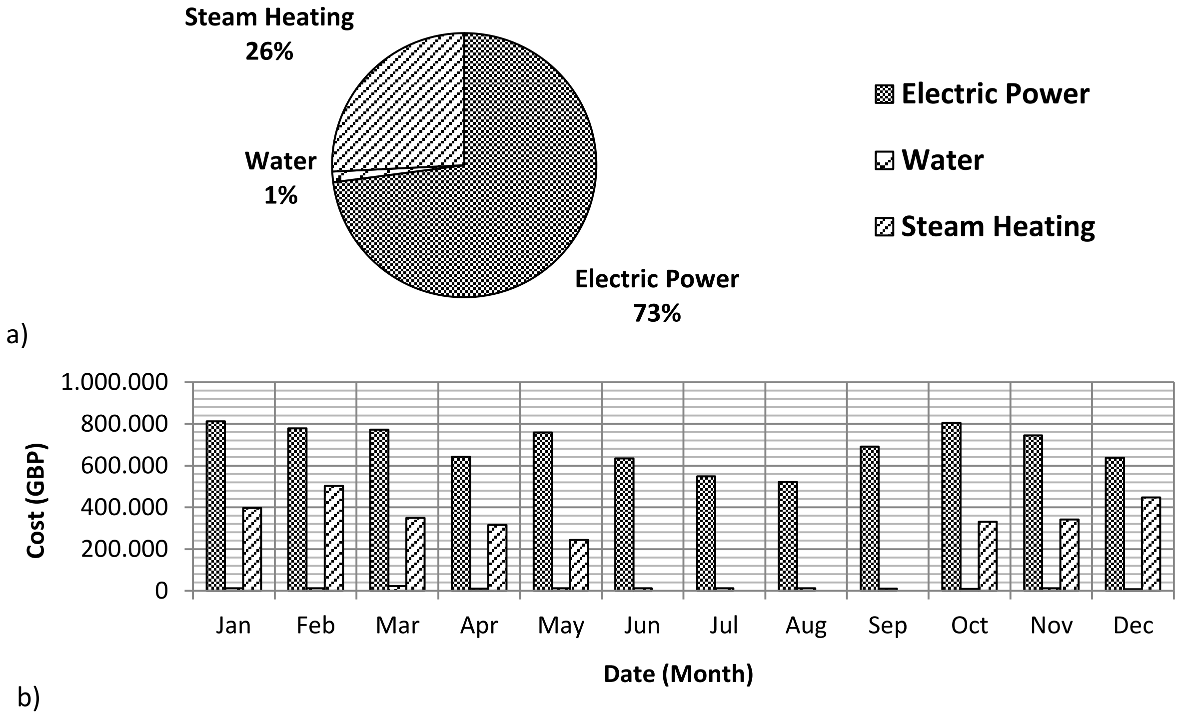


Figure 18: The utility statistic of the DEP in the year 2012 monitored over the entire year (a) and as averages showing the actual utility costs from January to December (b).

Wind does affect the thermal building performance, so external airflow data was collected to gain understanding of its strength and direction. The wind does not only affect airflow within the building, but also lowers the thermal properties of roof and building walls due to forced convection which is shown by Table 6. Figure 19 shows the direction in percentages in a radar plot over the DEP, whereas Table 5 quantifies such flows. Wind data was collected to get an initial understanding of its impact on the building. Table 6 shows does show a simplified calculation of the effects wind has on the DEP and it gives hints on its impact on old large industrial buildings with poor insulation. The direction of the wind does have an impact on the plant too, but in this project the actual impact on the temperatures was prioritised.

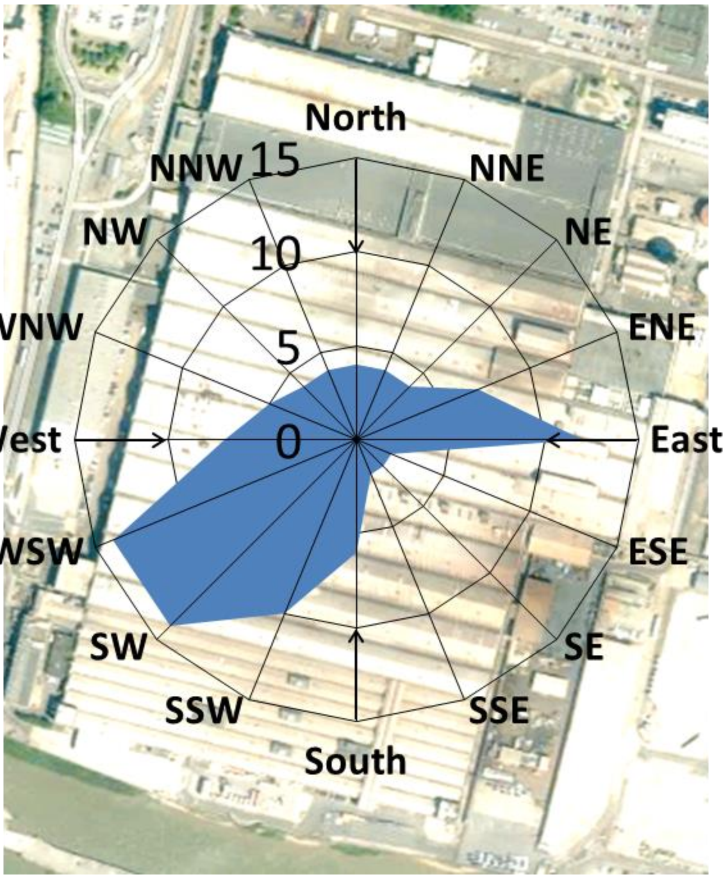


Figure 19: Wind directions close to the DEP measured for a one year period from September 2012 until September 2013. Data collected from the London City Airport, approximate distance to the DEP 7km, by a weather station (www.wunderground.com).

Wind Directions	**Direction Contents (%)**	**Min (ms^{-1})**	**Max (ms^{-1})**	**Avg (ms^{-1})**
North	4	1.03	7.19	3.14
NNE	4	1.03	8.22	3.41
NE	4	1.03	9.25	3.67
ENE	7	0.97	9.78	3.85
East	12	0.64	12.33	4.14
ESE	2	0.64	8.75	3.59
SE	2	1.03	7.19	3.37
SSE	2	0.97	9.78	3.73
South	6	0.64	11.31	4.13
SSW	10	0.64	12.33	4.44
SW	14	0.97	13.39	4.63
WSW	14	0.97	13.39	5.02
West	7	1.03	14.92	4.74
WNW	5	0.64	10.28	3.72
NW	4	0.97	9.25	3.72
NNW	4	0.97	8.75	3.62

Table 5: Wind directions and velocities close to the DEP measured for a one-year period from September 2012 until September 2013. Data collected from the London City Airport, approximate distance to the DEP 7km, by a weather station (www.wunderground.com).

Obsolete building technology and a poor thermal performance of the investigated manufacturing plant lowers the efficiency of the HV system and causes significant heat losses within the building. An Excel spreadsheet to calculate the thermal performance of the roof, utilising the formulas presented in section 2.3.3, was created and results are shown in Table 6. The roof has an approximate surface area of 378,100m^2 including all heated building attachments. If a wind of 3ms^{-1} over the building and an air velocity of 1ms^{-1} under the roof of the plant are considered, the loss over the entire roof is approximately 4.1MW. However, this calculation was made for a flat roof and therefore, simplified the actual heat transfer, but it indicates thermal insulation issues.

	Input Properties	**Input Values**	**Units**	**Calculated Properties**	**Calculated Values**	**Units**
Outside Air data	Temperature of outside Air	7	°C			
	Velocity of outside Air	3	ms^{-1}			
	Density	1.28	kgm^{-3}	Nusselt No.	100,559.48	
	Viscosity	0.0000175	$kgm^{-1}s^{-1}$	Prandtl No.	0.72	
	Specific Heat	1,002	$Jkg^{-1}K^{-1}$	Reynolds No.	184,320,000.00	
	Thermal Conductivity	0.0245	$Wm^{-1}K^{-1}$	Heat Trans. Coef.	2.93	$Wm^{-2}K^{-1}$
Inside Air Data	Temperature of inside air	20	°C			
	Velocity of inside Air	1	ms^{-1}			
	Density	1.2	kgm^{-3}	Nusselt No.	38,336.86	
	Viscosity	0.00001822	$kgm^{-1}s^{-1}$	Prandtl No.	0.71	
	Specific Heat	1,003	$Jkg^{-1}K^{-1}$	Reynolds No.	55,323,819.98	
	Thermal Conductivity	0.0256	$Wm^{-1}K^{-1}$	Heat Trans. Coef.	1.17	$Wm^{-2}K^{-1}$
Roof Data	Surface Length	840	m			
	Surface Width	450	m			
	Thermal conductivity	43	$Wm^{-1}K^{-1}$			
	Thickness	0.003	m			
Heat Transfer Rate					-4,105,541.74	W
Energy Per Day					-98,533	kWh

Table 6: This is an Excel calculation table which shows the thermal performance of the roof of the investigated manufacturing plant. It describes the heat transfer rate through the roof considering the external air velocity, the size of the roof, its insulation (including thickness of the roof), the internal air velocity and external and internal temperature.

Figure 20 was derived from three of the fixed continuous temperature loggers at the DEP. The first sensor T_{out} was fixed at the north side next to the engine plant to measure external temperatures. T_{Lynx} collected temperatures in the middle of the plant at the grid location P-

29 in an area where the Lynx engine was machined. Approximately 150m further south, but still close to the plant middle T_{Tiger} was fixed into an area where the Tiger engine is machined at the grid location H-31. These temperature loggers were chosen to represent averages of the plant during day and night.

Over the months the average outside temperature changes whereas the inside temperature is maintained constant within certain limits. The standard statistical error and the error of the temperature sensors of ±0.2°C were considered. With a sample number of approximately 4320 samples a month and an approximate average temperature of 20.66°C the standard statistical error has a value of 0.31°C. Hence, the total error is approximately ±0.36°C. In this experiment human errors were neglected because the fixed sensors system collected data automatically without human interference. However, it can be seen that the external temperature average dropped over the month while the internal temperature was held relatively constant by the HVAC system. The internal average temperature difference between summer and winter was less than 3 degrees. In general, the external temperature has a large influence on the internal temperature and the only way to account for that in such a large building is the HVAV system.

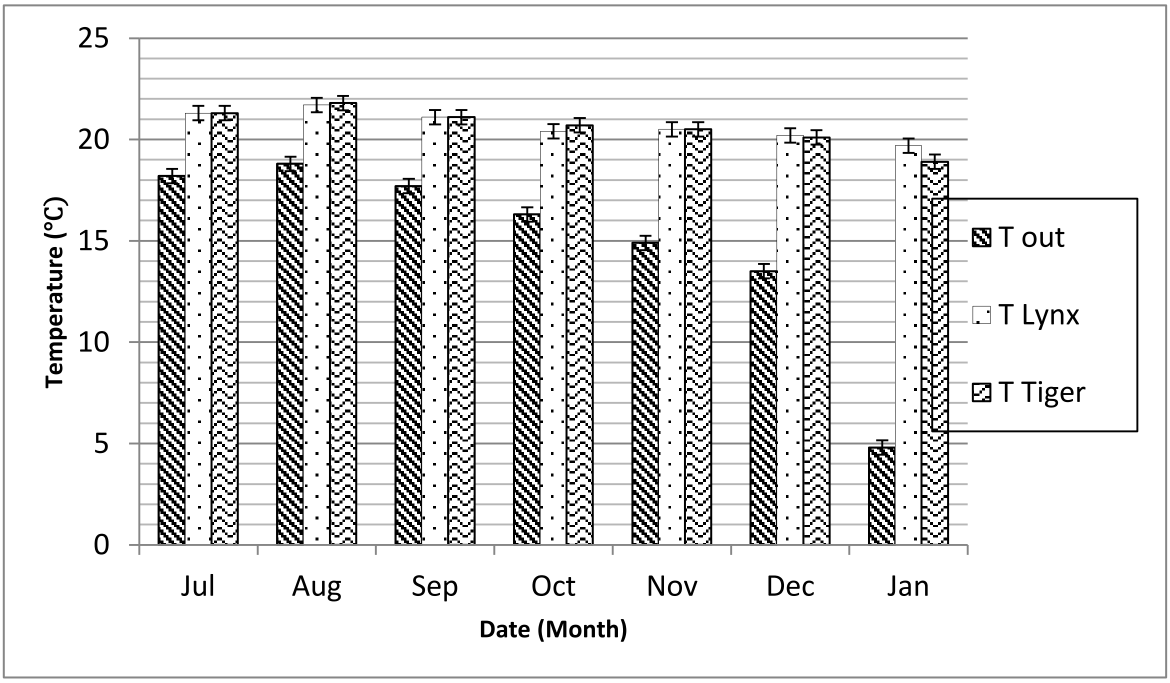


Figure 20: Temperature averages collected by fixed temperature data loggers outdoors, in the Lynx machining area at the internal grid location P-29 and in the Tiger machining area at the internal grid location H-31.

Figure 20 could be misleading because it shows average temperatures. Night-time temperatures are colder than daytime temperatures, so average temperatures seem to be close to an acceptable 19-20°C in winter months. Temperatures collected by the "Mobile Data Collection System" are shown in Figure 21. These temperatures were only collected during daytime; hence they are generally higher than average temperature readings of continuously logging sensors.

As previously mentioned the optimal working temperature for employees and machines in such a manufacturing plant, shown by a line in Figure 21, is 19°C. This graph shows that temperatures are generally higher than this plant optimum, by more than 2°C. Errors were considered as the standard statistical error in addition to the error of the temperature sensors of ±1.5°C. With a sample number of approximately 20,000-25,000 samples a month and an approximate average temperature of 22.45°C the standard statistical error is 0.14°C. Hence, the total error is approximately ±0.36°C. Other issues such as human errors or experimental mistakes were considered and experiments were organised by fixed procedures, such as explained in section 5.2, to reduce such faults to minimum. The actual values of such human errors were neglected due to a significant amount of sample in this average calculation.

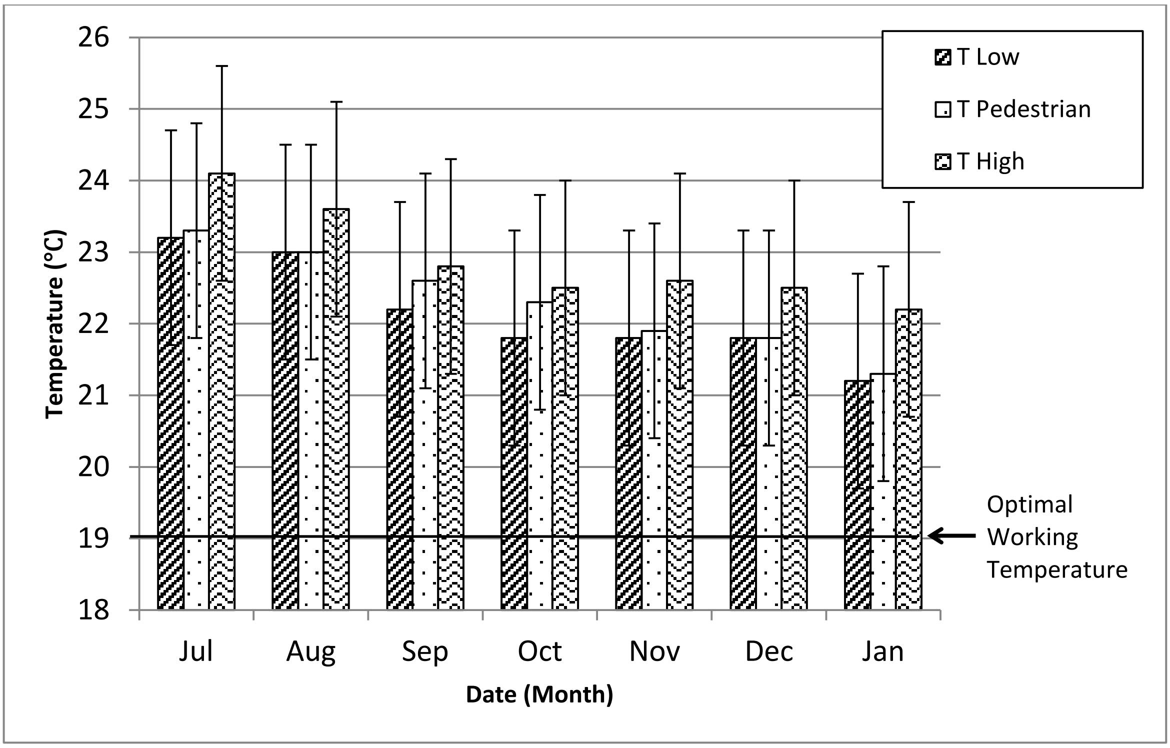


Figure 21: Temperature averages collected by the "Mobile Data Collection System" across the entire DEP at T Low at a height of 0.15m, at T Pedestrian at 1.35m and at T High at 4.5m.

This finding raises two questions:

- How much does it cost to heat the DEP by one degree Celsius per day?
- How much heat is actually generated by the HV system and how much contribution is from other components, such as machines, to the heat generated in this manufacturing plant?

The manufacturing plant has a total air volume of approximately $1.9489 \times 10^6 m^3$ with an average temperature just above 20°C. If the temperature would be changed by 1°C the following amount of energy ΔQ would be required. The heat capacity c and the mass m at 20°C are known or can be calculated.

$$\Delta Q = c_{20} m_{20} \Delta T \tag{17}$$

$$\Delta Q = c_{20} \xi_{20} V_{20} \Delta T$$

$$\Delta Q = 1.005\frac{kJ}{kgK} \times 1.205\frac{kg}{m^3} \times 1.9489 \times 10^6 m^3 \times 1K$$

$$\Delta Q = 2{,}360{,}166.6225 kJ \approx 2.36 GJ$$

In theory 2.36GJ would is consumed if the plant heated by 1K, however, this calculation does not take efficiencies or leakages into account. Hence, the actual heating cost has to be calculated in a different way.

The heating system had been switched on, on the 10th of October in 2012. It was turned on late because of repair and maintenance work. Due to this late HV system usage conditions before the heating was switched on were similar to those afterwards. These circumstances made it possible to compare conditions in the three weeks before the HV system was switched on with those three weeks afterwards. Figure 22 shows a time line explaining this scenario. The heating cost for October is known which makes conditions during both time periods comparable.

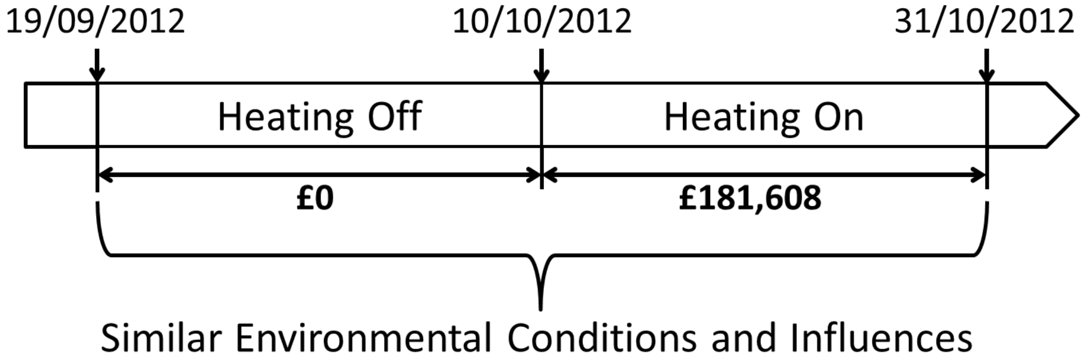


Figure 22: Time line over 42 days, comparing the heating cost and conditions for the first 21 day period and the second 21 day period in the DEP.

Because of similar conditions external temperatures could directly be compared with internal temperatures for both time periods as shown by Figure 23. The line with circular markers shows internal temperatures without the HV system in operation, whereas the line with squared markers shows internal temperatures with the HV system in operation. The temperature difference between those lines is visible. Figure 24 shows the actual difference of these lines shown in Figure 23. The average temperature variation is 2.84°C. Relating this figure to the cost of the HV system in October, the cost impact of the HV system becomes transparent.

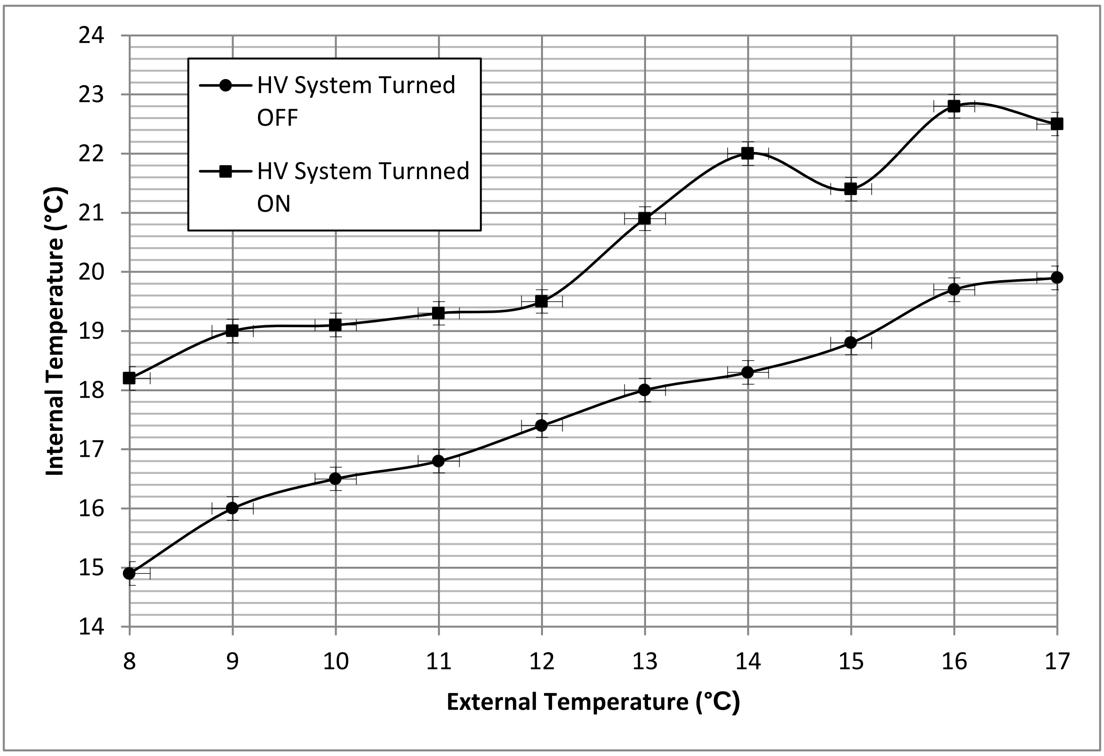


Figure 23: Comparison of external temperatures (x-axis) and internal temperatures (y-axis) in the DEP when HV system was switched off and switched on over a period of 42 days, 21 days from 19/09/12 to the 10/10/12 switched off and 21 days from the 10/10/12 to the 31/10/12 switched on.

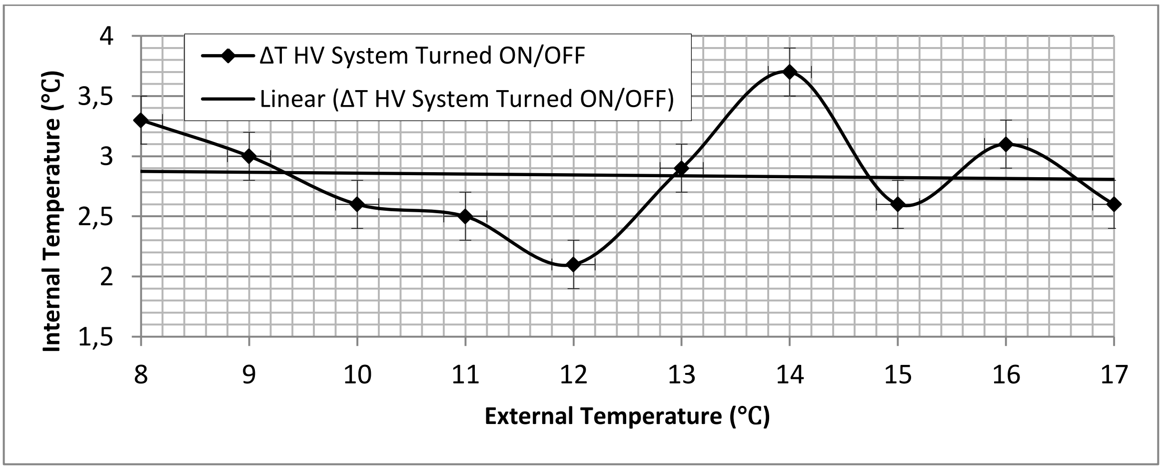


Figure 24: Internal temperature difference in the DEP when HV system was switched off and switched on over a period of 42 days, 21 days from 19/09/12 to the 10/10/12 switched off and 21 days from the 10/10/12 to the 31/10/12 switched on. External temperatures (x-axis) and internal temperature difference (y-axis).

Three weeks = 21 days, i.e. $\frac{£181,608}{21 days}$ = Cost per day = GBP 8,648 per day.

The average temperature raise by the heating system is 2.84°C.

$\frac{£8,648}{2.84°C}$ = GBP 3,045 per day per °C.

This assumption is an approximation due to measurement errors and other environmental factors and influences (for example radiation of the sun, wind chill effects, production breakdowns, management differences, etc.), but if the heating system inputs one degree Celsius into the plant it costs approximately GBP 3,045 per day. It can be summarised that in case the DEP would not be overheated at daytime, a large amount of energy and consequently heating cost could be saved. However, and unfortunately, a simple reduction of heating could create comfort problems; if the temperature in the manufacturing plant would just be lowered by an average of two degrees Celsius, some areas of the DEP might be well below 19°C. This means a more uniform temperature distribution across the factory has to be ensured to be able to decrease the average temperature.

To be able to visualise, temperature distribution maps across the factory were created by data from both temperature logging systems, the "Mobile Data Collection System" and the fixed sensor system. Both systems have different advantages and disadvantages in creating temperature distribution maps. These maps also were developed with different data reduction techniques; nevertheless, both sets of maps indicate the thermal condition and problems across the manufacturing plant.

Errors within the temperature maps are known as ±1.5°C for the mobile data collection system and $\pm 0.36^{o}$C for the maps with the fixed sensors. For the fixed sensors that is the total amount of error (including statistical and human errors) due to the fixed and automatic technique of data collection. Further errors for the mobile data collection system were neglected due to visualising issues, since at any point a different amount of data was collected. However, temperature maps were created to show trends and temperature pattern within the manufacturing plant and not to exactly recreate temperatures. For this reason, errors were acceptable.

The first two sets of maps were created by data of the "Mobile Data Collection System". Summer and winter conditions were observed due to different external temperatures and therefore different technical management strategies. The main management differences occur in winter, with the HV system is running, while in theory the doors are closed, whereas in summer this HV system is switched off and the doors are often open to allow air circulation. The internal conditions were recorded within two varying ranges of external temperatures, 5°C to 10°C for average temperatures in winter and 18°C to 23°C for average temperatures in summer. Due to continuously changed measurement locations, i.e. between 120 and 150 data points across the DEP, the measurement grid of these maps became an advantage of the data from the "Mobile Data Collection System". Moreover, this system collected temperatures at four different heights, 4.50m, 3.00m, 1.35m and 0.15m; hence the distribution could be presented for all these varying levels of height to point out the spatial temperature distribution instead of a single level. All measurements were linked to the time of measurement. Once this data input into the database, it could be linked to external temperatures at the same time (±10min), which were collected by an independent fixed sensor, with an approximate accuracy of ±0.36°C, at the north side of the manufacturing plant (direct sun influences were avoided by the shadow of the north wall). Apart from inconsistent measurement locations disadvantages were caused by limitations of free movement and safety issues. In many cases data points on production lines are missing due to accessibility restrictions for the measurement rig. This applies also to safety areas with a lot of vehicle movement.

Figure 25 shows the first set of these temperature distribution maps at summer conditions. The contour outlines have been chosen from 17°C to 27°C in 10 increments. Besides minimal and maximal temperature, the contours towards the "optimal temperature" of 19°C are marked as well. First peculiarities are persistently high temperatures, as already indicated by previous statistics. The top temperatures were recorded at P_1, the lowest readings at P_2. In reality, both areas are larger than shown on this map. Next to the lowest temperature spot is a safety zone, which was not accessible for measurements. The highest temperature zone is in reality larger too, but due to tight machinery environment it is difficult to reach. Apart from these maximum and minimum zones, there are slightly lower temperatures around 20°C at P_3, caused by the high roof, reaching up to 25m above floor level. Due to natural convection warm air rises with in buildings. This effect is attributed to the expansion of heated air and evaporated water molecules, decreasing the density of this gaseous fluid mixture and creating buoyancy against gravity. The temperature distribution map in Figure25 a) shows higher temperatures than those of lower levels b), c) and d). As a result, cold air from lower levels flows into the lower pressure areas below the rising warm air and causes a colder bottom layer shown in Figure 25 d). Cold air, from P_2 and P_3 for example, is pulled into warmer areas because of generated and natural convection processes. In some areas, such as P_4 at 3.0m of height, readings show specific temperatures caused by forced convection of diffusors of the HV system, but, in general, the temperatures increase with height.

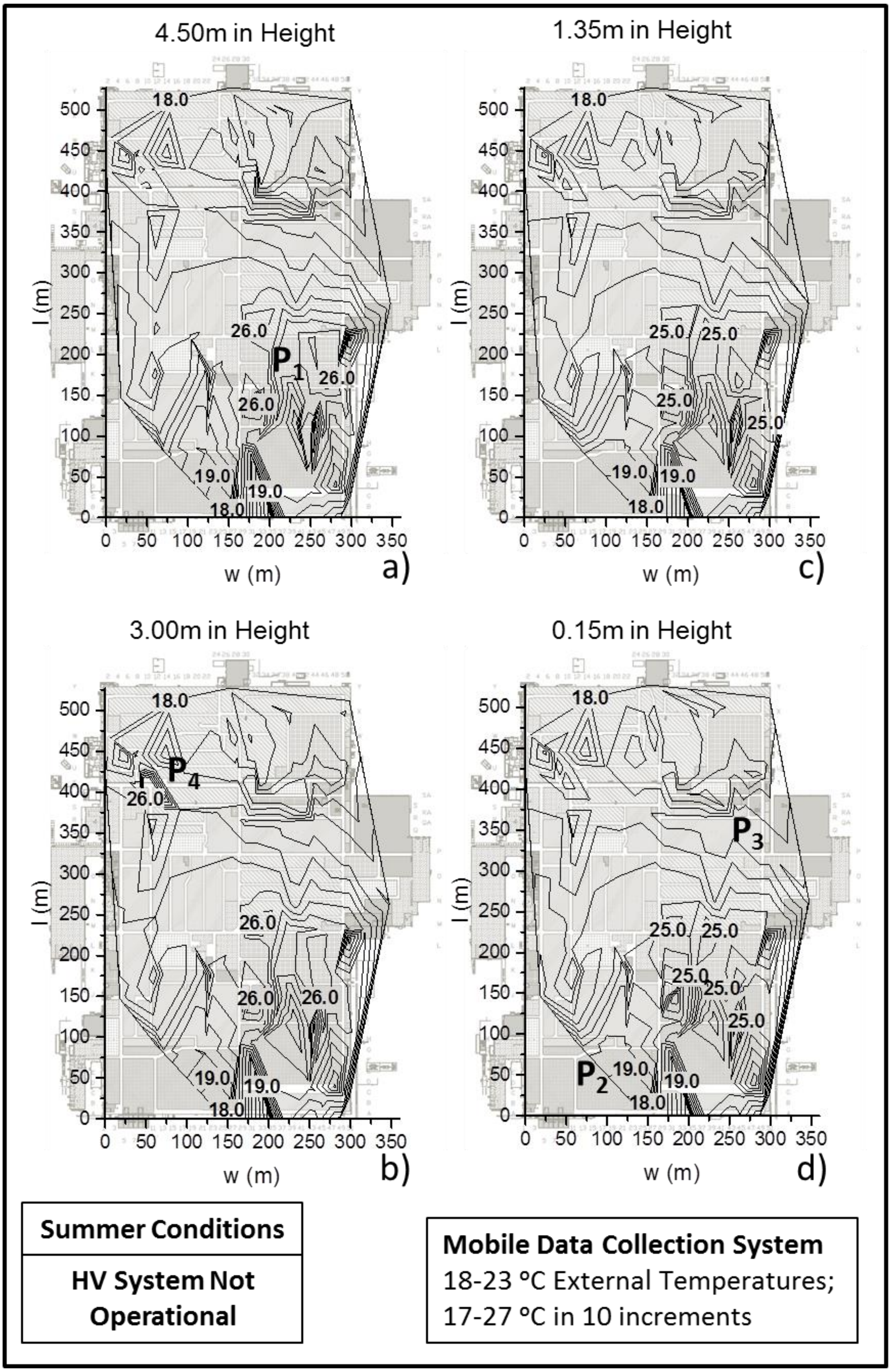


Figure 25: Temperature distribution maps in summer condition in varying levels of height, constructed with data gathered by the "Mobile Data Collection System"

Using the same method, temperature distribution maps for winter conditions are shown in Figure 26. In this case the maps are set up with contours from 15°C to 25°C in 10 increments. At a first glance, the manufacturing plant seems to be too “warm” compared to the previously defined “optimal temperature” of 19°C. A cold spot P_5 can be found in approximately the same region as before, showing a slight tendency towards the north of the plant, because of a major difference between internal and external temperatures in winter. This rise forces a faster convection current which enters further into the building. Colder temperatures in this area are caused by loading gates which are often left open during operation. There is another region at P_6 that tends to be colder, at the west side of the plant, which is caused by shipping doors. The previously mentioned hot spot at P_7 has a slightly different shape, but is still approximately at the same place. The differences in shape are caused by varying measurement points across the manufacturing plant. This particular production line generates a lot of heat and the airflow seems to be stagnant in this area. There is another hot spot P_8 at the eastern north side of DEP. In this part of the plant the roof stays below 10m in average. The machines heat up this area faster. In this area the hot spot is only caused by the low roof but the air is not stagnant. The hot area is slightly shifted to the west in map d) at low heights compared to a). The reason for this temperature shift is that colder air from leakages from the eastern side wall flows through the bottom layer of the machining line, creating convection current towards the west.

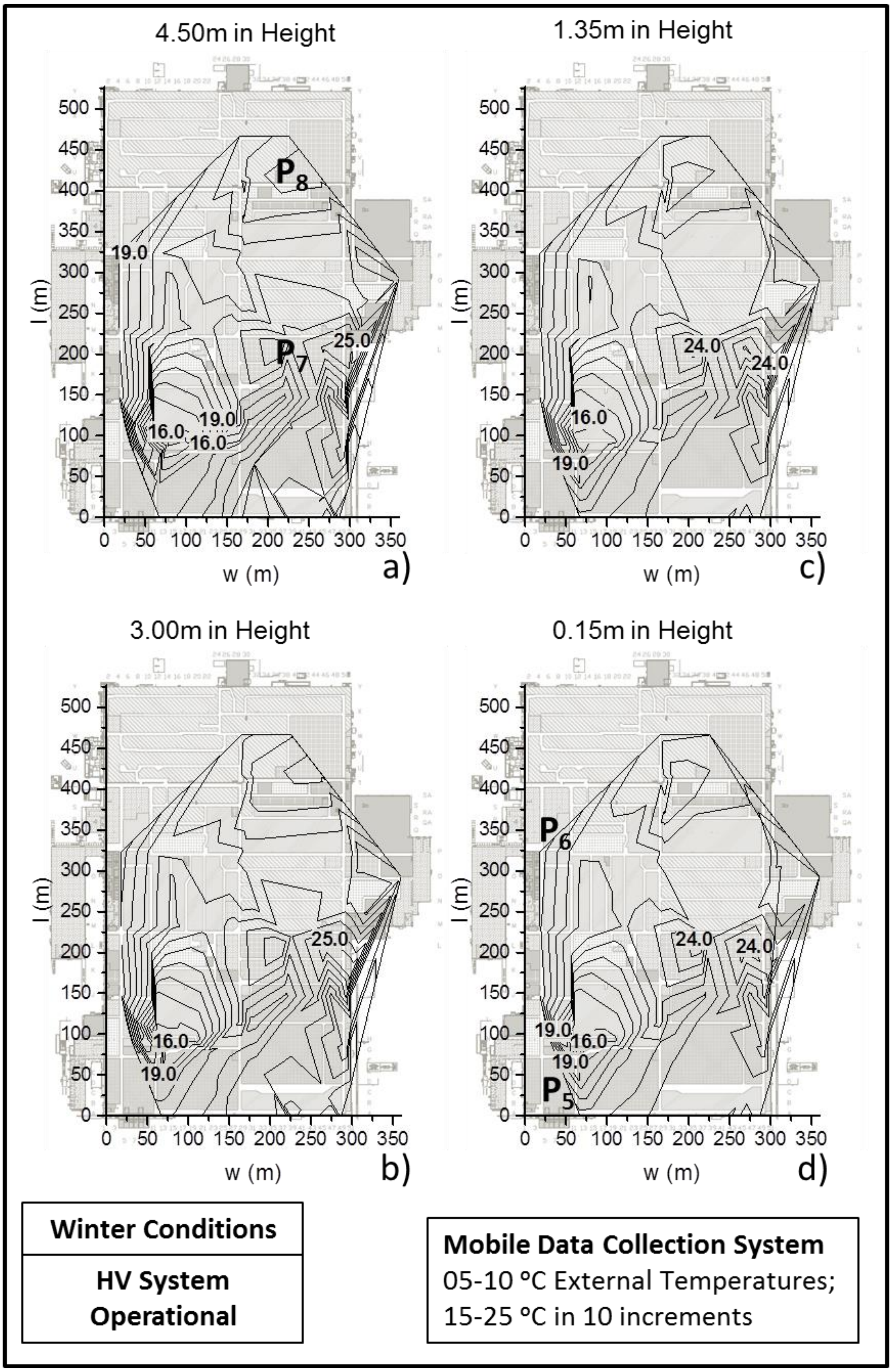
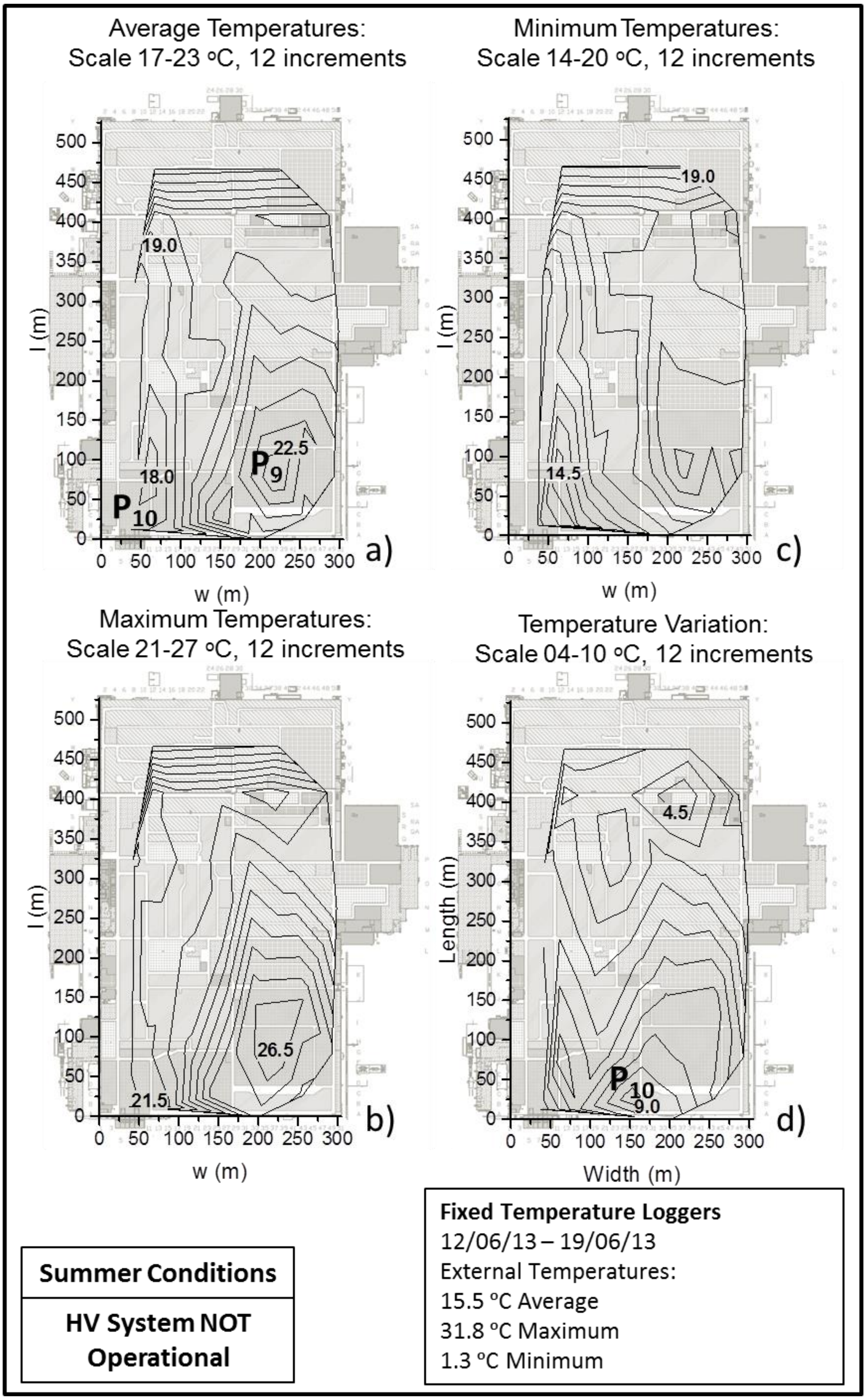


Figure 26: Temperature distribution maps in winter conditions for varying levels of height, constructed with data gathered by the "Mobile Data Collection System"

These maps indicate issues within the DEP. However, only averages are shown and the data point locations are inconsistent in case of comparing summer and winter conditions. Therefore, another set of temperature distribution maps was created by obtained temperature data of the fixed sensor system. In this case the temperatures were logged continuously over a time frame of one week, and then averages, maximum and minimum, as well as temperature variation were recorded. The advantage of this system is continuously gathered data that was not only used to show averages, but also minimum and maximum conditions. This system is also able to show temperature variation for the detection of further problem areas. Fixed sensors are not restricted by problem areas or safety zones. Once a logger has been installed, it collects temperatures regardless from any operational issue, which is another advantage. The disadvantages of this system are the low number of 28 data points for the entire manufacturing plant and all sensors indicate temperatures only at one level of height. Apart from that, these maps have different scales and the colour scheme cannot be directly compared with each other. The varying contour information is listed on top of every map because of this reason.

Figure 27 shows a set of maps with data collected by the fixed sensor system at summer conditions. Data was chosen for a typical summer week from the 12/06/13 to the 19/06/13 to produce this map. In all three maps, showing average, maximal and minimal conditions, the same pattern is indicated, in spite of different temperatures. In general, the pattern is similar to the other data collection system, but the hot spot at P_9 is shifted further to the south due to fixed sensors on this production line.

The ceiling's height of this area is between seven and ten meters, so high temperatures are generated by the production line. This production line has many machines which create heat. Due to access advantages of this data collection method this hot spot can be monitored in more detail. The issues with the loading gate at P_{10} show a greater impact towards the north of the engine plant. This can be explained by a lower production of the old "Lynx" engine line which has been completely stopped shortly after this chosen evaluation week. However, one of the warmest areas at P_9 is right next to the coldest area of the plant P_{10}. This creates problems such as convection current and strong temperature variations between these areas. The temperature variation in Figure 27 d) shows the difference between maximum and minimum, which indicates the biggest changes between the cold spot at P_{11}. Temperature differences in this area amounted to more than 9°C within one week only. This causes not only problems for the comfort of employees, but also affects the entire machinery environment in an area with lots of temperature sensitive CNC machines, which cost time and money. Moreover, the hot spot in the maximum temperature map b) shows temperatures above 26.5°C. Machines in this area run though cooling cycles which slows down production and employees are exposed to height temperatures. In standard operation the HV system is completely switched off and fresh air supply is only secured by open doors and windows. As this supply is not controlled, temperatures randomly adapt to zone conditions and show no uniform heat distribution across the manufacturing plant.



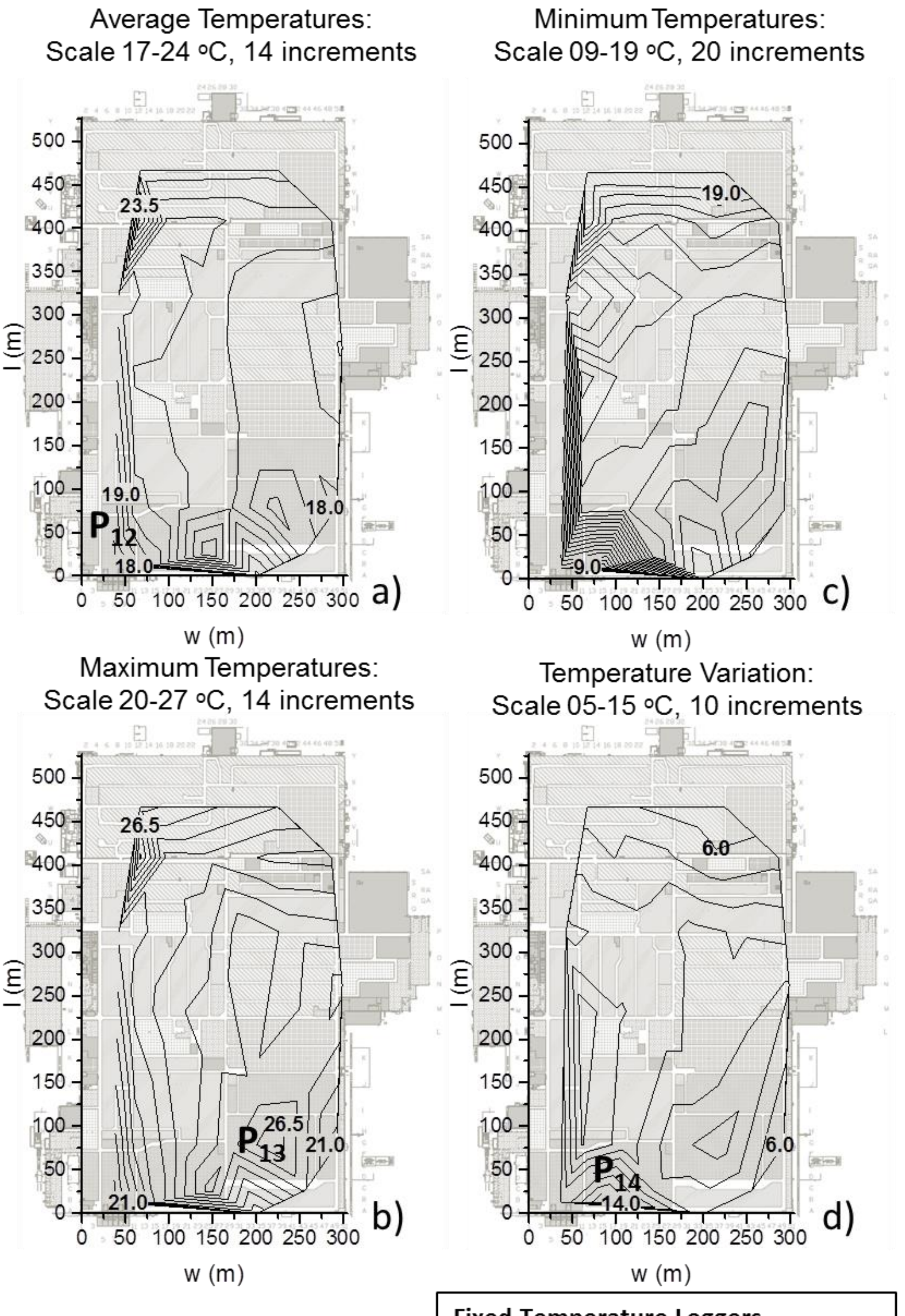
Summer Conditions

HV System NOT Operational

Fixed Temperature Loggers
12/06/13 – 19/06/13
External Temperatures:
15.5 °C Average
31.8 °C Maximum
1.3 °C Minimum

Figure 27: Temperature distribution maps showing average, maximum and minimum conditions and a temperature variation map for summer conditions constructed with data gathered by the fixed logger system

Temperature distribution maps for winter conditions from the same system are shown in Figure 28. A typical week for winter conditions from the 13/03/13 to the 20/03/13 was chosen to create this set of maps. In average temperatures seem to be more uniform than in summer. In winter the HV system is running; hence the heat distribution can be partly controlled. Apart from the cold spot at P_{12}, temperatures would be uniform enough to lower by two degrees in average which would save energy and lower the carbon footprint. However, even more significant would be the improvement of peak temperatures especially in winter; peak temperatures such as in Figure 28 d) could be controlled and easily reduced. Temperature surpluses are often caused by a combination of full production and external sun radiation. The maximum map shows temperatures above 26.5°C at P_{13}. The situation of temperature overshoots could be avoided by monitoring weather forecasts and controlling temperatures on time. On the other side the map c) shows the minimal temperature distribution across the engine plant and detected temperatures below the required 19°C. Low temperatures are created by a number of factors such as low outside temperatures, leakages, low production periods and lack of HV system controls. At low temperatures machines have to run heat up cycles which slows down production as well. Another area of interest is indicated by the temperature variation graph in Figure 28 d). The temperature difference varied more than 14°C at P14 within only one week of the frame of temperature variations. This area spreads along a production line with many sensible machines, causing production restrictions due to adjustment periods.



Winter Conditions

HV System Operational

Fixed Temperature Loggers
13/03/13 – 20/03/13
External Temperatures:
5.3 °C Average
9.8 °C Maximum
-0.4 °C Minimum

Figure 28: Temperature distribution maps showing average, maximum and minimum condition conditions and a temperature variation map for winter conditions constructed with data gathered by the fixed logger system

To be able to secure a more uniform temperature distribution within the DEP, leakages have to be reduced. The biggest amount of leakages in such an old mega-factory is caused by insulation issues across the entire engine plant. To insulate the entire building would be far beyond any planned budget possibilities. But there are other leakages, which could be reduced in a quite cost effective manner; Apart from insulation problems, the transport of machines, components and products created a great amount of leakages in the DEP.

Figure 29 shows temperature measurements logged by the fixed sensor logging system. These sensors were chosen to further observe temperature effects of loading gates within the factory compared to a stable temperature at the plant middle. This particular loading gate is at the south wall of the DEP. Directly after the loading gate there is a transport and storage area, but next to this area are machining lines with temperature sensitive CNC machines. Figure 29 monitors temperatures (probes are approximately at a height level of 1.7m) over the time frame of approximately 2.5 days. The line with black squared markers shows data of the probe closest to the loading gate (approximate distance 10m) whereas the line with the black circular markers represents smooth temperature measurements at the middle of the plant (distance between the location B-07 and M-26 is approximately 250m). In the middle of this manufacturing plant the temperature curve varies only slightly over the course of a couple of days whereas the gate area is constantly affected by temperature drops of up to five degrees Celsius. B-15 is a probe (distance between B-07 and B-15 is approximately 50m) at a machining line, thus suffering unstable temperatures due to this leakage problem. At the grid location G-11 (distance between B07 and G11 is approximately 70m) these temperature drops are still widely affecting the area as far as to the sensor location at G-19 (distance between B07and G-19 is approximately 100m), being behind one of machining lines, decreasing the effect by airflow blockage and separate heat inputs by the VH system and machines. Apart from discomfort issues and an unstable machining environment, these loading gates are a major cause of temperature drops in large areas, adding to the insulation problems of the walls and the roof.

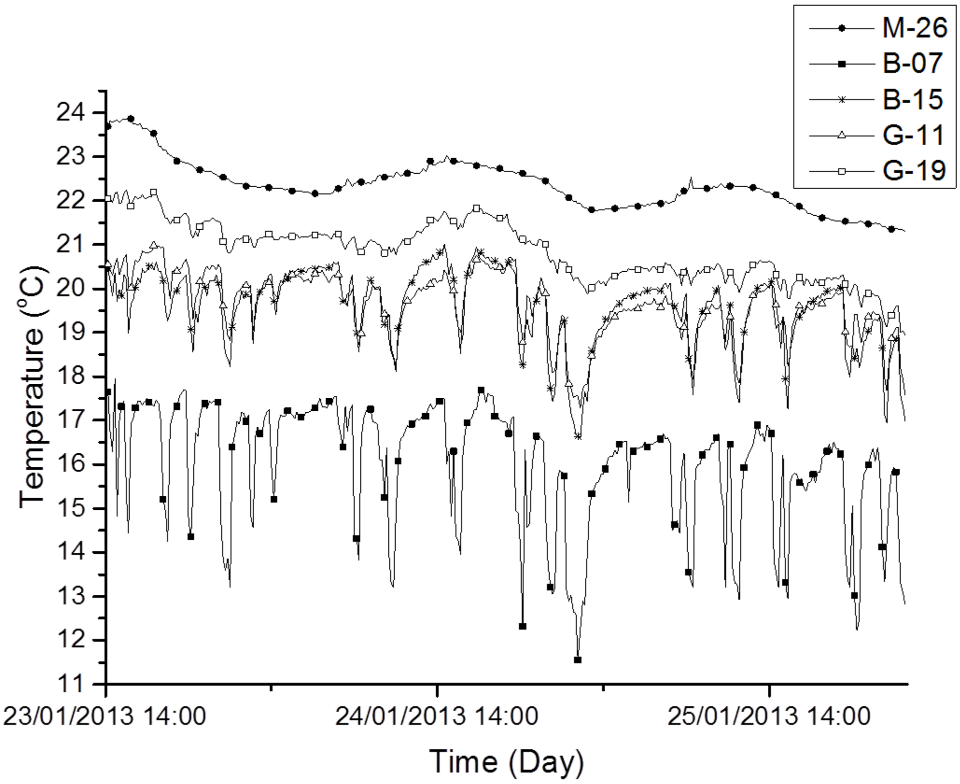


Figure 29: Temperature variation at fixed grid locations for gathering temperature drops across the DEP created by loading gate operation due to transport processes. Sensor locations G-11, M-26, G-19, B-15 and B-07 were chosen to observe this problem.

If this kind of leakages would be decreased, the overall average temperature could also be decreased due to a more uniform heat load across the manufacturing plant, saving energy and heating cost. Apart from savings, comfort of employees and the machining environment would additionally be improved, optimising operation and production processes across the factory. Earlier attempts of reducing leakages at this loading gate were inefficient due to significant design issues.

Double doors were installed, but these gates are not used efficiently since most of the time both doors are open during loading processes. These gates are too slow and proper handling would cost employees valuable time which would cost the company money. If these would be replaced with secure high-speed gates, operation could progress in a more effective manner. However, besides technical solutions, managers have to be aware of unnoticed impacts of problems such as this one and have to consequently eliminate such deficiencies as much as economically feasible. But not only manager awareness by itself, but also employee mentality, effective temperature monitoring, energy loss analysis, communication and technical improvements can strongly support low carbon policies within mega factories such as the Dagenham Engine Plant.

5.5 Conclusion

Lot of energy is used in large manufacturing plants to maintain the production environment in optimal condition. The heating cost of the mega factory which was evaluated in this study can amount to more than 26% of the utility bill. Besides innovative and expensive technological improvements of building construction and HV systems, cost effective solutions can sustainably reduce the energy consumption of such a factory.

For this purpose, thermal data was obtained to understand and analyse thermal problems in the plant. To obtain environmental changes over the seasons a minimal period of half a year was proposed. This period was found to be optimal and can be recommended for similar studies in the future, because all the most important temperature changes across a year were successfully recorded. A longer period could probably be valuable too, because various years could be compared with each other, but for the dependence between internal and external temperatures it would probably only bring few new findings. Averages over the years or checks on improvements of new implementations would be possible.

The application of a "Mobile Data Collection System" may be time consuming, valuable data within the building were acquired, especially considering its low cost construction. The actual data collection methodology with the mobile measurement rig was complex and had to be constantly adjusted to variations, such as blocked routes, production stops, HV System changes or accessibility restrictions, in the industrial live environment, but the technique was found to be convincing and open for possible changes. Especially in use for creating temperature distribution maps the system showed great potential, due its ability of collecting at as many location as required. Within a building of this size the number from 120 to 150 sample location seemed to be feasible and showed great detail in analysis. The disadvantage in an industrial live environment comes with restricted zones and other inaccessible locations were no data can be collected.

Also, airflow measurements were collected to obtain further ideas about the environment, but a lot of issues were created by the sensors and collection technique. It was established that impact of internal airflow movements depend on too many factors, such as open doors, open windows, temperature differences, leakages, external airflow currents and diffusors. The techniques applied were not able to collect all these details for the entire manufacturing plant in its full complexity at the same time. Furthermore, average analysis was not possible, due the usage of airflow vectors; hence the data is not only harder to handle, but also brings less possibilities for comparison over long term periods. This part of the study has great potential for future projects and identifies issues, which have to be considered up front.

The collection of the humidity data was successful but was mainly used for the actual production optimisation (consistency of fluids, different kind of glues or lock thighs) which is not subject of this study. However, future work could consider the human comfort in industrial environments. For that purpose, this data might be significant and can be recommended to be used as described even when the reaction time of the hair hygrometer was low.

The fixed sensor system was more expensive in hardware, but once they were fixed to their locations, data was collected automatically and problem areas could be monitored continuously. The system reliably collected data over the course of a half a year. This collection technique allowed a comparison between all sensors at the same time with ease. The system was also found ideal for a leakage impact analysis of open doors. The system was able to simultaneously pick up data from different locations within the plant, which showed weaknesses around loading gates. Furthermore, the system could be left installed for live use in the future. Hence, all temperatures can be constantly monitored by the responsible employees to be able to adjust HV System temperatures towards optimal condition. The weakness about this system was found in the price. Costs and budget restrictions enforces a measurement grid coarseness within such a large sized building.

The methodology to overcome this issue was the usage of two independent systems. Both systems were useful and can be applied with their own advantages, but in industry the fixed sensors might be more optimal due to its automatic data collection ability and continuous monitoring. The application of a database for the storage and analysis of such large data sets is highly recommended to the practicing engineer. Data was stored in different tables where it could be manipulated and reduced to compact data sets for visualisation. Furthermore, these tables were compared and correlations between all data sets were found with ease. However, if less data is collected programs such as “Excel” or “Minitab” for example may be more effective.

In case of the observed factory with a size of 183,243m^2, heating cost can exceed GBP 500,000 a month in winter. The average daytime temperature was found to be 2-3°C higher than necessary over the winter months due to poor temperature distribution within the plant. To heat the plant by 1°C per day costs approximately GBP 3,045.00. In addition to major insulation issues, leakages at loading gates create an unstable thermal environment over large areas of the factory. Also properties such as external airflows have an impact on the internal environment. A simplified calculation showed that 98,533kwh per Day is lost via the roof if the wind speeds is approximately 3ms^{-1}.

Lager unused spaces within the factory are colder as they have no heat output from machines and could create convection currents. This leads to an unstable temperature environment which not only creates many comfort problems, but also slows down temperature sensitive CNC machines which require frequent recalibration thus creating time loss and large additional power costs due to adjusting cycles of such equipment.

All older factories of such a size have thermal problems, but such a case study can help finding core weaknesses, which can be common to buildings with common characteristic and support potential improvements. Cost effective solutions, such as safe high-speed doors, awareness of where and how thermal losses occur, continuous temperature monitoring and communication between HVAC system operators and other factory users can create a more uniform temperature distribution for a more stable manufacturing environment. The average temperature within the manufacturing plant could be reduced by adequate measures and the comfort for employees and the machining environment could be simultaneously improved to guarantee a stable operation and a lower carbon footprint to meet the targets of low carbon emissions.

Chapter 6

6 CFD Simulation Model

6.1 Introduction

This chapter presents a CFD simulation approach of a large manufacturing plant to further understand its internal thermal environment. The building including all internal components was modelled to evaluate energy wastage. Due to computational constraints various assumptions, such as for example simplification of geometries, averages of surface temperatures, simplification of leakages or steady state simulation, were made to simplify the model. A validation process against data collected by both of the earlier mentioned collection systems proved the model reliability within a desired accuracy. The model had to be accurate enough to realistically simulate thermal plant behaviour and fluid flow, but had to still allow feasible simulation times within computational limits. Once the model reached the required accuracy analysis of the data showed interesting thermal behaviour, which could be utilised to further design cost effective engineering solutions the reduce energy consumption by adequate measures.

6.2 Support and Management

Due to the size and the complexity of the engine plant the model development was split into groups shown by Figure 30. The project initialisation and the planning process were made by author who was the project leader. The actual CAD model construction was shared between all parties Ford, Autodesk and author. Ford and the project leader set up the layout, the building shell and most relevant components within the DEP, such as HV system plant rooms, diffusors heating ducts, separate heating units, lights, offices or other room facilities and machines. Autodesk helped out with three-dimensional drawings of machines and the extraction bars and the AutoCAD to Inventor conversion. Autodesk also simplified the model in close cooperation with Ford and the author to be able to simulate the model within a reasonable accuracy and timeframe. Once the Inventor model was constructed it could be simulated in Autodesk CFD. All input data and boundary conditions were collected by the author in cooperation with Ford, but it was simulated by Autodesk. All simulation results were pre-analysed in cooperation between Autodesk and the project leader, but the validation and adjustment inputs was worked out by the candidate. The actual model adjustments were made by Autodesk with the lead of the author. Once the model was validated the model was analysed and graphs were developed in the team of the University of Greenwich, Autodesk and the Project leader.

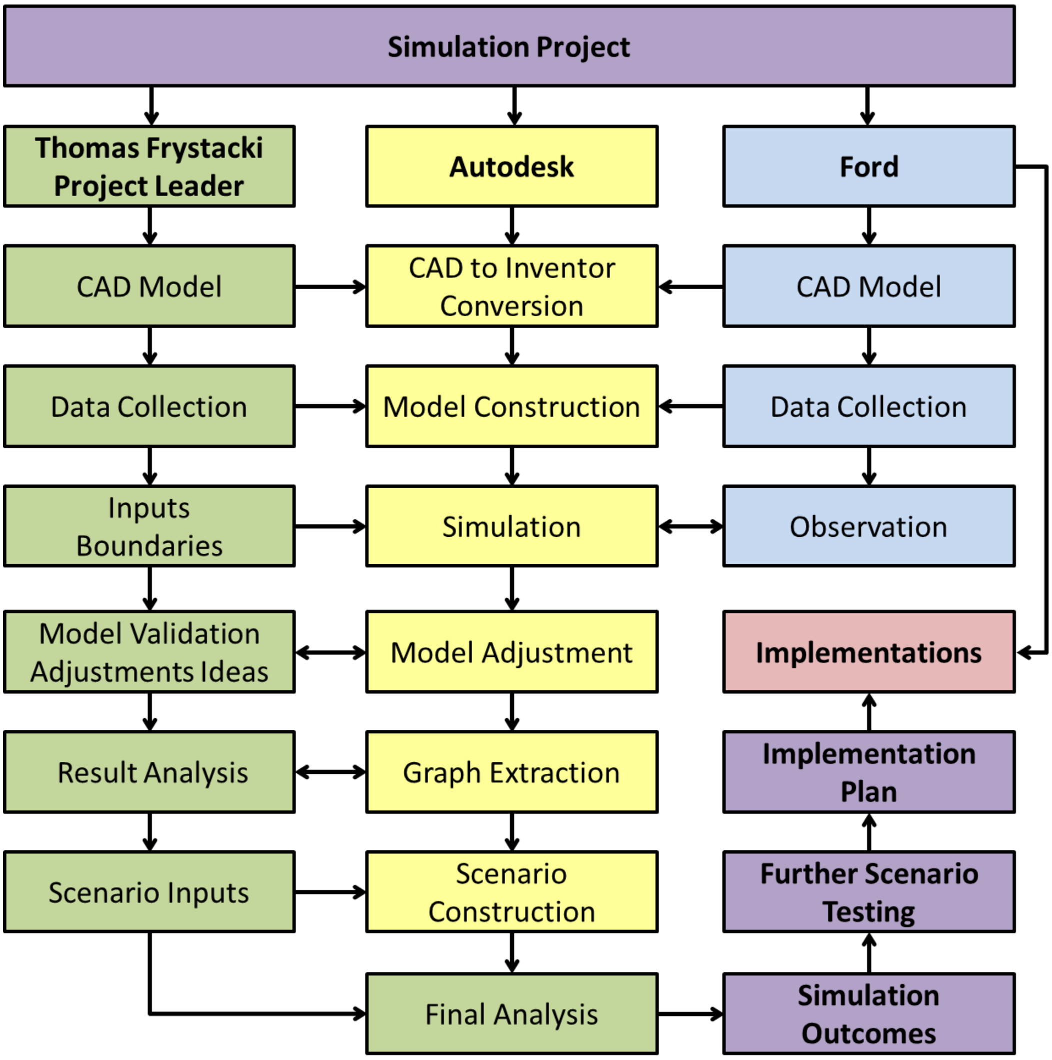


Figure 30: CFD development team and their inputs in design, construction and analysis.

6.3 Model Construction

"AutoCAD" was used to create the surface and solid blocks of the plant building with all components such as HV systems, machines, machine extraction systems, lights and leakages built into the model. Appendix C shows the initial CAD model including all these components. The "AutoCAD" model was then converted to an "Autodesk Inventor" model and input into "Autodesk CFD". There is software on the market capable of performing such simulations, but integrating 1,978 parts with 21,300 surfaces is not an easy task. "Autodesk CFD" was selected due to its suitability in simulating such problems. The software is capable to load three dimensional CAD drawings to a CFD solver which allowed the creation of a factory model to solve for different variables. One of the advantages with the Autodesk software also was that an AutoCAD model, which could be converted into a useful model foundation, already existed in two dimensions, rather than starting from scratch. Furthermore, Autodesk markets their products free for academic use, which made their product even more suitable for a low budget university projects.

The full "Navier-Stroke" equations with the standard k-ε turbulences model were solved over the domain in a steady state. The k-ε model was used as it performed reasonable well in similar studies, as was shown by Magdalena Hajdukiewicz in 2013 (Hajdukiewicz et al. 2013).

Test simulations of various components of the plant were made to understand to effects of simplification. Some of these test runs are shown in Appendix E. One example was made for the lights. Appendix E shows the effects of such simplifications. Differences can be observed, if only one double light fitting is shown. However, if many lights are shown in a room or building, the actual differences are close to negligible. For that reasons such simplification are an effective method, which enable more complex simulation models.

Initially, a uniform grid was used then refined in areas of interest, especially close to wall boundaries and openings in the building. When the mesh is not fine enough, simulation results would decrease in accuracy. On the other hand, if the mesh is chosen too fine, simulation times would increase significantly. Especially in areas of the model with greater details, such as diffusors for example, the grid has to be refined in order to produce realistic results. Various test runs showed issues in such areas and helped to optimise the model between accuracy and simulation time. There is a grid size where accuracy does not improve noticeable, but only simulation time will increase. Once this point of grid refinement is reached, the simulation is adjusted to its optimum. Test runs were also made for some of the components on their own; to observe various grid refinements in greater detail, see Appendix E. In the actual model the finite grid included 16,498,987 tetrahedral and hexahedral elements giving a typical computer run time of 28 hour with a Dual Intel Xeon 8 core i5 2687W processor with 3.1 GHz clock speed and 128 GB RAM.

6.4 Boundary Conditions

The manufacturing plant is exposed to the surrounding climate, see chapter 2.3.2. Temperature changes, radiation of the sun, rain, wind, pressure and humidity are the most important factors which show effects on such a building (Neville 2011). It would be more comprehensive to simulate all these factors, but to stay within current computational limits, simplifications are required. The largest effect on the internal plant environment has the external temperature. The model is limited to steady state; hence, for the main validation process a realistic scenario for the most amounts of data has to be created. In the period of data collection for winter conditions the largest amount of data was acquired for the external temperature of 7°C. The wind velocity at the geographic location of the plant was measured between 0 and $15ms^{-1}$, as shown in table 5 in chapter 5.4. If the wind is considered in a CFD simulation, the model becomes considerable larger, because an air volume around the building would have to be included in the model. To obtain realistic results from such a simulation this air volume would have to be approximately 10 times larger than the actual building. Such an increased model would reduce the accuracy of the simulation results within the building drastically (Neville 2011). For this reason the actual wind around the building was not simulated. However, the most important effect of wind, the decrease of thermal efficiency performance of the roof and walls can be included into the model. Other factors such radiation of the sun or rain has an effect, but it would be too difficult to validate.

For these reasons, the plant was simulated in winter conditions with an external temperature of 7°C (on a cloudy day), taking account of airflow in and out of the building, including HV supply and return system as well as machine extraction system. As mentioned above this temperature was selected to reproduce conditions under which data collection was performed and therefore, helps in the validation process of the simulation. In winter time the most internal data was collected when the outside temperature was approximately 7°C. Therefore, for model validation purposes the plant was simulated at similar conditions. The development of such methods was more interesting for temperatures that occur often than for maximal or minimal external temperatures. With the use of minimum and maximum values interesting data, especially to test scenarios for unexpected issues, can be created, but for the validation process the utilisation of long term conditions are more reliable due to the larger data set. However, a simulation of extreme conditions and its effect on the plant's performance could be performed in future applications of the validated model.

The HV air input is applied through diffusor vents while air was extracted through the HV return system and machine extraction system. Collected data and a past study (Olson 2012) showed that the combined output of extraction system and HV return was greater than the HV diffusor input. To obtain a balanced system, an additional source of leakage was introduced. Higher outputs cause infiltration in the form of leakages through gaps in the roof, windows, walls and doors. Such leakages were simplified and included in the model to create a balanced system. Leakage was included through gaps above and below roof windows with a total surface area of $728.739\mathrm{m}^2$ as shown by Figure 32.

In addition to roof leakages, infiltration through loading gates was included in the model. By solving the governing equations in their steady state the cyclic behaviour of the infiltration flow through loading gates was eliminated. The flow through these gates was assumed to be steady and limited to 20% of the total input flow. Figure 31 is a schematic diagram showing the main flows in and out of the building, whereas Table 7 quantifies such flows. In the actual manufacturing plant more sources of leakages occurred, but it would have been difficult, time consuming and therefore, not feasible to identify all and then include them in the model. For this reason, the leakages were simplified and reduced to the two main sources of leakages. The expected issue with this method of simplification comes with temperature and velocity variations. Less leakage will alter both, temperature and velocity, which had to be considered, once the model was validated against collected data.

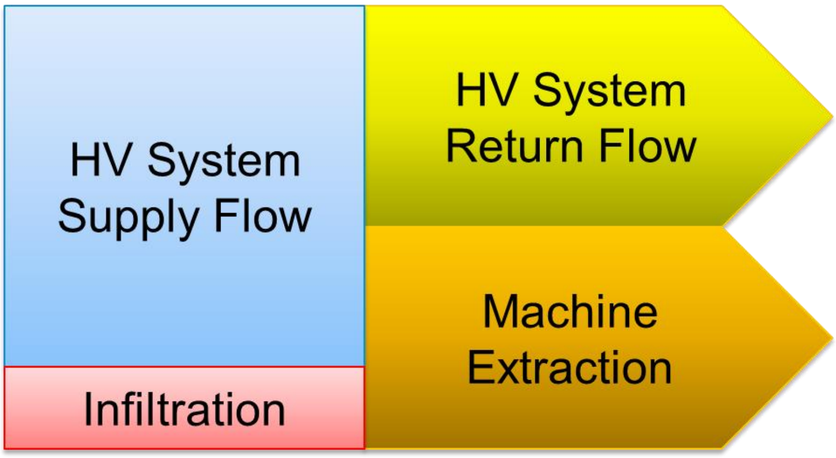


Figure 31: Schematic diagram of airflow in and out of the simulated model. The HV system supply flow and the infiltration equal the combined output of HV system return flow and machine extraction.

System	Flow Rate (m^3h^{-1})	Model I/O
HV System Supply Flow	2,924,100	Input
HV System Return Flow	1,635,660	Output
Machine Extraction	1,686,344	Output
Leakage Infiltration	397,904	Input

Table 7: Airflow in and out of the simulation model. The HV system supply flow and the infiltration equal the combined output of HV system return flow and machine extraction.

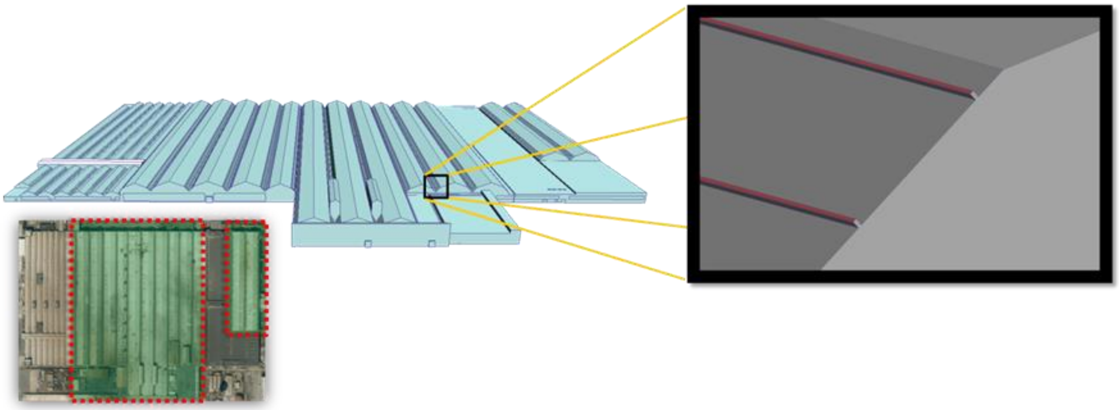


Figure 32: Infiltration above and below roof windows. Roof leakages were simulated in the red marked areas of the DEP.

The main HV system is orientated north to south as shown by Figure 13 in Chapter 3 and the main ducts towards the diffusors are heated and non-insulated. Temperatures of heated and ventilated diffuser heads are 40°C and 25°C respectively and are assigned following standard operational practice. These values were measured by thermal cameras and surface thermometers. These temperatures were also assigned to non-insulated main ducts surfaces without the need for duct flow information. Only diffusor supply and plant room return air was simulated. Under such conditions, the outlet flow rate was dependent on diffusor type and the plant room, which it was connected to, as shown in Table 8. Appendix A shows two different types of diffusors, but there are 7 different variations of the main diffusor type, which are all included into the CFD model.

HVAC Unit	Number of Diffusors	Number of Supply Vents	Supply Flow Rate (m^3/h)	Return Flow Rate (m^3/h)
1	17	93	221400	128520
2*	11	54	221400	128520
3*	12	68	221400	128520
4*	11	63	221400	128520
5*	12	62	221400	128520
6*	11	66	221400	128520
7	11	66	221400	128520
8	23	48	221400	128520
9*	21	112	153720	81000
10	12	72	153720	81000
11	24	34	153720	81000
12	24	24	153720	81000
13*	16	60	153720	81000
14*	8	24	76860	40500
15*	11	43	153720	81000
16*	14	44	153720	81000

Table 8: HV system and boundary simulation inputs including the unit number, the number of diffusors and outlet vents, the supply air and the return air are shown. *Heating disabled and only ventilated.

In addition to the main heating system, 23 smaller "Myson" heating units, which are shown by Appendix A, with a total outlet flow rate of 248,832m^3h^{-1} and air temperature of 65°C were added to the CFD model. These units input a lot of energy into the plant but in a very inefficient way. If innovative strategies, methods or technologies of energy saving are developed or tested such systems have to be included, to make sure improvements work.

Machine extraction systems were simulated by overhead outlet bars which allow the simulation of extra vents, built in the system to cater for further expansions of the production line. Usually the effects of machine extraction occur at systematic openings around machines. It would have been possible to simulate the extraction for every machine individually. However, empty extraction valves would have been not included in the simulation. These were present in all of the extraction pipes for eventualities such as unplanned machine additions. To be able to include all of these empty extraction bars and the actual machines without additionally complicating the model, overhead extraction bars were used address this issue. Machine extraction values for all machining lines are shown in Appendix F.

Machines were simplified to blocks with surface temperatures of 30°C, 35°C or 40°C depending on their type. Thermal images were made for each type of machine, which has various heat spots particularly at electric motors or other electric control units. After various test runs the temperatures for machines were adjusted to improve accuracy. This simplification affects the immediate environment of such machines, but such effects are less significant if an entire manufacturing plant is observed. Thermal images of most machine types within the DEP are shown in Appendix G.

In addition to heat generated by machines, a simplified heat layer of 1.33MW accounts for the energy output of approximately 12,000 double light fittings in the building. This simplification could be made due to the uniformity of the lights. A wall conductivity to simulate conduction through walls was also applied by a simplified approximate average of all building materials utilised in the manufacturing plant (Ford 2013b). The conduction coefficient was taken as 2$Wm^{-2}K^{-1}$ for exterior wall and 2$Wm^{-2}K^{-1}$ for roof surfaces, while for windows this coefficient was equal to 5$Wm^{-2}K^{-1}$. In general, temperature ranges between -5 and 65°C had to be considered in the modelling process to cover all temperatures within this manufacturing plant. Furthermore, air velocities between 0ms^{-1} and 15ms^{-1} and absolute pressure between 1.5bar and 0.5bar were considered. The CAD model of the simulated plant can be seen in Figure 33 and in Figure 34.

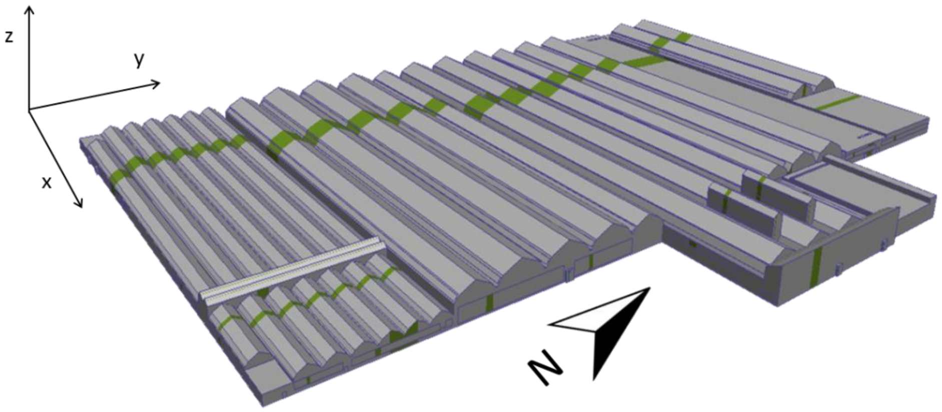


Figure 33: "Autodesk Inventor" model showing the simulated Dagenham Engine Plant.

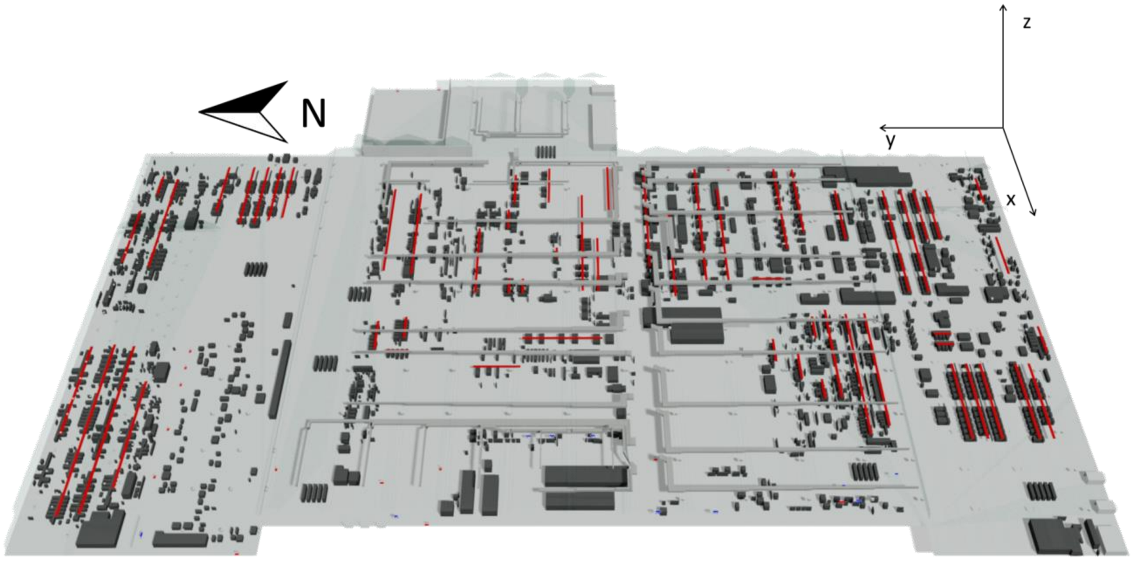


Figure 34: "Autodesk Inventor" model including all internal components and control systems such as machines, offices, restrooms, main ducting and extraction bars.

6.5 Assumptions Made

Due to resource limitations, especially in computing power the following assumptions were made to simplify the model.

- Leakages were limited to the main section of the roof and loading gates;
- Airflow rates through loading gates were reduced to 20% of the total input flow;
- Output differences of HV units were equalised;
- Ducting and diffuser leakages were neglected;
- Machines were simplified to blocks with surface temperatures;
- Simulation was performed for one particular weather condition;
- Lights were simplified to a uniform heat source layer;
- Attached outdoor buildings were eliminated.

6.6 Results and Discussion

Two methods of validation, quantities and qualitative, were used in order build confidence in the simulation model. For the qualitative validation a limit of difference between measured and simulated values was set initially. A temperature of ±1.5°C in average was chosen, because this value approximately matched the error of the mobile data system. In addition to the temperature difference, it was important that the general temperature pattern of the simulation matched the measurements at most areas. However, due to the large scale of the model it was impossible to calculate exact percentages of validation; hence, a quantitative validation method, between measurements and simulation, had to be developed.

Temperature distribution within the plant was simulated and compared to field measurements (Frystacki et al. 2015). Measured values were also used as boundary conditions for the simulation. These measurements where utilised to validate a static snapshot in time which was the reason that all collected data had to be manipulated to create a base of comparison. For all temperature data obtained by the mobile collection system, reference values of external temperatures were collected. These reference temperatures were used to filter all internal data for specific external temperatures. In the following temperature maps internal temperatures are only monitored for the external temperature of 7°C ± 1.5°C. Hence, the model is quantitatively validated against a range of temperatures for the same external temperature.

Such a building model in the UK should consider a temperature validation range (internal and external) between -5°C and 65°C (external temperatures in winter and warm temperatures of electric motors and heating units were considered). However, in this simulation in winter conditions the actual temperature range was chosen between 7°C (external temperature) and 65°C (temperature of warmest components within the building). In this model air velocities between 0ms^{-1} and 15ms^{-1} and absolute pressure between 0.5bar and 1.5bar were considered, to be able to cover all properties at realistic behaviour within a manufacturing plant in the UK.

Comparisons of measured and simulated temperature maps were made at 1.35m above floor level, as shown in Figure 35. Due to the large scale of the plant the measurement grid was coarse resulting in large distances between interpolation points and therefore, not capturing fine details. The point P_{1m} shows large heated areas not observed in the simulation and was mainly due to heavy vehicle traffic that prevented access for data collection. Temperatures at P_{1sa} and P_{1sb} were close to the actually measured values but data between these points interpolated in the measured map. If this is considered in the comparison to the simulated temperature distribution map of Figure 35b similar hot spots can be observed in the same region even when the measured data misses the cold spot between P_{1sa} and P_{1sb}. The simulated temperature map shows a lowered temperature at P_2. This is due to the presence of a loading gate in the vicinity, which is also confirmed by the measured data seen in Figure 35a. In a similar way, door infiltrations are seen to affect the environment around location P_4 although this is a non-production area. In this area the simulated temperatures were approximately 1°C lower than the measured ones. At the middle of the plant, around location P_3 measured temperature maps are also showing a consistently higher temperature of 1°C compared to the simulated temperature map. Infiltration occurs through gaps of the entire building shell, but simulated roof leakages were only included in the middle part of the plant, which increased the flow rate through the simulated gaps. This results in a temperature gradient between the middle (P_{3s}) and the southern part of the plant (P_{7s}). In addition to that, the layout of machinery around P_6 and P_7 limited access for field measurements around those locations. The result was a coarser measurement grid resulting in poor interpolations between measured data. Due to access issues these areas were better monitored by the fixed sensor system as depicted by Figure 38.

The pressure distribution map throughout the plant is shown in Figure 39 confirming the difference in pressure due to a different ratio between machine extraction rate and fresh air supply and infiltration rates resulting in airflows through door openings at the fire wall at P_8 and P_9 with speeds of more than 1ms^{-1}.

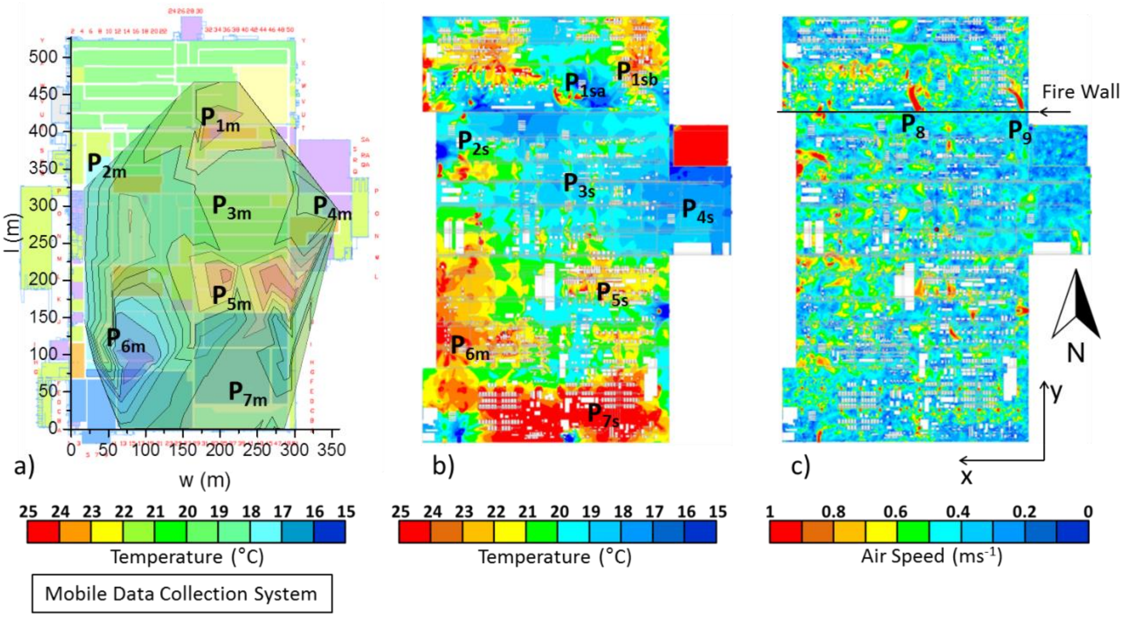


Figure 35: Comparison between temperature maps at 1.35m height: a) measured, b) simulated and c) airflow. Markers P_1 to P_{13} show points of interest. P_{xy} where x marks number and if y equals s simulated or m measured.

In Figure 36 and Figure 37 temperature and airflow differences in heights of 4.5m and 0.15m are presented. In general, a similar temperature pattern is shown, but temperatures are higher in greater levels of heights, which were expected because hot air rises due to its density change. This can be seen, in both, the simulated and the measured temperature maps. Interestingly the airflow shows higher speeds closer to the ground which is due to several factors. Due to a common loading gate height of 4m infiltrated airflow influences cannot at seen in 4.5m of height. At this height the highest speeds are observed around diffusor outlet vents, which force air downwards. This downward air is adjacent to loading gate, which is the main reason for higher airflows close to the ground.

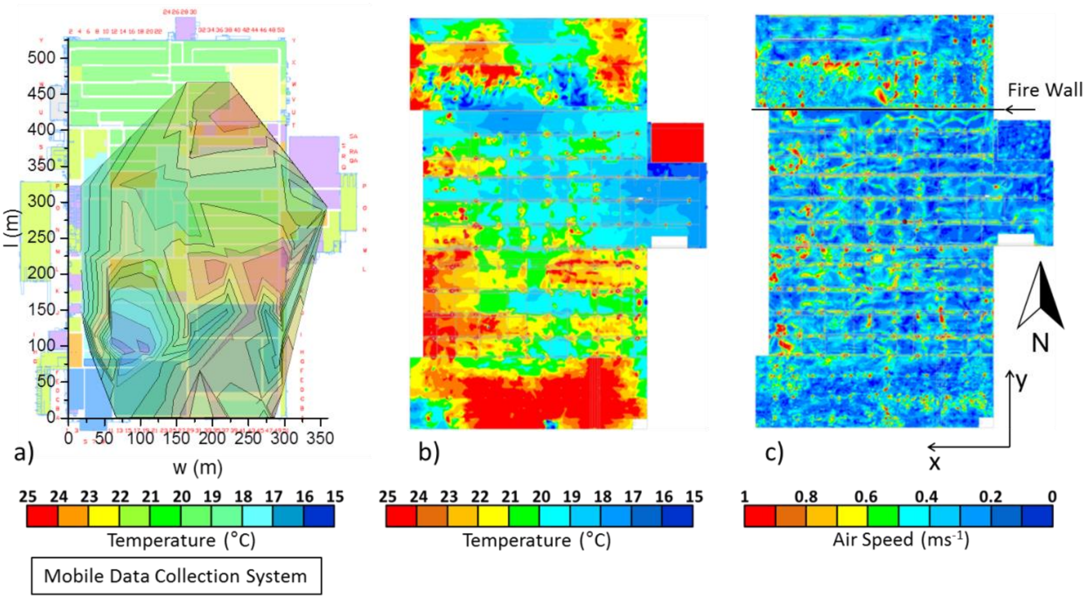


Figure 36: Comparison between temperature maps at 4.50m height: a) measured, b) simulated and c) airflow.

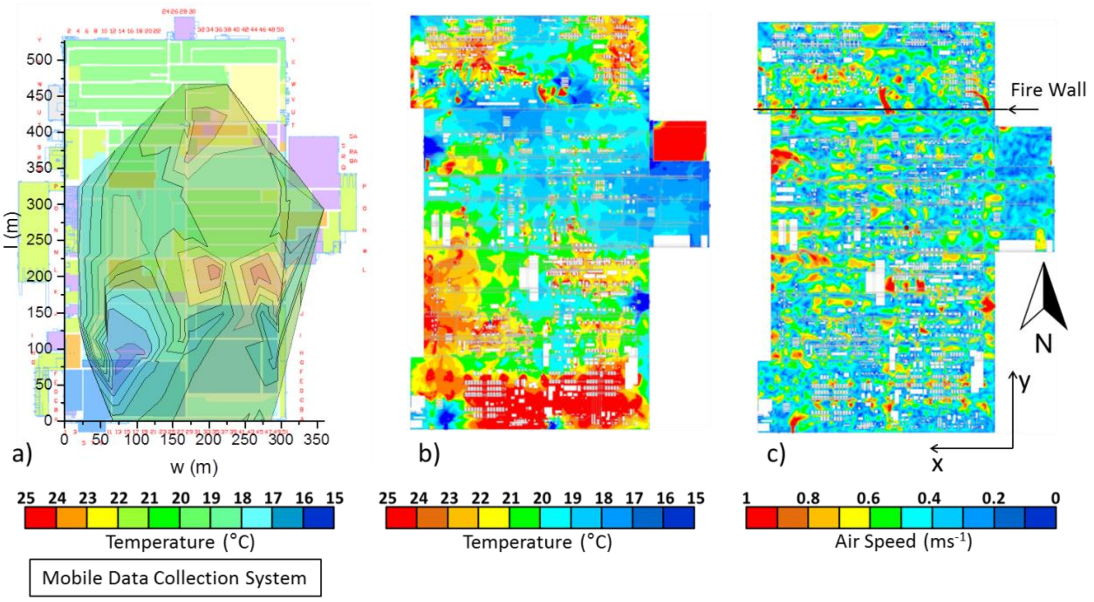


Figure 37: Comparison between temperature maps at 0.15m height: a) measured, b) simulated and c) airflow.

A second data collection system in the form of 28 fixed sensors located at 1.75m above floor level was used to log temperatures over a week's period from the 13/03/2013 to the 20/03/2013. The average external temperature for this period was 5.3°C. At P_{10} a hotspot caused by an independent heating system was observed. Due to large distances between measured data points the impact of this heating unit is larger than in the simulated results. Temperature maps in Figure 38 are showing a discrepancy of about 1°C between measured and simulated results at P_{11}. Again, this is due to the leakage assumption made when setting up boundary conditions. At P_{12m} the discontinuity of part production along the production line decreased temperatures in this area at the time of measurement. There are hot spots between P12 and P23 in the simulated map which not reflected in the measured data. Partly these hotspots come from machines but the impact of the door at P_{13} does show lower effects in the simulation. Low temperatures at P_{13} were mainly due to the presence of loading gates in this side of the plant and a north/south temperature gradient is observed with higher temperatures at P_{14}. Assumptions made about roof and walls are also reflected in the simulated results as these are showing higher temperatures then the measured ones by about 2°C at the south side of the plant. This area seems to also have more leakages then assumed when observing the building, in the simulation the leakages in this area were neglected, which explains this difference.

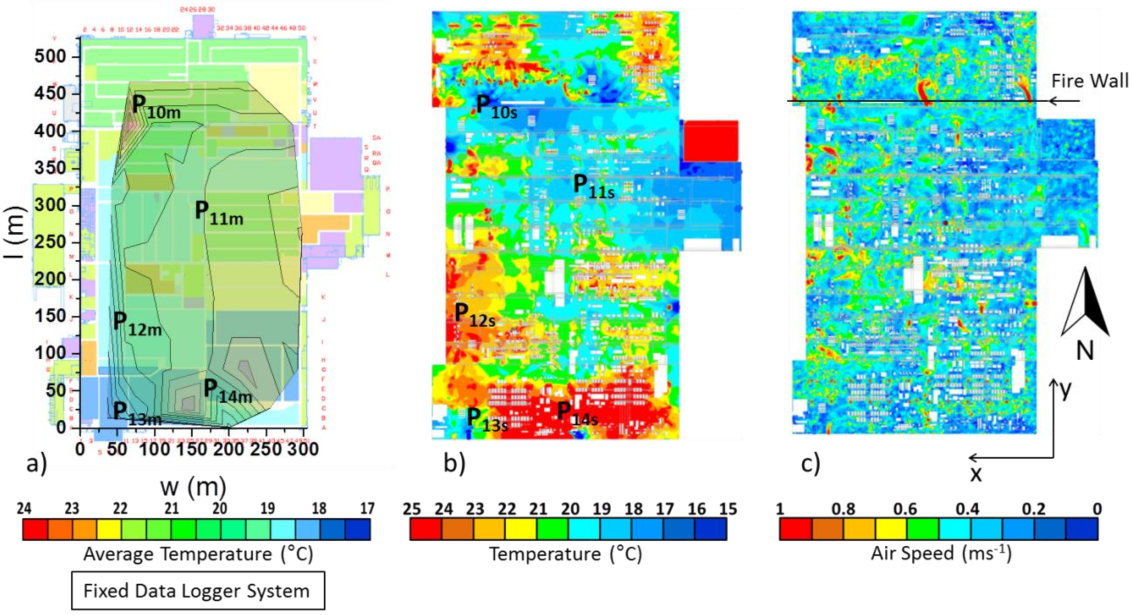


Figure 38: Comparison between temperature maps at 1.75m height: a) measured, b) simulated and c) airflow. Markers from P_{18} to P_{29} show points of interest. Pxy where x marks number and y is s if simulated or m if measured.

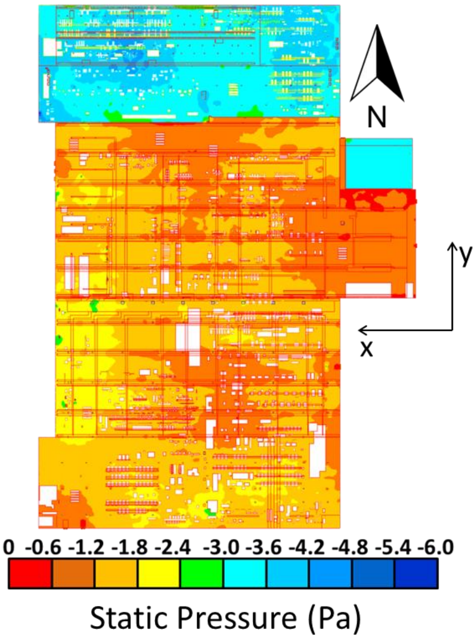


Figure 39: Simulated pressure map of the manufacturing plant showing pressure below atmospheric within the plant.

In general, if the model shows a similar temperature pattern to the measured temperature distribution maps and if the temperatures differ less than ±1.5°C in average over the entire plant the validation can be considered successful. Larger areas differ less than 1.0°C and only few parts seem to differ noticeably more. Some variations were expected due to lacks in both, simulated and measured maps. Issues were caused by inaccessible measurement locations, measurement inaccuracies, and coarse measurement grids. On the other hand, temperature distribution differences were also caused by the model due to steady state simulation, model assumptions and general simulation inaccuracies. Considering all these facts, results obtained for temperature distribution are in good agreement with measured values. This gave a degree of confidence when analysing longitudinal and transverse flow circulations and temperature distribution within the building.

6.7 Longitudinal and Transverse Temperature Maps and Flow Pattern

The natural airflow within such a large building is created by temperature variations and the building shape. Due to density changes air with increasing temperature, heated by machines and HV units, is forced upwards to the roof, which is then cooled down through conduction by roof panels and forced downward. Leakages above and below the roof windows also contribute to this downward flow. This creates a natural convection flow pattern within the building, which is disturbed by other airflow currents within the plant.

Such flow circulation can be observed in Figure 40a at the middle of the plant close to the location of P_3 in Figure 35, where two distinct recirculation regions are observed. Interestingly, these are not symmetrical which can be a result of temperature and pressure differences in the building. In this case a heated airflow is observed to interact with the natural convective flow pattern. Forced in from the lower right hand side, this warm airflow current rises and pushes more air into the upper left hand space under the roof, which creates an asymmetrical flow pattern. The temperature distribution at the same transverse location is shown in Figure 40b. The warm rising air is cooled down on the way up towards the top of the building where it is forced along under the roof panels. The asymmetrical pattern is also observed in the temperature distribution as shown in Figure 40b. In addition to natural convection, roof sections guide the airflow in an east-west direction as shown in Figure 41, which is conflicting with the north to south orientation of the HV system.

The actual flow direction, eastwards or westwards, depends on influences of HV units or other heat sources within the plant. Such flow originates at the east and west and travel towards the middle of the plant as shown in roof panel bay III in Figure 41. In bay IV and V the eastward flow shows higher strength and reaches further than the westward flow. Under the roof panel bay II the flow is observed to be similar to bay III, but at the eastern middle the airflow is disturbed by an upward current caused by an HV unit. Figure 42 covers the whole plant in the same area as the main HV system, but all previously observed patterns also occur in the entire region of the graph. None of these flows travel along the HV system orientation, which is suspected to be one of the causes in lowering the effectiveness of the HV system.

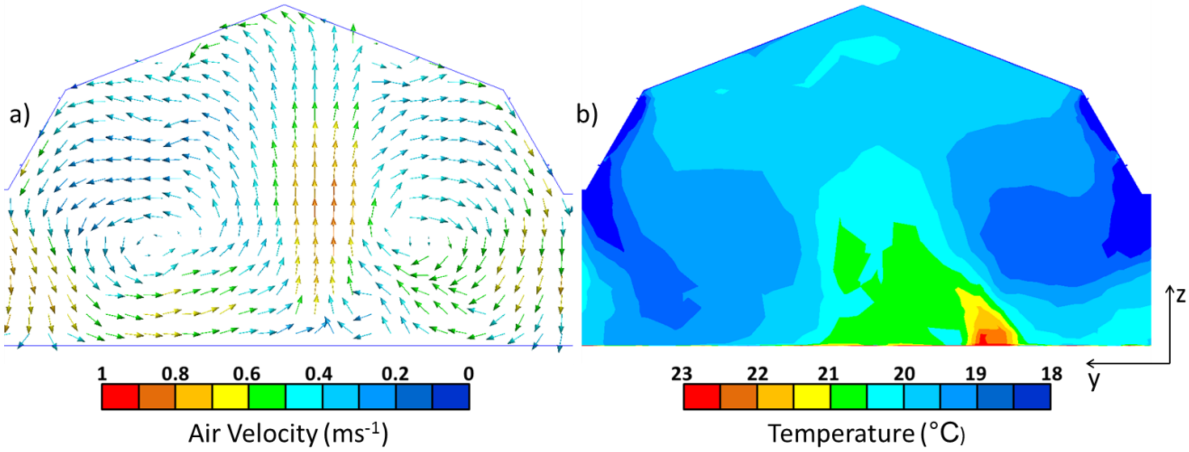


Figure 40: Airflow and temperature profile a) velocity vectors, b) temperature contours.

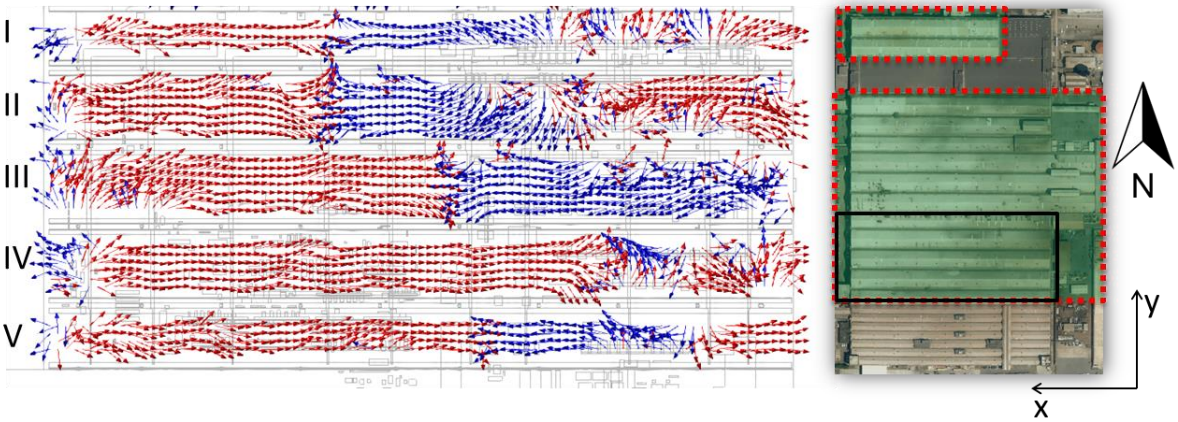


Figure 41: Cross flow under the roof at a height of 14m from east to west and vice versa. Airflow is shown by vectors, blue for westward flow and red for eastward flow. The red dotted area marks areas where main cross flow occurs, while the black rectangle marks the area shown, in the vector profile.

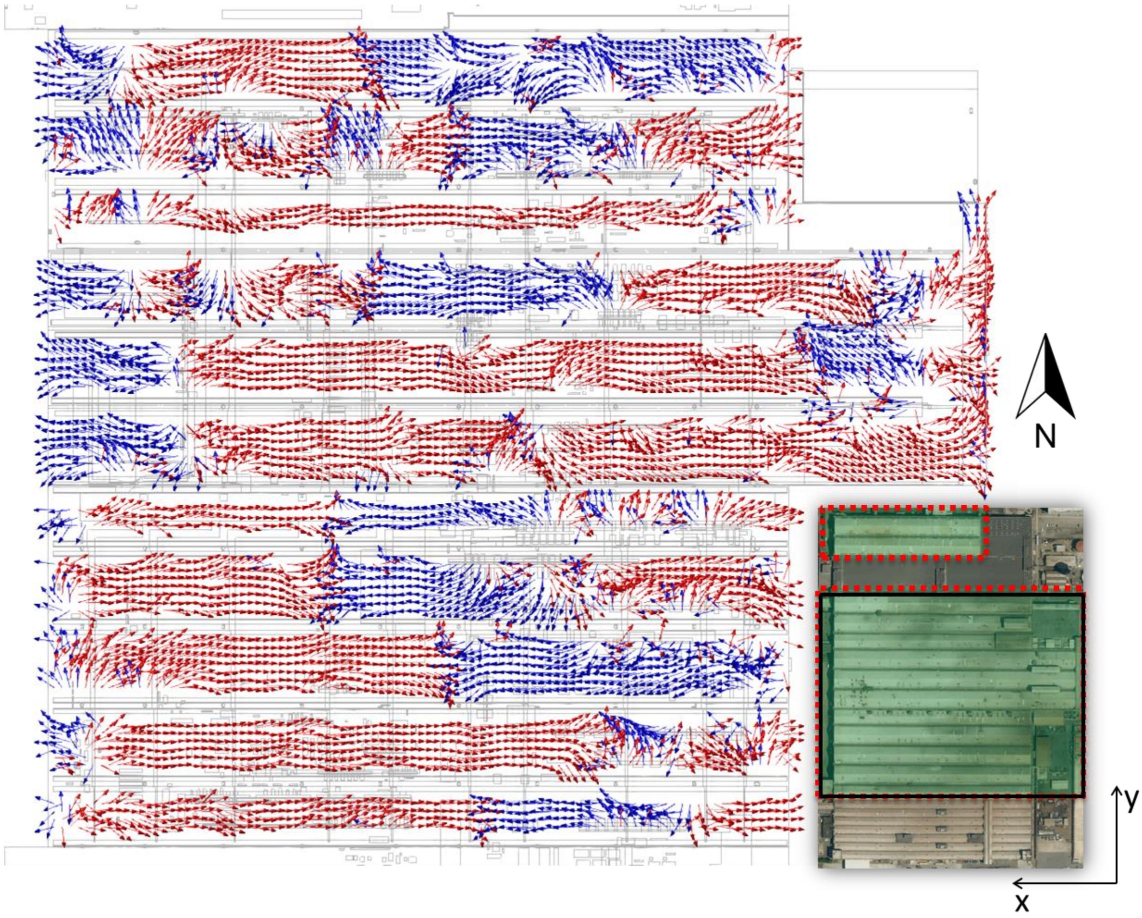


Figure 42: Cross flow under the roof at a height of 14m from east to west and vice versa. Airflow is shown by vectors, blue for westward flow and red for eastward flow. The red dotted area marks areas where main cross flow occurs, while the black rectangle marks the area show, in the vector profile.

Figure 43 shows a cross sectional diagram to visualise one of the cross flow currents observed in Figure 41. Figure 43a shows velocity vectors to highlight the direction and strength of the airflow, while Figure 43b shows temperature distribution contours at the same location. Heated air is guided along the roof section where it is cooled by lower temperatures of the roof strengthening the cross flow by HV units that accelerate and force hot air across the roof panel. Fast moving air is cooled down by conduction through the roof resulting in a decrease in heating efficiency. Whereas the airflow under the roof is guided along the roof panels, the flow in lower plant regions in the x-z plane has a more complex pattern. It has the tendency to travel in the opposite direction but with lower velocities. In the middle of Figure 43a, rising air heated by machines creates a vortex flow below the hot air moving alongside the roof panel. This can also be observed in temperature distribution contour Figure 43b. It can also be seen that this temperature increase slows down the cooling process of the air stream under the roof.

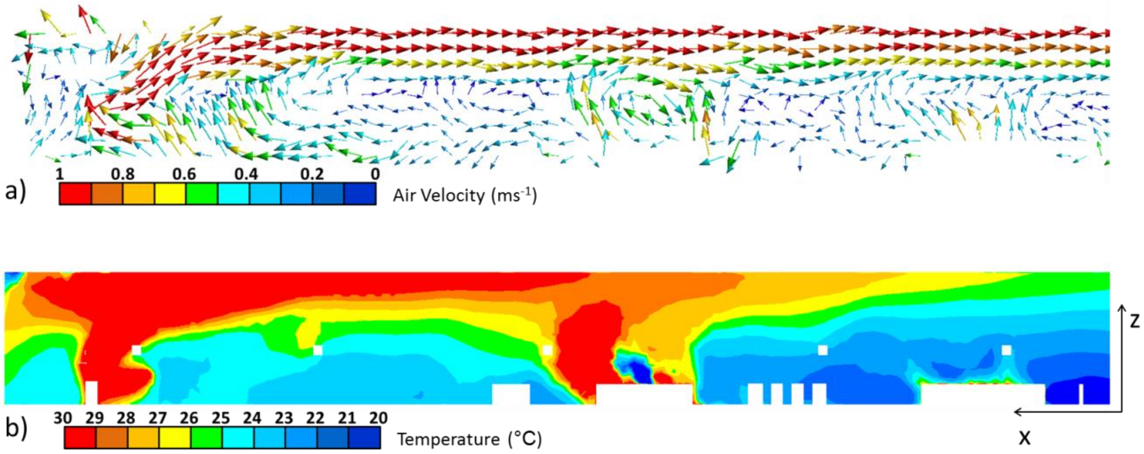


Figure 43: Cross sectional airflow and temperature diagram showing a cross flow in east to west direction. a) velocity vector field, b) temperature contour.

This airflow is forced through three thirds of the plant width before it moves towards lower levels where it loses its momentum. Figure 44a presents changes in the velocity of this air stream as it flows across the plant. The air speed is monitored along the dotted line in Figure 44b.

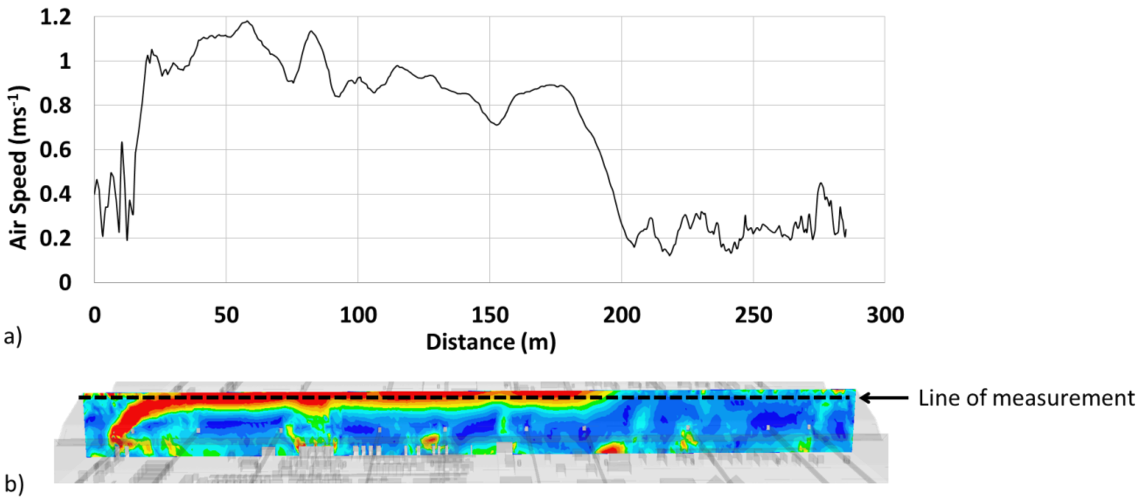


Figure 44: Cross sectional visualisation of airflow speed of cross flow current. a) change in velocity over the plant, b) cross sectional air speed contour highlight airflow behaviour under the roof.

Figure 45 shows air particles which were traced back and forwards across the manufacturing plant. It shows the main air movements in the plant from east to west in a three dimensional view.

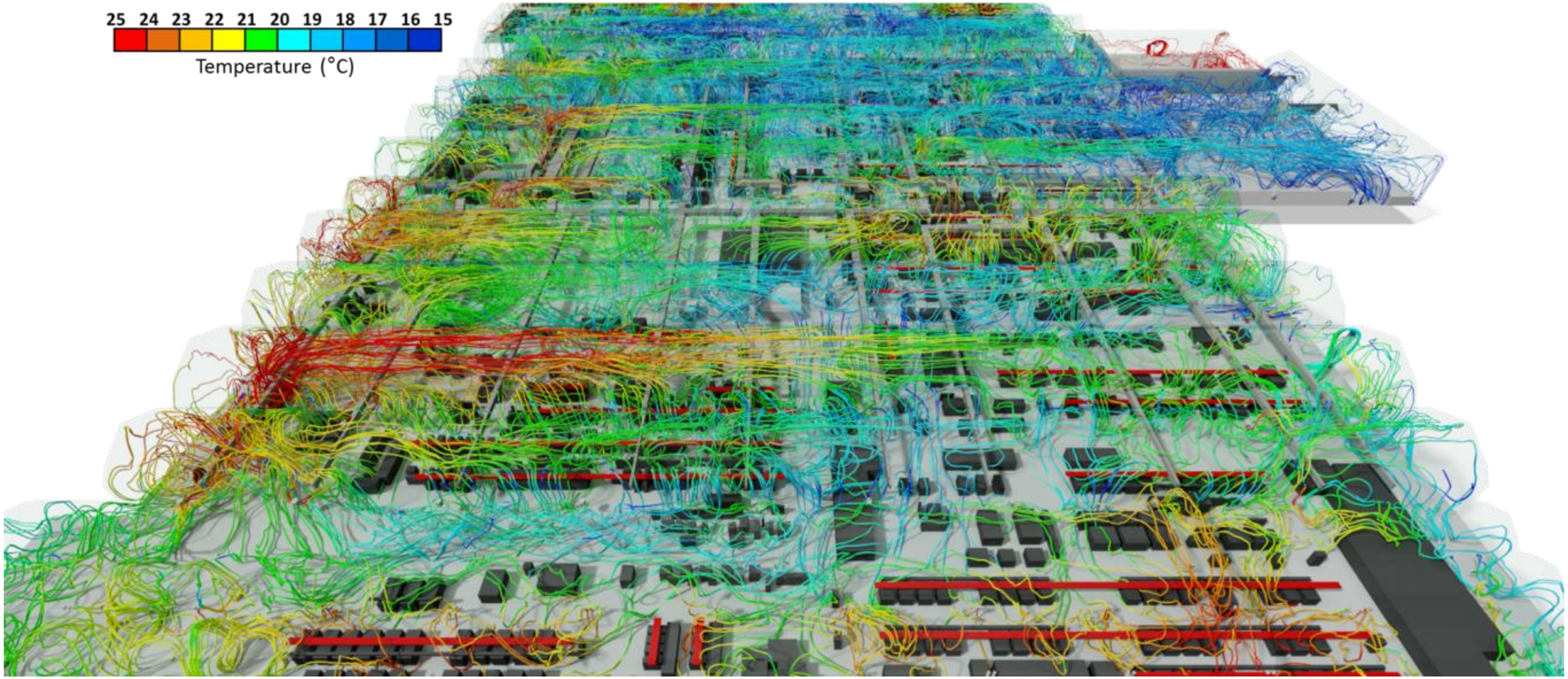


Figure 45: Air particles traced back and forwards to observe the main movements in the manufacturing plant.

6.8 Recommendations

The HV system is designed in such a way that after leaving the diffusers air is recycled via the plant room for re-use after being filtered and mixed with fresh air. There are, however, indications from the simulated results in Figure 41 that this cycle is disrupted by cross flows, making the HV system less effective.

A rearrangement of the roof or the HV system would both be too expensive, but other lower priced solutions could be simulated. Partitioning the plant in north to south direction would alleviate the problem but will affect vehicle traffic and could cause issues with moving parts. Part partitioning on the other hand could be a more viable solution. Partitions can extend a certain distance from the roof downwards and act as barriers to block the cross flow. With the partitions lined up in the direction of the HV system, cooling and heating will be uniformly distributed across the plant, resulting in a more effective HV system. In addition to partitioning, leakage limitation and increased fresh air supply rates from plant rooms could create a positive pressure within the plant. This will counteract infiltration and improve efficiencies.

6.9 Summer Scenario

In addition to the winter scenario a summer scenario was simulated. From an energy reduction point of view, the summer scenario is less important because all the HV systems within the DEP are switched off. It is still an interesting scenario due to machine cooling and comfort issues.

The summer scenario was simulated with an external temperature of 20°C. This is not an extreme summer temperature but a sensible one to investigate as a lot of the internal data collected was performed at this condition. In common practise of the thermal management in the plant, all door gates are kept open to ventilate and cool the plant in summer. The roof windows were simulated in open condition so leakage areas were increased from

$728.739\mathrm{m}^2$ to $22{,}945.6\mathrm{m}^2$ in total. Due to the common practise of keeping doors open, hence, no reduction of the incoming airflow rate was required. For simulating machine heat, the same surface temperatures as for the winter scenario were applied, 30°C, 35°C and 40°C depending on the type. Thermal images were compared and no significant differences were observed.

Compared to the winter scenario warmer temperatures occurred, which is shown by Figure 46. Due to higher external temperatures, warmer temperatures within the engine plant were expected and also measured. However, in the northern side of the plant temperatures seem to be warmer than in the measured data. In the plant windows are often open at the northern wall in summer which was neglected in the simulation. This resulted in higher simulated temperatures with a difference of approximately 3°C. Additional simulation and validation runs would have minimalised this issue, but due to time and budget constrains it was not possible to optimise this particular problem. In the middle of the plant simulated and collected temperatures seem to match over wide areas. This seems to be optimal because it shows that the largest area in the plant is simulated realistically. In the Southern part of the plant higher temperatures were simulated, due to similar data collection issues as in the winter scenario. Due to hardly accessible machinery environment most measurements were made next to lines, which implied slightly higher temperatures. However, the largest difference to the winter scenario is observed by the airflow map, showing high incoming air speeds which were expected due to the negative pressure within the plant. Due to the external machine extraction, the pressure within the DEP is below atmospheric which is shown by Figure 47. Open doors and windows reducing the effect of negative pressure within the plant compared to the simulated winter conditions.

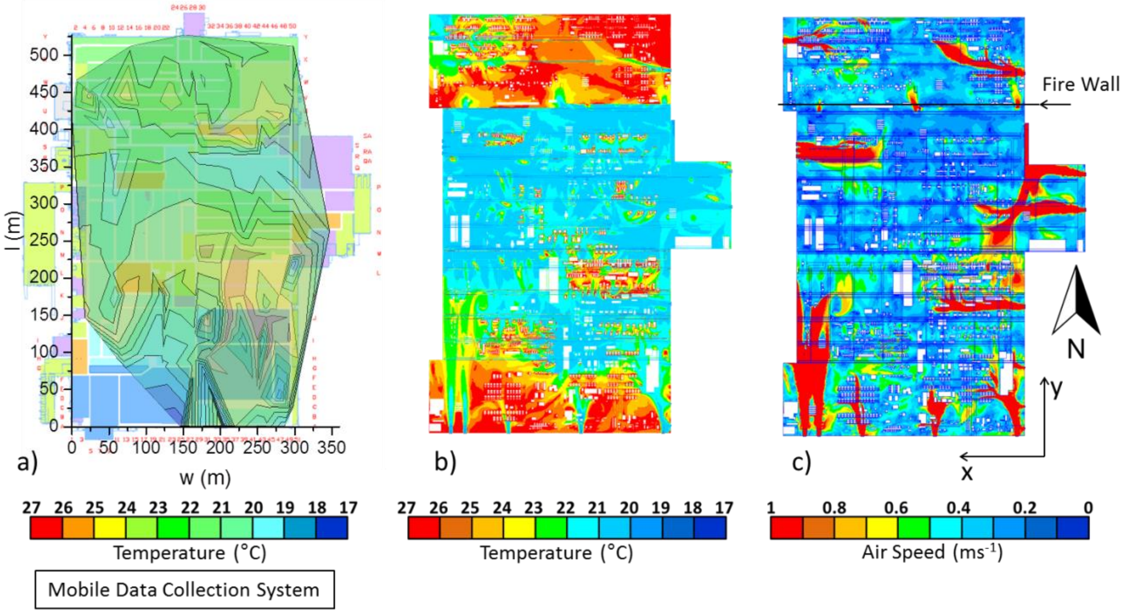


Figure 46: Comparison in summer conditions between temperature maps at 1.35m height: a) measured, b) simulated and c) airflow.

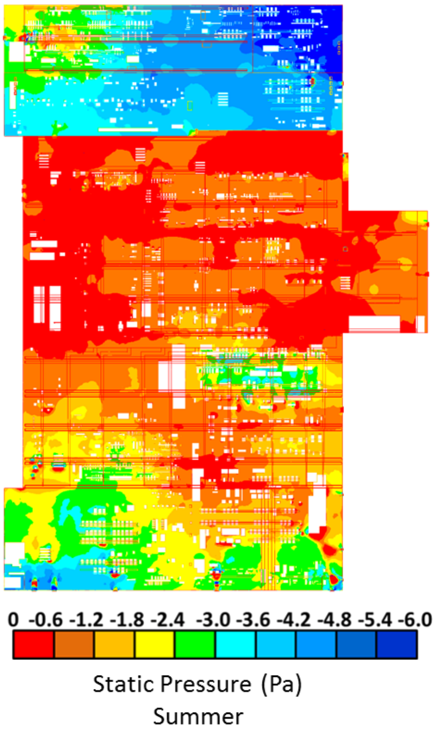


Figure 47: Simulated pressure map of the manufacturing plant in summer conditions showing pressure below atmospheric within the plant.

High temperatures are not optimal for the employees' comfort, but also cause issues for the machinery environment, due to machine internal cooling processes. Modern machines slow down production because of such cooling cycles which also increases the use of energy. However, in such a large manufacturing plant an air cooling system would be too expensive and would also consume more energy than the machines.

The infiltration in summer is higher than in winter, since the HV system is not inputting any fresh air. Due to this larger infiltration the air speeds are generally higher and amount up to 7ms^{-1}. If the HV system would ventilate, the temperatures within the plant would be more uniform, air speeds would reduce and the climate for employees and machines would improve. However, due to high energy demands of the obsolete HV system it is switched off.

In general, the simulated and collected data are matching over large areas of the plant in the summer scenario, even if the validation results show few inaccuracies. However, in this study the summer scenario is only made for comparison. Time and budget constrains limited the model accuracy in the case of the summer scenario, but if potential improvements are tested in the winter scenario, the effects of changes can also be predicted in summer, which can help to build additional understanding of the thermal environment. However, energy is mainly saved in winter, which reduces the importance of a summer scenario. For this reason some inaccuracies in the summer scenario can be accepted.

6.10 Conclusion

The thermal environment of a full size manufacturing plant has been simulated. Under various assumptions all components such as the building shell, the HV system, infiltration, machines, machine extraction systems, additional heaters and lighting were included into a factory model with a floor area of 183,243m^2. Simulated results were validated against sets of measured data. To the authors knowledge CFD studies of such a large and complex plant are not available in the open literature.

This study showed a comprehensive approach of simulating such complex buildings including all details. It was necessary to simplify the model as far as required to stay within limits imposed by time and budget constraints, but not to suppress the effects of some important factors. However, it was possible to simulate such complex plant with current technologies especially within computational power limited the accuracy of such a simulation. The required accuracy was reached when the model was able to show effects in detail without overcomplicating the simulation by the usage of to many elements within the model. The required accuracy was found after various test runs; the finite grid included 16,498,987 tetrahedral and hexahedral elements for the simulation of 1,978 parts with 21,300 surfaces.

All simplifications were introduced due to practical reasons. Test simulations were made to build knowledge for the influences of such conversions. Simplifications implied the reduction of leakages around the plant to the most significant sources which were the door gate and the roof leakages. Due to the simulation of study state flow rates through such door gates had to be reduced. Output flow rates of various old diffusors within the plant were equalised, ducting was reduced to the main ducts and machines were simplified to blocks with surface temperatures. Furthermore, lights were simplified to a uniform heat source layer and building attachments, which had no direct influences on the thermal environment of the main plant, were neglected. Once all boundary conditions were assigned, the model was simulated and then validated against collected data. The temperature distribution maps were used to compare temperature on different levels of height successfully. Besides all the simplifications the results showed interesting and convincing data, which seemed to be reliable enough for the further utilisation of creating scenario testing possibilities in future work.

Simulation outcomes highlighted the appearances of unwanted airflow currents that disrupt the general strategy of the HV system. In addition to that, a negative pressure within the manufacturing plant forces large infiltration rates which further limit the effectiveness of the HV system. Part partitioning, leakages reduction and higher fresh air supply rates could improve HV system efficiency and reduce energy consumption of the plant. There were opportunities for improvement regarding simulation technique and methodologies, but the main purpose, to create knowledge about the internal environment of such a large and complex building, was fulfilled.

Chapter 7

7 Discussion

The objectives set at the beginning of the project in section 1.2 were used as the main template to achieve the ultimate research aim, to evaluate strategies for reducing energy consumption of existing large industrial estate.

7.1 Energy Issues in Manufacturing Plants

In addition to electric energy consumption one of the key issues in large manufacturing plants is the thermal environment. In this study industrial energy usage research is successfully performed by a case study, which also answers the questions, key issues within industrial energy usage research and the implementation of such research in industrial live environments, asked in section 2.2.6. The actual methodology of obtaining data within such a manufacturing plant is explained in section 5.2.

A significant amount of energy is utilised in order to maintain the production environment of a large manufacturing building in optimal condition. Due to obsolete technologies and management issues the heating cost alone can in case of the DEP amount to more than 26% of the utility bill. In addition to the most recent, innovative but expensive technology improvements, cost effective solutions combined with more efficient use of existing technologies can sustainably reduce the energy consumption of such a factory by significant amounts. A research project was undertaken to be able to quantify energy problems within the thermal manufacturing environment.

7.2 Mega Factories Compared to Medium Sized Offices

The first obvious difference between mega factories compared to medium sized offices is one of size. However, the issue of size is only one of many points which have to be considered in an investigation of the thermal performance of large industrial buildings.

The biggest considerations for thermal energy research within medium sized office spaces are their heat sources, such as HVAC system, lighting, computers and employees as well as insulation properties of building materials to utilise space efficiently all mentioned heat sources should be evenly spread across the room, thereby reducing large airflow issues within rooms. Also insulation improvements, for components such as walls, roof, windows or doors, should be carried out uniformly and not only for isolated sections of the building. These facts simplify the entire methodology of environmental investigation projects.

Some of the major issues associated with large old manufacturing spaces is the fact that, in most installations, the non-uniformity in roof elevations, coupled with poor distribution of heating and ventilation systems as wells as draft resulting from operational procedures, associated with internal traffic and loading bays, results in large temperature gradients in all directions of the plant. This, consequently, induces large air circulations, partly associated with buoyancy that affects the internal environment. This, however, cannot be said about small to medium size spaces where the internal environment can be controlled more easily, avoiding such issues.

7.3 Experimental Research

7.3.1 Experimental Research - Methods and Findings

The first project objective entailed the investigation of feasible data collection methodologies to understand and analyse thermal energy issues of a large industrial live environment. There is a large difference between thermal energy usage research in a small "clean" room and a large industrial live environment. In general, research methodologies have to be more flexible, to be able to follow safety regulations and not interrupt the actual manufacturing process. Due to the larger size a lot of environmental properties but also environmental changes have to be accounted for.

A manufacturing plant is not only larger but also sensors have to be chosen according to the task of obtaining data in a dusty and oily environment. Sensors have to be more robust and the system has to be approved and allowed by the plant safety management. All of these points have to be considered when creating a methodology for the data collection within such a manufacturing plant, which answers the first question of section 2.4.8, about the differences of data collection between small clean rooms and complex industrial live environments. However, considering these points, two systems, a mobile data collection test rig and a fixed sensor system, were engineered, installed and tested. The data collection methodologies and the utilisation of both systems had different kinds of advantages and disadvantages which are shown in Table 9.

The Mobile Data Collection System	
Advantages	**Disadvantages**
Low Price	Time consuming
Quick to install	An engineer or a technician is required to collect data
An optional amount of various data points	Reference values of external conditions required
Temperature readings at various heights	No direct comparison to other locations at simultaneous times
Flexibility in area of operation	Access issues in industrial live environment
Flexibility in field of application	Safety issues in restricted areas
Robust system with exchangeable parts if damaged	
The Fixed Sensor System	
Advantages	**Disadvantages**
Continuous data collection	Expensive
Data from various locations simultaneously	Installation is time consuming
Automated data collection once it is installed	Wireless system (in some factories not allowed)
Data easy to compare with data from other sensor locations	Battery change required
Live data can be used for instant adjustment	Coarse measurement grid (In large factories sensors might be far apart)

Table 9: Advantages and disadvantages of both systems, the Mobile Data Collection and the Fixed Sensor System are shown.

Even when mobile data collection system was designed to mainly collect temperatures, it was also able to support the collection of airflow and humidity data. This airflow data had to be logged manually, but the actual problem of the system was caused by consistent environmental changes. Airflows within the plant were caused by a variety of scenarios. Due to the lower pressure within the plant, open doors caused large airflow currents. It was not possible to log all open and close doors at the time of a measurement. Furthermore, the old Myson heating units caused strong airflow currents, but the direction was adjustable by every employee. In addition to that it was not possible to log the running times of the main HV-system. Sometimes more diffusors were switched on, sometimes less and since this was controlled manually, it was impossible to log exact HV system strategies. A similar issue arose with the opening of the roof and wall windows. It was not possible to log all these factors, which made it impossible to correlate dependencies from the acquired data sets. Even when it obtained interesting data, it could not be used for the direct validation of a simulation model. However, all airflow measurements were used to acquire boundary conditions which could be used for the model design. In future work applications airflow measurements within such complex buildings could be improved and new methodologies may be able to account for such continuous environmental changes.

On the other hand, humidity measurements did not cause similar issues, because it showed more consistent values throughout the factory. It was also possible to perform average calculations which made the data reduction more effective than with airflow for example. However, humidity measurements were mainly made to obtain data which was interesting for production. It would be interesting to extend this study and include human concerns such as comfort issues to optimise the thermal environment. Such applications were not included in the scope of the project, but would also be interesting in future applications.

In general, the data collection using the mobile system has to be flexible within the observed industrial estate due to standard manufacturing processes, restricted areas, inaccessible areas, vehicle traffic or other disturbance issues such as route blockages, due to repair and maintenance works, caused issues and enforced a large amount of flexibility in the measurement strategies. The large size and the complexity of the observed building made it a slow process of obtaining data. However, the applied methodologies were found to be successful, if the previously explained limitations of this system are acceptable. On the other hand, fixed sensors were easy to set up, but time consuming to install across such a large factory floor area. Once the sensors were installed the actual data collection was found to be advantageous to the project. Continuous live data from different locations in a simultaneous manner without any accessibility issues were obtained successfully. If the grid coarseness and all the expenses are acceptable the system can be recommended for future projects.

It was found that for scientific projects both systems were relevant and a comparison of both systems increased the possibility of observations and potential findings. In many cases it was considered advantageous to be able to have two different sources of data, not only for comparison, but different data also enabled different kinds of analysis. However, if there is only time or budget for one system it could be chosen depending on the actual requirements of tasks. For scientific low budget projects, the “Mobile Data Collection System” might be a reasonable and feasible tool, whereas for industrial purposes the “Fixed Sensor System” probably showed the greater potential especially due to continuous live use, which also answers both questions of section 2.3.6. These research questions asked about the most effective methods and techniques of obtaining thermal data within such a plant.

7.3.2 Experimental Research – Outcomes and Recommendations

All collected data was analysed for energy reduction concepts. Climate conditions have a large effect on the thermal environment within any building. Especially external temperature significantly influences the internal environment. However, one of the observed issues was consistently high average temperatures through all the time the HV system was operational. The average day time temperature was found to be 2-3°C higher than necessary within an optimal production climate. In addition to consistent over-heating, a poor temperature distribution across the plant caused various cold spots, which forced higher temperature in the rest of the plant in order to maintain every part of the plant above the optimal temperature of 19°C.

An estimation within this study suggests that only 1°C of overheating cost the DEP approximately GBP 3,045.00 a day (section 5.4; page 74). Furthermore, external and internal airflows reduce the thermal building performance, due to weak obsolete insulation of the roof and the walls. In addition to major insulation issues, production related issues at loading gates create an unstable thermal environment over large areas of the factory. Such problems could be minimised by communication and knowledge of responsible employees but also by cost efficient techniques such as secure high speed doors. If leakages would be decreased the temperature distribution would be equalised by adequate measures, the internal condition would be more stable and the overall temperature could be minimised. Furthermore, if the overshoot of temperatures during the daytime could be reduced by providing HV system adjustments thermal energy consumption could be reduced to a minimum without the installation of the newest but expensive technology options.

7.3.3 Temperature Maps – Method and Findings

In addition to other techniques of analysing data internal temperature distribution maps were designed to visualise the temperature distribution of the observed manufacturing plant in various levels of heights. It was found that the usage of such a method enabled significant research opportunities. Not only the temperature distribution itself could be monitored and compared to other findings, but also one of the most complex CFD simulation models at current times could be validated against these maps at various heights within the factory. To answers the questions of section 2.4.8, existing methods of data collection bring a lot of useful findings, but with innovative additions, such as internal temperature distribution maps, this data can also be valuable for mathematical/ simulation models and therefore, support the prediction of large internal environments. In this study the design of temperature distribution maps was made in three dimensions due to various layers, which was helpful to validate a thermal model of the factory. This technique can be recommended for similar projects within such large premises.

7.4 Simulation Model

7.4.1 Simulation Model – Modelling Large Scale Manufacturing Plants

To further understand and analyse the thermal environment of the manufacturing plant the second objective implied the design and construction of such a simulation model. To the authors' knowledge, CFD studies of such large and complex plant environments are not available in the current literature at the time of writing. This suggests it is the first time that an entire large scale manufacturing plant with a floor area of 183,243m^2 including all components, such as the building shell, the HV system, infiltration, machines, machine extraction systems, additional standalone heating systems and lighting were included into a CFD simulation model.

One of the largest and most complex CFD simulations in open literature, a library with 800m^2, was performed by Magdalena Hajdukiewicz in 2013. The building model within this research work is 183,243m^2; hence it is 229 times larger than the library. Furthermore, the library was naturally ventilated although radiators, natural ventilation and additional heat sources such as lights, computers and human occupants were considered. However, the complexity required to simulate an entire manufacturing plant is considerably higher.

7.4.2 Simulation Model – Boundary Conditions and Assumptions

In order to simulate any model all boundary conditions have to be collected and then input in the model. Every surface, leakage, diffusor input or extraction output of the model needs to be defined. The model will only work if all of these boundary conditions are defined, which also answers the fifth question, about the required boundaries, of section 2.5.5. The issues with simulations in such an extent come with time, budget and computational limitations. For these reasons simplification of the model had to be undertaken to be able to successfully achieve the task of creating such a factory model.

One of the greatest impacts had the limitation to steady state. This implied that the entire simulation would be a snapshot in time rather than a changing environment with initial conditions and simulated cycles. Especially in manufacturing plants components are transported in and out of the plant, which creates a lot of vehicle traffic and door opening which also means leakage cycles. It would have been more accurate to simulate a full cycle of an entire day, week or year including door openings and shift changes at production lines. Even with the most recent technologies it was not yet possible to perform such a simulation within reasonable timeframe and budget. That meant the simulation had to be performed in steady state which is a snap shot in time. Due to steady state no impulse airflow behaviour could be simulated. There are different techniques to model such a problem:

- Door openings could be neglected which would increase the simulated error, because no fresh air would be inserted through the door. The main problem with such a technique is that no machine extraction system could be simulated due to thermodynamic principles. When air is extracted from a closed system, air from the outside must be allowed to come back into the system; otherwise the system would not exist as such.

- The doors could also be modelled as constant openings. In this scenario a lot of leakage would be created by continuous door openings and large areas would be simulated with low temperature values causing a disadvantage. On the other hand, the advantage of this method compared to the closed door is that the system would be realistically simulated in equilibrium.
- In this project the method modelled was a mix between both. Doors within the engine plant were researched and average opening times were observed and manually measured. This procedure allowed the calculation of average flow-rates entering each door. The disadvantage of this technique is caused by the air velocity. In order to keep flow rates small, the velocity had to be reduced. In addition to this reduction no impulse was simulated and the actual flow did not reach as far into the building as in measured observations, but within the limitations of steady state it was assumed to be the most accurate modelling technique.

As mentioned just above the most convincing method of constant open doors with reduced airflow rates was chosen, but there might be other solutions to this issue which could also be further investigated in future projects.

Further simplifications implied the reduction of leakages to the main leaks within the manufacturing plant. It is impossible to find all leakages within such a large building within reasonable time constraints, but it would also not be feasible to model all the observed issues. For this reason, most leakages were ignored for the modelling process, but next to the door issues the biggest leakage, gaps next to obsolete roof windows, was modelled. Such a simplification showed impact on the simulation because in the main part of the plant were those leakages were included most of the fresh air was pulled into the building which lowered the temperature in the middle part of the plant, whereas other areas such as at the northern and southern part of the plant temperatures were simulated higher due to missing leakage.

In addition to leakage reductions machines were simplified to blocks. Most machines have a variety of electric motors and electrical panels creating heat sources around machines. All these point heats were neglected and the machine was simulated as a block with only one temperature. The temperatures were chosen depending on machine type but were slightly adjusted after a few test runs of the model. This definitely had an impact in the closer machine environment, but when the temperatures for the entire manufacturing plant were observed, the impact of this simplification did not show any significant issues in the validation process.

Also machine extraction was simplified due to practical reasons. Extraction bars above machines were used instead of extracting separately for each machine. A simulated extraction for every machine does not take empty valves which were included in the pipe works for possible machine additions and pipework leakages into account. In fact, this simplification was considered to be more exact than other techniques, even if the bars itself slightly change airflows within the machinery environment.

Furthermore, all lights were simplified due to a uniform light arrangement of allowed the simulation of a simplified heat layer of 1.33MW which accounted for the energy output of approximately 12,000 double light fittings in the building. In addition to the validation such issues entailed the biggest challenges within the construction of a CFD model to answer the first two questions, about the biggest challenges and issues of large scale CFD factory models, of section 2.5.5. However, all these simplifications were necessary to be able to simulate this plant within the earlier mentioned limitations. It could be another opportunity for future work to closer investigate such simplifications for optimisation.

7.4.3 Simulation Model – Validation Methodology

In addition to the data collection, which is vital for the validation of such a complex model, a validation process was created in order to understand the internal environment of the manufacturing plant. Simulated temperature distribution maps were directly compared to the measured maps in various heights, for the quantitative validation of the model. The frame for the qualitative validation was set with a temperature distribution difference of ±1.5°C in average, if the temperature pattern of the simulation generally matches the temperature distribution of the plant. This also answers the third question, about the validation of the manufacturing plant, of section 2.5.5. Even when the simulation was considered successful, expectantly issues arose within and the actual modelling of the engine plant, but also within the process of validating collected against simulated data. The following paragraphs critically discuss the main issues within the model simulation and the validation process of this study.

For the validation temperature data from all parts of the plant was collected, with reference to the outside temperature. It was not enough to just collect random internal temperatures; these temperatures had to be collected for specific external temperatures. This was achieved by fixed external reference sensors which were used in queries to find the optimal simulation temperature of 7°C. This is the answer to the fourth question of section 2.5.5, for the validation process temperature data from every plant area was required.

Within the validation process the following main sources of issues were observed.

- Issues caused by restricted data collection in a complex industrial live environment
- Issues caused by model assumptions and simulation
- Standard issues and limitations of CFD simulation

Figure 48 shows validation issues between data collected by the Mobile Data Collection System and simulated data, whereas Figure 49 shows the difference between the fixed sensors and the simulation. Considering all data collection and model assumption issues the temperature pattern created in the simulation was considered acceptable. At most areas within the model the differences were less than 1˚C, which was in this project considered a reasonable margin. Such variations were expected because the actual fluctuation of temperatures within the plant for the same outside temperature was mostly higher than 1˚C depending on the area within the plant. However, the validation process showed areas which differ noticeable more. Furthermore, there were areas where no data was collected; hence, a validation for such areas was not possible. The causes for these differences and issues are explained in the following section.

7.4.4 Simulation Model – Validation and Findings

There were several reasons for differences between measured and simulated data; some of these areas are shown in Figure 48 and Figure 49. First of all, there are areas, such as A_{1m} and A_{3m}, where no internal temperatures were measured for the external temperature of 7˚C, whereas all areas (excluding attachments) were simulated. This was one of the issues using a Mobile Data Collection System, because it was not always possible to collect data in every area for any specific external temperature. This caused areas with coarse grid points within the measured data maps and even showed areas with no data at all. In such areas the validation process often showed either wrong results or no results at all. A related issue was observed with the fixed sensors in areas such as A_9. It was a larger storage area with no production lines, and not sensors were installed, which caused the difference between simulated and measured data in this area.

Similar issues were caused by the physical access within restricted areas, such as heavy machinery environment or storage areas with continuous vehicle traffic. In the measured temperature maps such areas are only interpolated and fail to show accurate temperatures. Examples are shown by A_{2m}, A_{5m} and A_{6m}. Furthermore, some samples were also taken next to continual heat sources, which enlarged measured heat areas due to coarse grid structures. Large interpolation between measured points, caused high or low temperature samples to cover larger areas in the measured temperature distribution maps, but it may only be a little diffusor or machine heat outlet valve such as shown by A_{7m} for example.

The Fixed Sensor System, on the other hand, mainly created issues due to a coarse grid. The advantage of this system compared to the Mobile Data Collection System was continuous live data at every location which could be directly compared. It would be optimal to have more sensors, but the costs for a larger sensor network would be unreasonably higher considering the project budget. Areas such as A_9 seem to be warmer than the simulated values. Due to a coarse grid the entire cold area shown in A_{9s} is missed by the fixed sensor system. The area A_8 which was the same as the A_2 shows low temperatures in the simulation which was not shown by any of the measurements. As mentioned already this area is actually colder than measured values show. Due to grid coarseness in A_{10} and A_{11} the fixed system fails to show the warmth of an entire production line. Such missing high temperature areas lower the accuracy of a validation process, which is one of the main issues of this system. On the other hand, in A_{12} the fixed sensors measured high temperature areas in a tight machine environment, which isn't shown by the data of the Mobile Data Collection System. Grid coarseness limited the high temperature area to smaller heat points, but the Fixed Sensor System was usable in such an environment which was a definitive advantage to the Mobile Data Collection System.

There were also simulated issues caused by model assumptions and simulation limitations within the CFD. As mentioned before one of the greatest limitations was to simulation in steady state, hence, door leakage flow-rates were reduced. The impact of this assumption can be observed in A_5. The low temperature area in the measured map was larger than the simulated one. This larger area was also caused by another reason; the tight machinery environment in the North of that low temperature spot. Due to this reason an area with large interpolation occurs which let this area seem larger than it actually is.

Another issue was caused by the assumption of leakages within the simulation. Due to size and complexity of the plant, it was not feasible to find every leakage to model. Assumptions had to be made due to time, budget and computational limitations. The greatest source of leakage was in the main part of the plant at the roof windows. In other parts of the plant leakages also occur, but in a more complex manner. Due to the difficulty of determine exact data within a reasonable timeframe this leakage had to be neglected. This issue created different kinds of inaccuracies which are explained by the following paragraph.

The simplification of leakage created differences in pressure across all plant areas. Areas without roof leakages but production lines, showed lower pressure levels than roof leakage areas. Due to the internal pressure, lower than atmospheric, air was pulled though leakages into the plant. In the simulation such leakages were reduced to the largest sources, doors and the roof windows. The internal temperature in leakage areas was lowered by the incoming fresh air. Hence, if larger leakage rates are neglected, temperatures in simulated values are higher than in measured data sets. Temperature differences caused by such leakage reductions are show in A_6 and in A_{12} for example. The area at the south of the manufacturing plant has a low roof and a lot of machines with high machine extraction rates. Leakage areas were neglected in this area which increases the temperatures compared to measured data.

There was a cold spot in the simulated area at A_4 which seems to be created by the third main issue. CFD is a mathematical prediction method of fluid dynamics. It simulated airflow as accurate as possible but there were air currents which would differ to measured airflows. Even after closer observation this cold spot is difficult to explain, but it came from a leakage area under the roof and concentrates in this area.

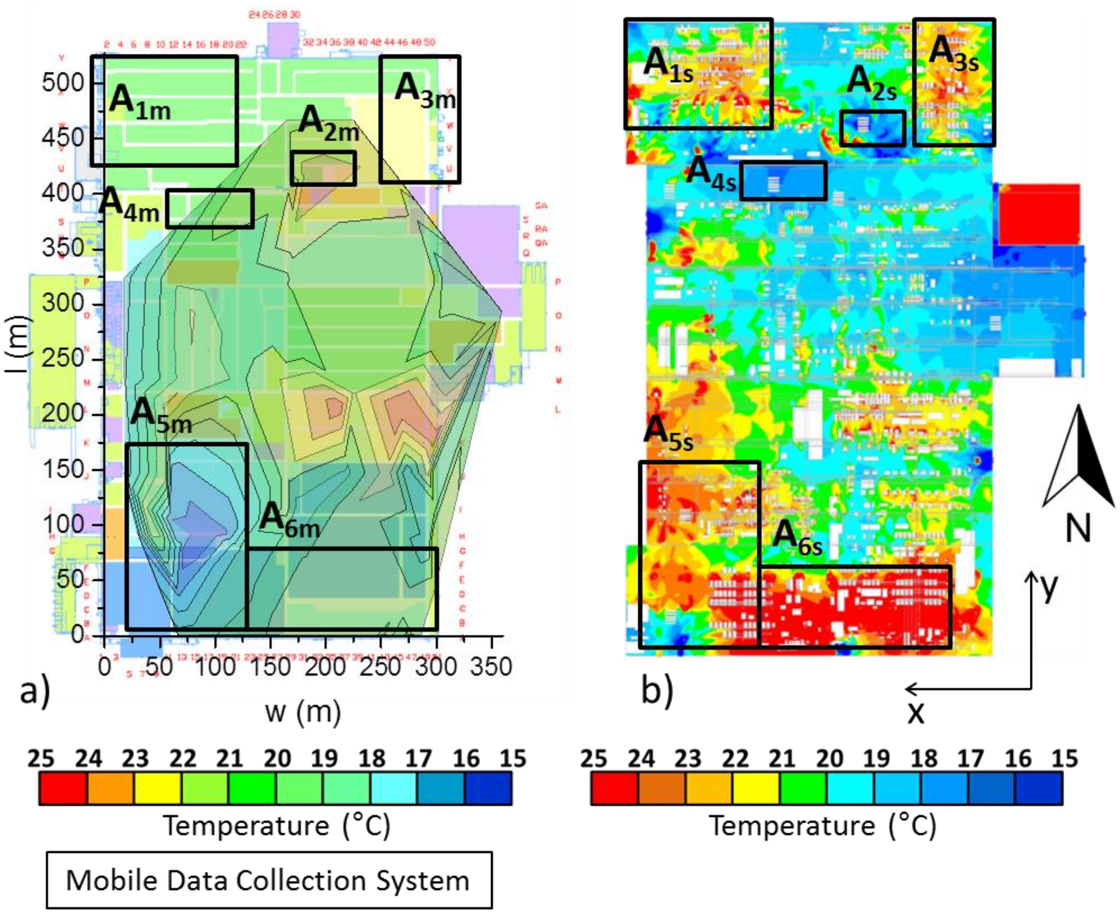


Figure 48: Differences between temperature maps at 1.35m height: a) measured and b) simulated. Markers from A1 to A6 show Areas of interest. Pxy where x marks number and y is s if simulated or m if measured.

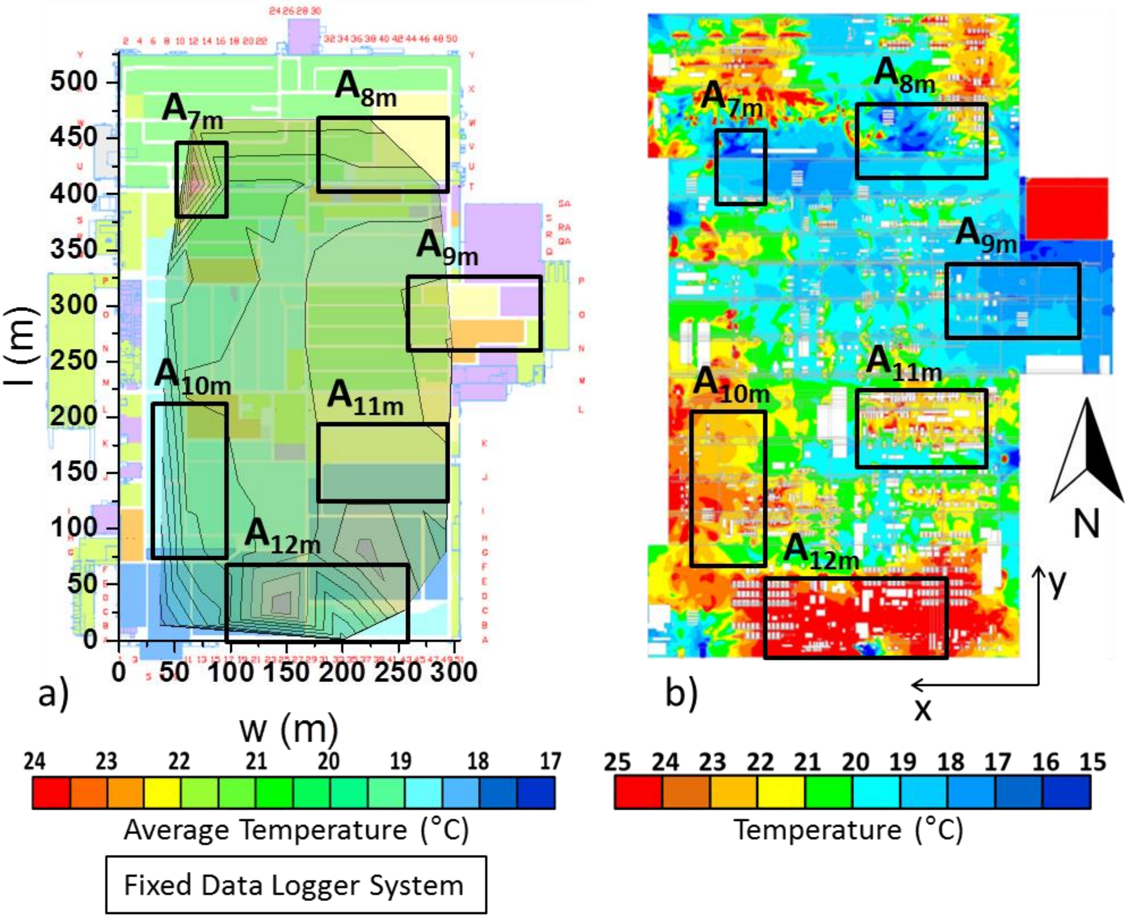


Figure 49: Differences between temperature maps at 1.75m height: a) measured and b) simulated. Markers from A7 to A12 show Areas of interest. Pxy where x marks number and y is s if simulated or m if measured.

The validation process showed up a lot of differences between simulated and collected data, however, the simulation was still considered a success since it was able to show effects of the environment even if minor differences between simulation and reality exists. Most differences were below 1˚C and even measurements showed greater fluctuations of internal temperatures for similar external temperatures.

The model validation was made for the following ranges:

- Temperatures were considered between -5°C and 65°C
- Air velocities were considered between $0ms^{-1}$ and $15ms^{-1}$
- Absolute pressure was considered between 0.5bar and 1.5bar

Within this ranges the simulation was considered to be in good agreement with the measured date, applications outside these limits are unknown. Furthermore, in the model the finite grid of 16,498,987 tetrahedral and hexahedral elements were included. For this particular model the number was found to be optimal, but for other building simulations such a number is also unknown, because it depends on the exact task of simulation.

7.4.5 Simulation Model - Outcomes

Simulation outcomes highlighted the appearances of unwanted airflow currents that disrupt the airflow strategy of the HV system. A negative pressure within the manufacturing plant additionally limits the effectiveness of the HV system. In addition to that, a negative pressure within the manufacturing plant forces large infiltration rates which further limit the effectiveness of the HV system. Part partitioning, leakages reduction and higher fresh air supply rates could improve HV system efficiency and reduce energy consumption of the plant. The simulation model showed successful outcomes and findings obtained significant weaknesses within the building. There were opportunities for improvement regarding simulation technique and methodologies, but the main purpose, to create knowledge about the internal environment of such a large and complex building, was fulfilled.

7.5 Evaluation of Methodologies – Outcomes and Findings

To be able to choose the optimal strategy for the analysis of the thermal environment of such a factory, factors such as relevance, time, cost, effectiveness, resources and previous studies have to be considered. In case of the Dagenham Engine Plant all the tools utilised showed new and innovative ways of analysing the thermal environment. Data collection showed great potential due real data values which could be linked to costs and showed issues which can be improved in future work. Especially the fixed sensors can be integrated into a long term saving strategy because it continuously monitors and logs data which can be as an instant source of adjustment reference. It would also be possible to include this system into fixed company processes to ensure continuous energy reduction within the manufacturing plant.

The mobile data collection system and the simulation, on the other hand, are able to show issues in detail but it would not be feasible to utilise such techniques for continuous long term processes. Both techniques showed great potential and could also be deployed in future. The mobile collection rig could be used to analyse particular issues to understand required areas in more detail. Low cost and quick analysis could be the advantage over other systems for such a purpose. The future work opportunities of the simulation, on the other hand, show great potential. Especially CFD simulation of such buildings will improve its standards because continuously rising computational power enables faster simulation which will allow more and more details and maybe even live simulation. Even at the moment case studies and scenario testing could show great potential for improving the thermal environment of such a plant. However, at the moment such complex simulations are still expensive and time consuming. The most significant potential is to test changes before implementation to be able to optimise such procedures.

All in all, this study showed that in such a complex plant, especially if obsolete technologies lower the thermal energy efficiency, a fixed temperature sensor system is strongly recommended, whereas mobile data collection systems and CFD simulation are tools with great potential, which could especially be useful to find and test changes to improve the thermal energy situation before implementation.

7.6 Recommendations for Implementation

In addition to the evaluation of different techniques, the analysis of the thermal environment and recommendations were also part of this study. The research project suggests the following improvements and implementations within the DEP:

- Cost effective solutions, such as safe high-speed doors, awareness, consistent temperature monitoring and communication can create a more uniform temperature distribution for a more stable manufacturing environment.
- The average temperature within the manufacturing plant could be reduced by adequate measures and the comfort for employees and the machining environment could be simultaneously improved to guarantee a stable operation and a lower carbon footprint to meet the targets of low carbon emissions.
- Part partitioning, leakages reduction and higher fresh air supply rates could improve HV system efficiency and reduce energy consumption of the plant.
- Once implementations take place the process has to be repeated to continuously optimise issues and include such strategies in fixed company processes.

To further this work and confirm some of the conclusions drawn, a simulation of the part partitioned plant need to be carried out. A different HV system management strategy, with the adjustment of higher fresh air rates, could be modelled and analysed. A full cost benefit analysis could be made which would support the implementation of such improvements. Additionally a pilot implementation of some of the solutions discussed and worker feedback would help improve the solutions before a final implementation.

7.7 Methodology Recommendations

In this study various methods were researched, engineered and tested. The third objective entailed recommendations for the upcoming engineers. If all approaches are accounted for, the most promising method of understanding and analysing the thermal environment of a large scale industrial live environment can be recommended in the following steps:

- Visual inspection of the manufacturing plant to fully understand the research task. Due to unique way such plants are constructed and run, methods could alter to fit the environment.
- Since such work is made in a live environment, all safety related procedures have to be fulfilled before any actions can take place.
- For the data collection the most promising system are fixed sensors, however, if more data is required in certain areas a mobile data collection system can be recommended.
- To store, manipulate, reduce, analyse and present data a custom build database is fully recommended, since it was the basis of the project and enabled interconnections between all parts of the work.
- For the construction of a CFD model various software are available and would be able to perform such a task. If more programmes are used (for example a combination between CAD and CFD software) it is recommended to use to same company which can simplify possible conversions.
- The usage of a K-epsilon (k-ε) turbulence model seemed to perform reasonable well and can be recommended.
- In current times simplifications are necessary to stay within computational and time limits. However, test simulations of simplified components are recommended to find possible weaknesses of the model in advance.
- For the validation process of such a large building the usage of temperature distribution maps can be recommended.
- For the full analysis of the thermal environment a combination of both, experimental and simulated methods, is highly recommended.

General methodologies for data acquisition

Even though the spatial density of sensors used in this project can generally be recommended, exact figures would have to be tweaked taking into account major variations in the building. Although an exact number of sensors cannot be recommended, the following methodology for data collection can be considered.

Initially it is recommended to acquire rough measurements and build a basic understanding of the internal environment of the building. The internal geometry of the building also needs to be taken into account in order to be able to develop a research method. Due to the work being carried out in a live environment, health and safety issues must be considered beforehand. Once the internal environment of the building is understood data collection strategies can be developed. In general more measurements are required close to boundaries such as doors or heat sources, especially if measurements are utilised for validation purposes. Fewer sensors are required around areas where the thermal gradient is low, such as large unheated storage areas or tightly packed machining lines. Conversely, a higher sensor density is needed in areas with large thermal gradients, for instance in close proximity to doors, ventilators, or between machining and unheated storage areas, in order to acquire reliable information on boundary conditions. Permanent sensors are best installed in areas where the change in temperature gradient is likely to occur, for example near doorways opening to the outside. Furthermore, it is recommended to monitor high and low temperature areas in order to understand the feasibility of balancing out temperature differences in case of over and or under heating of these areas. The height of sensors needs to be adjusted with respect to the building height and the objectives of the investigation. If the objective of the work is to improve human comfort them sensor height should be set in the area of the average upper body. On the other hand if the objective of the work is to validate a simulation model then an even sensor distribution across the height of the building, taking into consideration accessibility issues, would be recommended.

7.8 The Overall Achievement of Aims and Objectives

All the objectives of this research were fulfilled to work towards the ultimate aim of the project which is highlighted in Table 10. The aim was to; “Develop a method to study thermal performance of large industrial buildings through physical measurements and numerical simulations”. Such a method of study was developed and applied to a large industrial estate.

Objectives	Fulfilments of Objectives
1. Develop an effective data capture system and a standardised procedure in order to collect thermal performance data of large industrial buildings for use in developing validated simulation models	A couple of data collection systems were developed and applied to capture information on internal thermal environment of an industrial plant. The systems and procedures used, including advantages and disadvantages were discussed in section 7.3.
2. To build a simulation model of the plant and using a proven existing simulation tool and validate against the collected data	A simulation model was built with an existing simulation tool (Autodesk CFD) and validated against the all acquired data.
3. Recommendation of a standard procedure for the operational improvement of the thermal performance of similar industrial spaces based on the analysis of, both, measured and simulated data	A set of methodologies were applied to one of the biggest and most complex factories in the UK. Standard procedures were discussed and recommendations made in addition to hints that can help improve future investigations and plant internal environment through physical data capture and simulation.

Table 10: This table explicitly clarifies the fulfilment of the overall aims and objectives within this project.

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Chapter 8

8 Conclusion and Future Work

8.1 Conclusion

In addition to all fulfilled objectives within this study, original contributions to knowledge were created by this research about the evaluation of the thermal environment of a large industrial estate. Different methods, experimental and simulation techniques were created to build knowledge about their advantages and disadvantages. All applied approaches proved their relevance within research and industrial engineering. This work guides the reader along such methods to give hints for application.

Once the actual research problem was understood and defined a methodology for the comprehensive temperature data collection within a large industrial live environment was engineered and tested. In addition to other data collection strategies, tools such as a "Mobile Data Collection System" and a "Fixed Sensor System" were utilised within this methodology to obtain thermal energy data. Results were used to evaluate the thermal environment of the manufacturing plant. Innovative forms of presentation such as three-dimensional indoor temperature distribution maps were created, which were able to support the data analysis, but also the validation process of a simulation model.

One of the most complex building models in open literature was constructed to perform a simulation of the thermal environment of a full scale manufacturing plant including all important components. This model was validated against measured temperature data and improved various times until measured and simulated values showed good agreement to be able to obtain realistic results.

The application of experimental research and the simulation model have both advantages and disadvantages. To perform a comprehensive evaluation of the thermal environment of large scale buildings a combination of both methodologies can be recommended. Only a combination of both techniques showed the full potential of this work. For long term industrial application and consistent improvements the “Fixed Sensor System” was preferred. For scientific applications and spot analysis the “Mobile Data Collection” showed great potential and for a full and comprehensive thermal energy evaluation of a manufacturing plant, the simulation model was the most effective tool. However, such complex models, within current computational limitations, only obtain realistic results in combination with experimental research, due to the process of validation.

All methodologies within this report were engineered, tested and explained and can be used by researcher and engineers in future projects which was the ultimate goal of this work. Therefore, the project was considered to be successful.

8.2 Future Work

In every part of the project additional ideas are able to further this work to the next level. These ideas may not necessarily be cost effective or relevant for industrial use, but could have significant scientific value. This section resents potential future applications for scientists and engineers.

8.2.1 Future Work – Data Collection

- More temperature readings could support a more efficient experimental analysis. Temperatures could not only be collected up to a height of 4.5m, but in the entire building up until a roof height of 25m. Furthermore, more locations on the grid could have been explored. Such an application would require more resources such as time and costs, but more comprehensive temperature maps could have been developed.
- It would also be interesting to collect more temperatures directly within the machinery environment. It was difficult to gather temperatures close to machines do to safety and access issues. This task would not only improve the experimental model, but could also enhance the validation method of a simulation model.
- More fixed sensors could be utilised to gather more data on a finer grid. These sensors are expensive; hence, in this project these sensors were limited to 37 pieces for budget reasons.
- More efficient experimental methods for the evaluation and analysis of fluidal behaviour within large factories can be researched. Especially the experimental research of fluidal behaviour within industrial estates was proved to be a difficult task. It would also be interesting to validate measured against simulated airflow data within such large premises.
- It would also be possible to make a fixed sensor grid for airflow measurements. Sensors are expensive and airflow influences such as open doors, open windows and HV-system management would also have to be collected in order to evaluate an experimental airflow model. This would be expensive but could have great scientific value, because it could be used for the validation process of a simulation model.
- All sensors could have increased accuracies to gather data in a more accurate manner. For this project the sensor accuracy was found to be optimal, it could however be tested, if more expensive sensors would improve the outcomes of such a study.
- Measurement strategies could be improved. It was found that the data collection process, especially with the mobile data collection system required a lot of flexibility

in an industrial live environment. It may be possible to reduce the flexible content to a minimum to develop more accurate collection procedures.

8.2.2 Future Work – Simulation model

- A more accurate model with fewer assumptions could be developed. In current times that would be difficult, because this simulation was performed close to the current technical and computational limits, but once computational power and simulation techniques improve, this might be possible soon.
- In such a model weather conditions such as changing temperatures, wind, radiation of the sun, rain, clouds or effects of humidity could be simulated and energy saving strategies could be optimised according to the gained knowledge.
- It would also be interesting to perform industrial building simulation of entire cycles over the seasons of a year instead of steady state, as soon as computational limits allow such a task. A lot of assumptions around this issue could be improved once such a model is possible.
- Measured airflows could be included in the validation process of a simulation model.
- More exact methods of validations could be developed. For example a more refined grid in terms of temperature measurements, or experimental pressure data could improve such model validation methodologies.
- A lot of scenarios to test potential improvements could be made. This would need a lot of resources such as time, money and equipment, but it could effectively evaluate advantages of such potential improvements.

8.2.3 Future Work – Other Areas of Research

- Multiple case studies, such as the one described within this project, could be undertaken to prove the validity of the used methodologies in other climates with other technical issues.

- Other forms of energy consumption could be evaluated. For example electric energy of machines or air compression would be interesting areas to focus further research.
- It would also be interesting to research the environmental management of such a manufacturing plant. Once strategies are known, it may support implementation of energy reduction methods. Also fixed processes could be improved to enforce continuous energy reduction in the manufacturing plant.
- Future work could also include research on the human comfort within manufacturing plants. If a thermal energy study is made, it could put more attention on the well-being of employees.
- A new BMS (Building Management System) could be developed for the utilisation within existing manufacturing plants.
- New HVAC systems could be evaluated and included in the manufacturing plant if feasible.
- Insulation issues within the manufacturing plant could be improved

However, most of these tasks would be great from a scientific kind of view, but would probably not have such a great impact on cost and benefit as the study which was described in this report. This project enabled scientific energy research of industrial large scale thermal environments, in order supports the ultimate goal of energy reduction.

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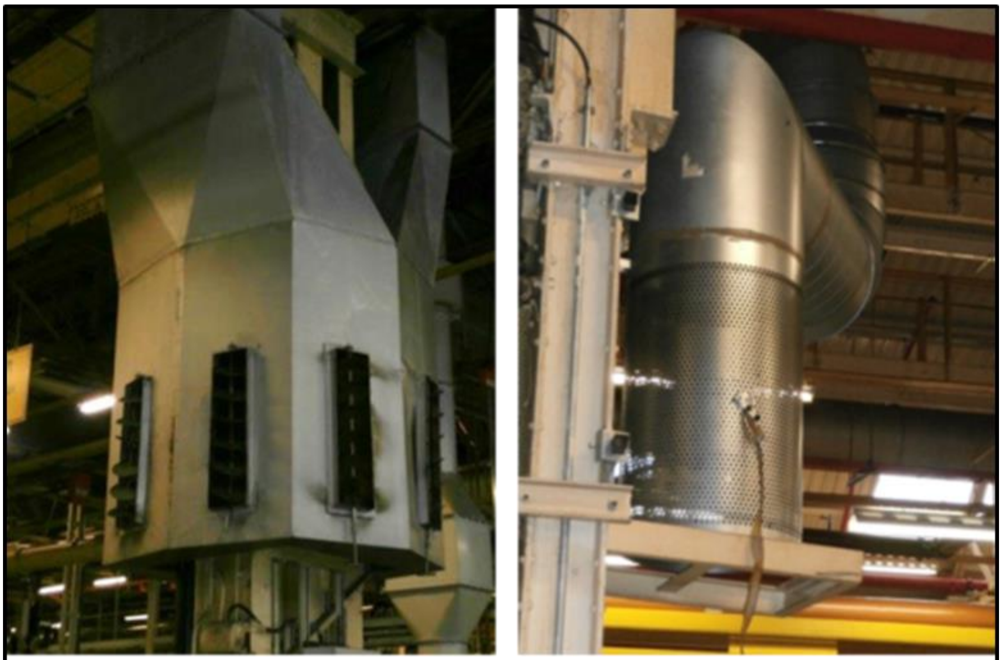
10 Appendix

Appendix A

At the beginning of the project an initial visual inspection was made, to be able to understand the thermal environment and its known issues and to plan further progression. Appendix A shows some of the existing equipment but also visible problems to give the reader a brief overview.



Old Diffusor Main Type

New Krantz Diffusors

Figure I: Comparison between different diffusor types within the DEP.

Figure II: Additional heating units which support the main heating system in the DEP. These Units are referred to as "Myson Heaters".

Open Double Doors Broken Maintenance Doors

Figure III: Consistently open double doors and broken maintenance doors show two examples of large leakage issues within the DEP.

Fire Door Leakage Airflow Diffusion Trials

Figure IV: Further leakages at fire doors but also attempts to reduce leakages are shown.

Figure V: A typical example of a CNC machine which operates in the DEP shown from all angles.

Appendix B

To store, reduce and analyse all collected data a database was developed. The following Table I shows all tables and their columns within the database. Appendix B gives hints how the database was used within this Project, which explains how the usage of a database could improve future projects as well.

ColumnLoc	**ID**	**ColLoc**	x	**y**
Describes coordinates of columns in m	Key number; Numbering fields in column	Names the Column Locations of the DEP	Shows the width of the plant in m (in east to west direction)	Shows the length of the plant in m (in north to south direction)
EnvironmentalCondT	**ID**	**DateEnv**	**TimeBST**	**TemperatureinDeg**
Table to Log Weather Data from Weather station at LCY Airport Approximately 7km away from the DEP	Key number; Numbering Fields in Column	Date and time of measurement.	Shows time according the winter and summer time	Temperatures in degrees Celsius
	WinchillInDeg	**DewPointInDeg**	**HumidityinPc**	**PressureInPa**
	Wind chill in degree Celsius	Dew Point in Degrees	Humidity in Degrees	Absolute pressure in Pascal
	VisibilityInKm	**WindDir**	**WindSpeedInKmh**	**WindSpeedInMs**

	Visibility in km	Wind direction	Speed of wind in kmh^{-1}	Speed of wind in ms^{-1}
	Gust Speed	**Events**	**Conditions**	**Comments**
	Gust Speed of Wind	Weather events such as rain or fog	Actual weather conditions more accurately than events	Manually entered comments if needed
ManualLogT	**ID**	**DateManLog**	**TimeManLog**	**Location**
Manually logged airflow and humidity with in the DEP	Key number; Numbering Fields in Column	Date of log	Time Of log	Column location of DEP
	DraftHDirection	**DraftHvelocity**	**DraftMdirection**	**DraftMvelocity**
	Draught direction in 4m of height	Draught velocity in 4m of height in ms^{-1}	Draught direction in 2.20m of height	Draught velocity in 2.20m of height in ms^{-1}
	DraftLdirection	**DraftLvelocity**	**Humidity**	**Comments**
	Draught direction in 0.75m of height	Draught velocity in 0.75m of height in ms^{-1}	Humidity in percent	Manually entered comments if needed
	DateTime	**WindDirection**	**WindSpeed**	**OutsideTemp**
	Date and time of log in one field for better comparison with other tables	Draught direction of wind	Wind speed in ms^{-1}	Outside Temperature
PicoT	**ID**	**DatePico**	**TimePico**	**Location**

Data collected by the mobile data collection system, Pico PC-08 logging system with thermocouples in 5 different heights	Key number; Numbering Fields in Column	Date of measurement	Time of measurement	Grid column location of measurement within the DEP
	SampleNr	**llChannel2**	**hmChannel3**	**hhChannel4**
	Sample number of each set of measurement. Mostly collected in 500 sets.	Temperatures of channel 2 in 0.15m of height	Temperatures of channel 3 in 3m of height	Temperatures of channel 4 in 4.5m of height
	hlChannel5	**lhChannel6**	**Comments**	**DateTime**
	Temperatures of channel 5 in 1.35m of height	Temperatures of channel 6 in 1.30m of height hidden under trolley plate	Manually entered comments if needed	Date and time of log in one field for better comparison with other tables
TinyRadioT	**Sampnr**	**DateTime**	**P-23TL**	**P-41TL**
Data of Tiny Radio fixed data loggers, automatic temperature and humidity log	Sample number assigned by Tiny Radio system	Date and time of measurement	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	W-24H	**W-24TM**	**J-08H**	**J-08TM**
	Location grid column of DEP, Humidity measurement at 3m	Location grid column of DEP, Temperature measurement at 3m	Location grid column of DEP, Humidity measurement at 3m	Location grid column of DEP, Temperature measurement at 3m
	M-36H	**M-36TM**	**B-16TL**	**P-08TL**

	Location grid column of DEP, Humidity measurement at 3m	Location grid column of DEP, Temperature measurement at 3m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	P-15H	**P-15TM**	**W-38TL**	**C-25TL**
	Location grid column of DEP, Humidity measurement at 3m	Location grid column of DEP, Temperature measurement at 3m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	J-16TL	**T-48TL**	**T-12TL**	**M-18TL**
	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	C-43TL	**C-43TH**	**J-43TL**	**T-36TL**
	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at Truss Height	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	G-19TL	**M-26TL**	**B-08TL**	**J-33TL**
	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70
	G-11TL	**G11TH**	**M-11TL**	**T-25TL**

	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at Truss Height	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	T-25TH	**N-50TL**	**N-50TH**	**J-23TL**
	Location grid column of DEP, Temperature measurement at Truss Height	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at Truss Height	Location grid column of DEP, Temperature measurement at 1.70m
	G-49TL	**W-12TL**	**P-32TL**	**G-37TL**
	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m
	A-34TL	**G-29TL**	**T-17TL**	**-**
	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	Location grid column of DEP, Temperature measurement at 1.70m	-
TinyT	**ID**	**DateTime**	**TimeTiny**	**SampleNrTiny**
Old fixed data loggers include outside temperature	Key number; Numbering Fields in Column	Date and time of log in one field for better comparison with other tables	Column was just made to make sure the time of tiny is the same as other date time, but is empty	Sample number assigned by Tiny logging system

	TinyNOut	**TinyNIn**	**TinySOut**	**TinySIn**
	Outside temperatures in the north	Temperatures in the northern plant middle	Outside temperatures in the south (data was rarely used because of strong sun influences)	Temperatures in the southern plant middle

Table I: Shows all tables which were integrated in the Database to be able to store, query and then output the presented data within this report. There is another table "PlantT" which is not shown due to its large size. It shows details within the plant at every column location but was mainly used to coordinate column locations in some of the queries.

Appendix C

Before a CFD simulation was performed an initial CAD Model of DEP had to be created. As mentioned in the main part of the report, a two dimensional CAD model was transformed into a 3 dimensional AutoCAD model, before it was converted into an Autodesk Inventor model. Appendix C shows the initial CAD model.

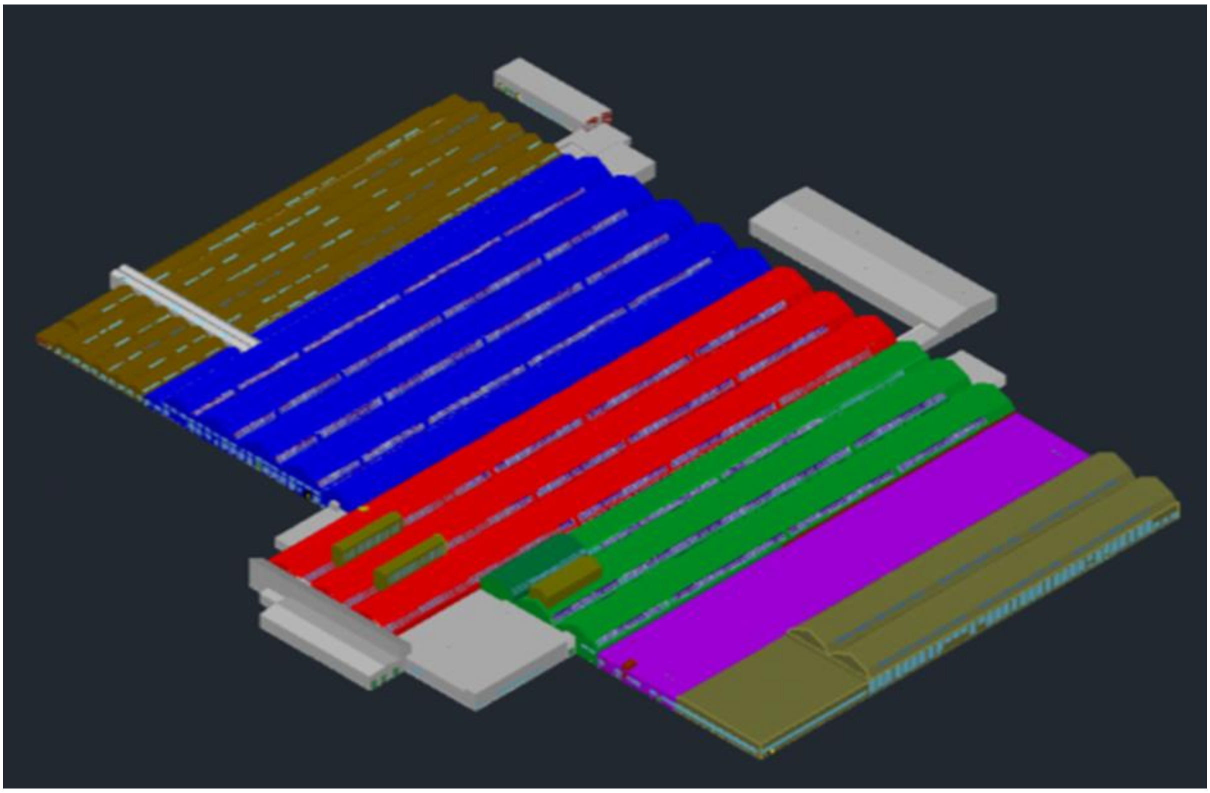


Figure VI: Initial AutoCAD model of the DEP before it was converted to an Autodesk Inventor model and simplified for CFD simulation.

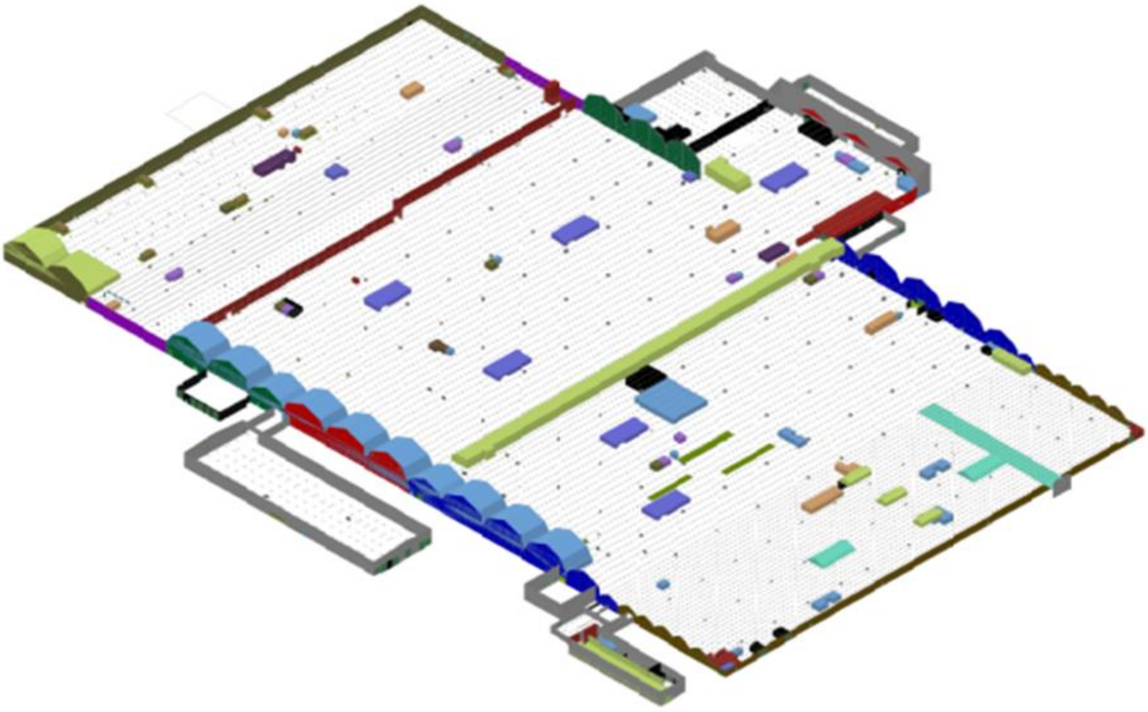


Figure VII: Shows the interior of the initial CAD model including lights, diffusors, restrooms, offices and plant rooms. However, at this point there were no machines, extraction bars or ventilation pipes included.

Figure VIII: Shows the Tiger head line with machines, columns, extraction units, electric panels and conveyors. A lot of these details of the initial CAD model were simplified for the simulation.

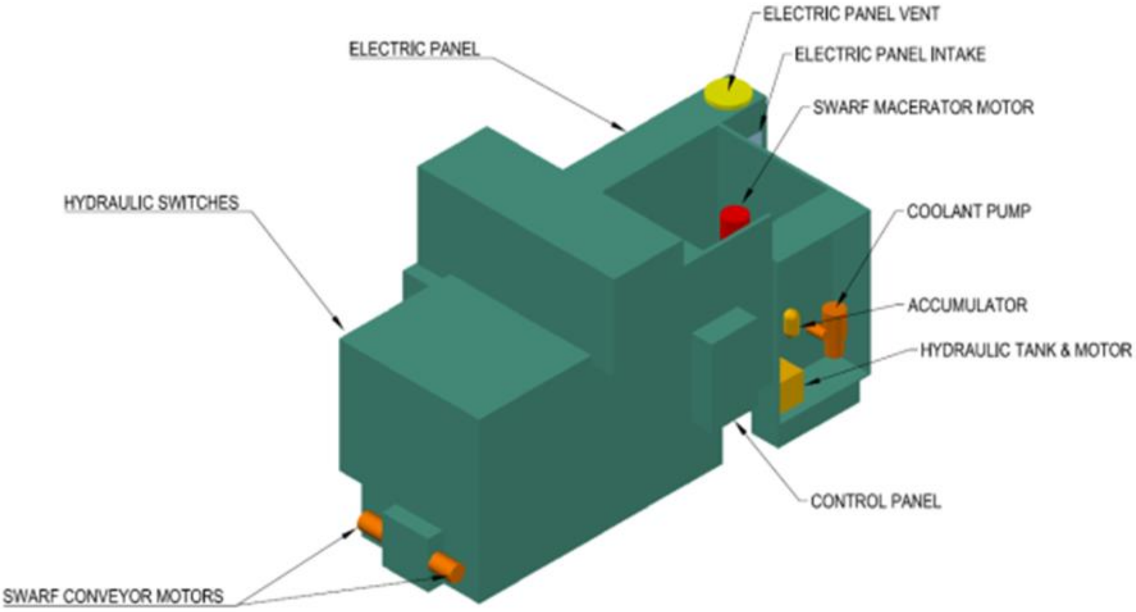


Figure IX: Initial CAD model of a CNC machine. It was mainly used to understand the complexity and the temperature transfer of a CNC machine.

Machine Parts	**Surface Temperature in ˚C**
Machine Main Body	22
Swarf Conveyor Motors	32
Control Panel	27
Hydraulic Tank & Motor	24
Accumulator	30.5
Coolant Pump	36.1
Swarf Macerator Motor	27.5
Electric Panel Intake	-
Electric Panel Vent	38.2
Electric Panel	31.0 - 27.0
Hydraulic Switches	45.5

Tabelle II: Average surface temperatures of CNC machines were obtained by a surface thermometer.

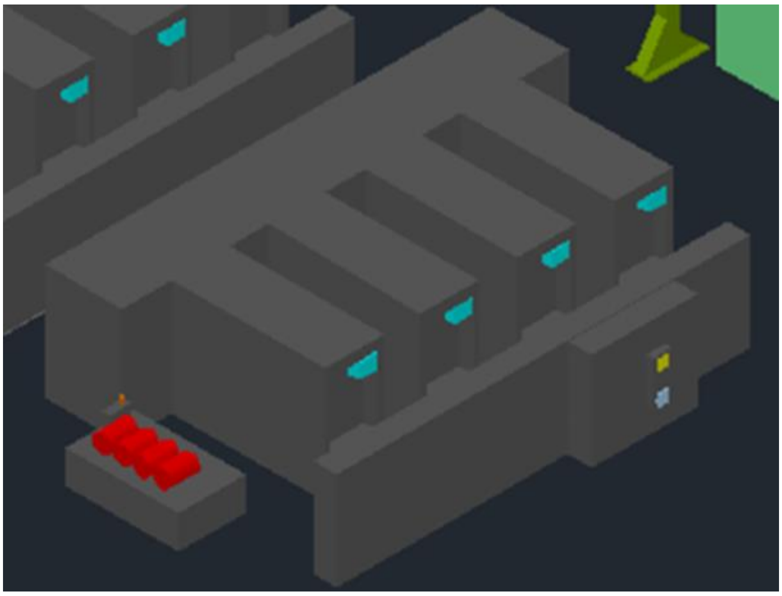


Figure X: Shows another machine within the initial CAD model. In this case a transfer machine is shown.

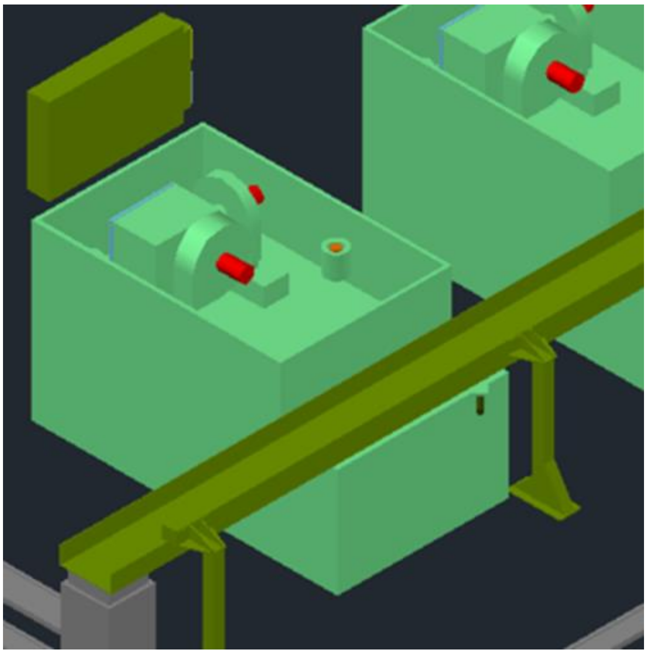


Figure XI: Shows a large scale washing machine of the initial CAD model.

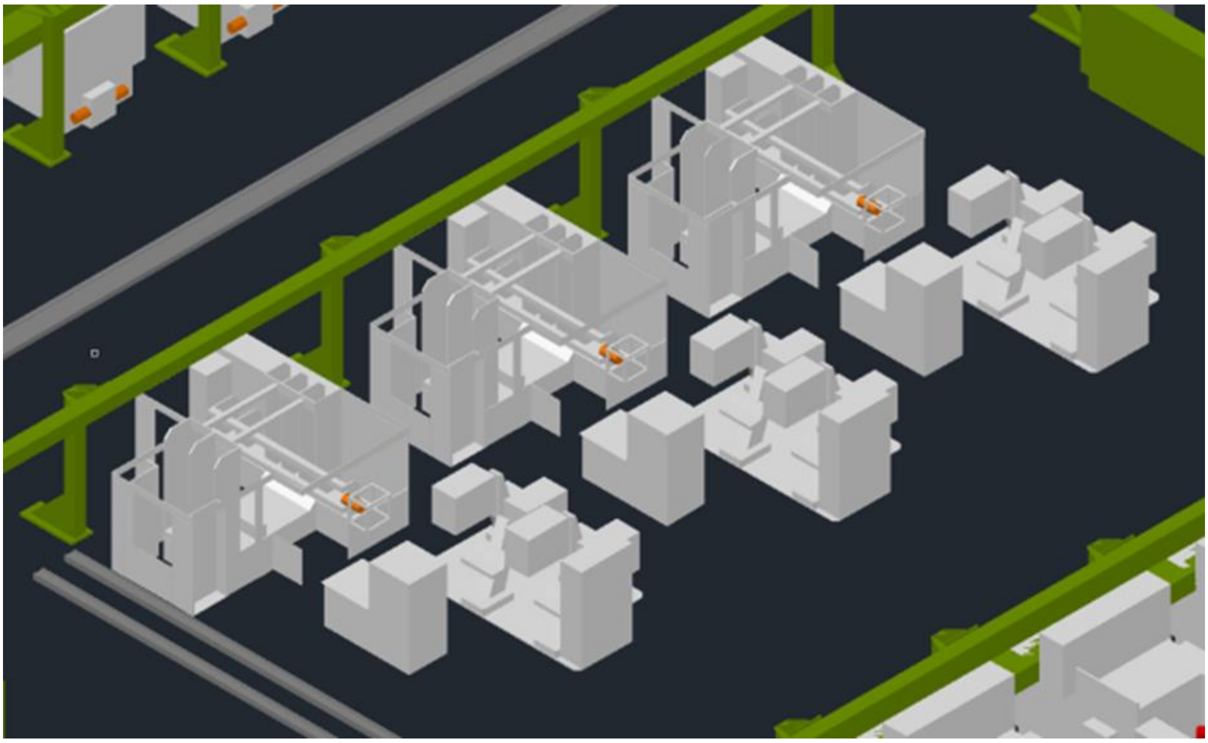


Figure XII: Sorting and bolting machines are shown by this figure.

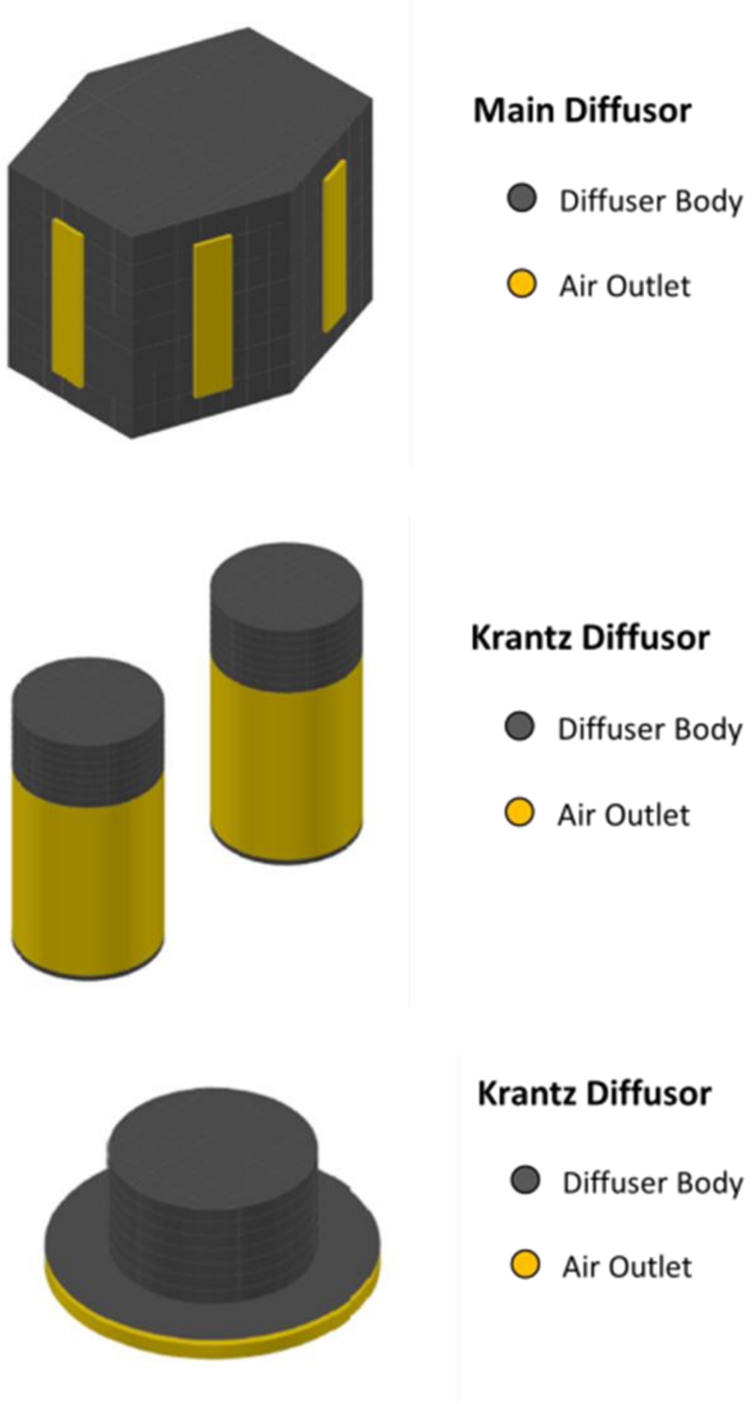


Figure XIII: CAD models of typical diffusors within the DEP were created to support a realistic CFD simulation.

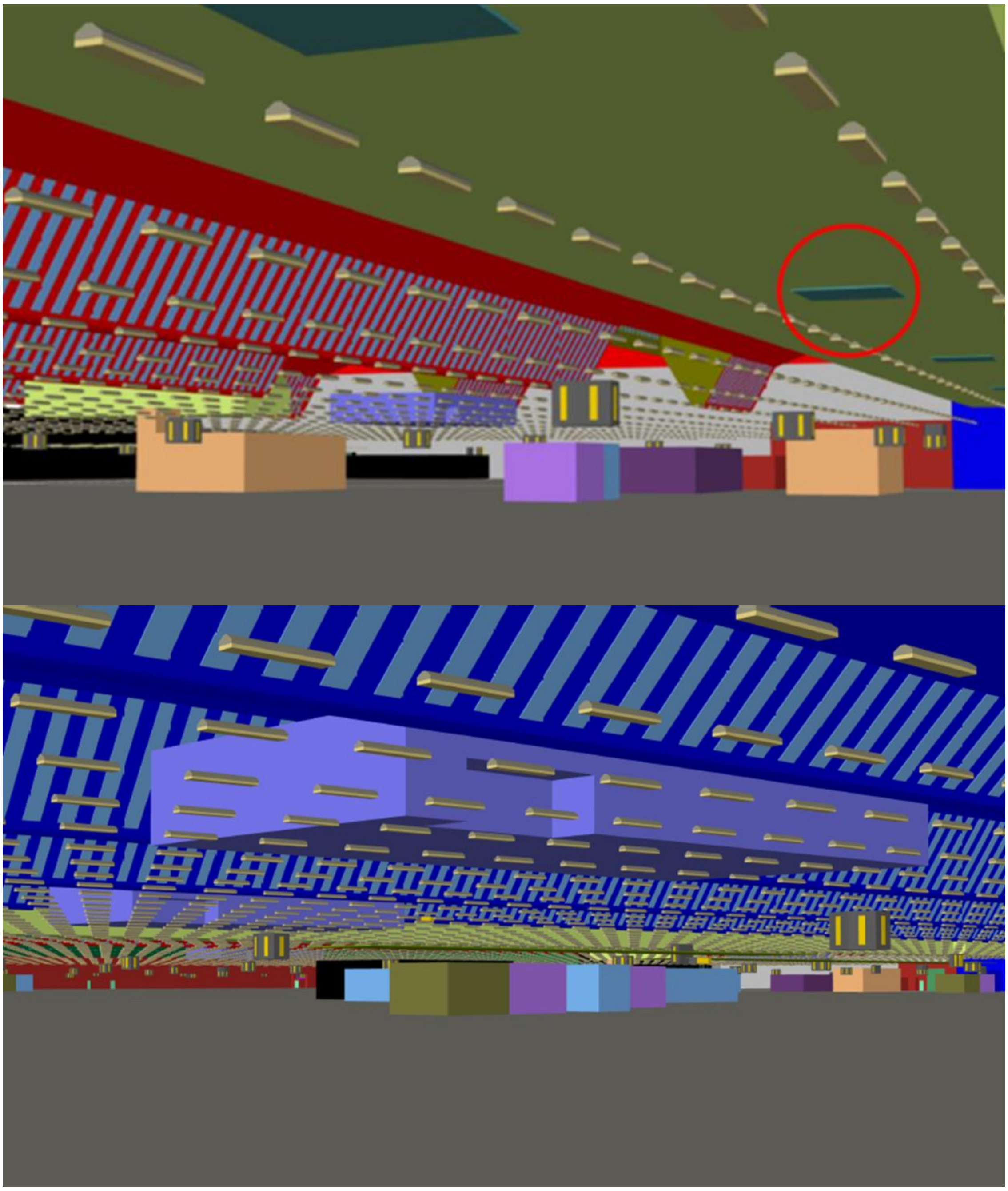


Figure XIV: Further CAD Models of Plant rooms Roof fans, “Myson heaters” lights and roof windows are shown. Basically most of the interior except machines, columns and pipe works can be seen.

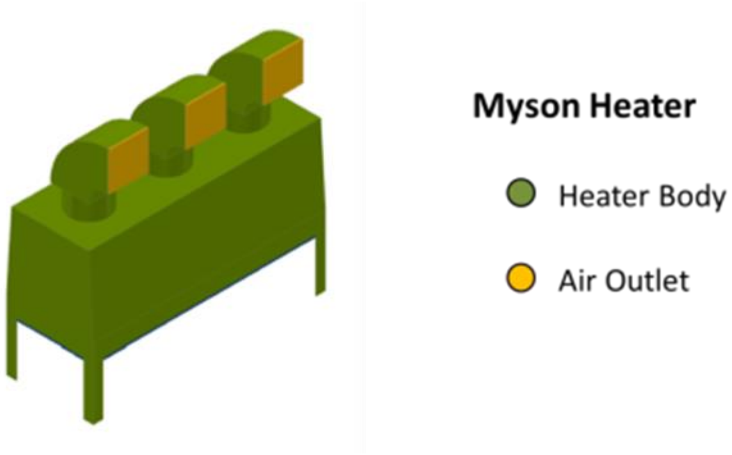


Figure XV: Shows a CAD model of one of the "Myson heaters" which was photographed in Figure II. Such heating units exist with two or three diffusor heads.

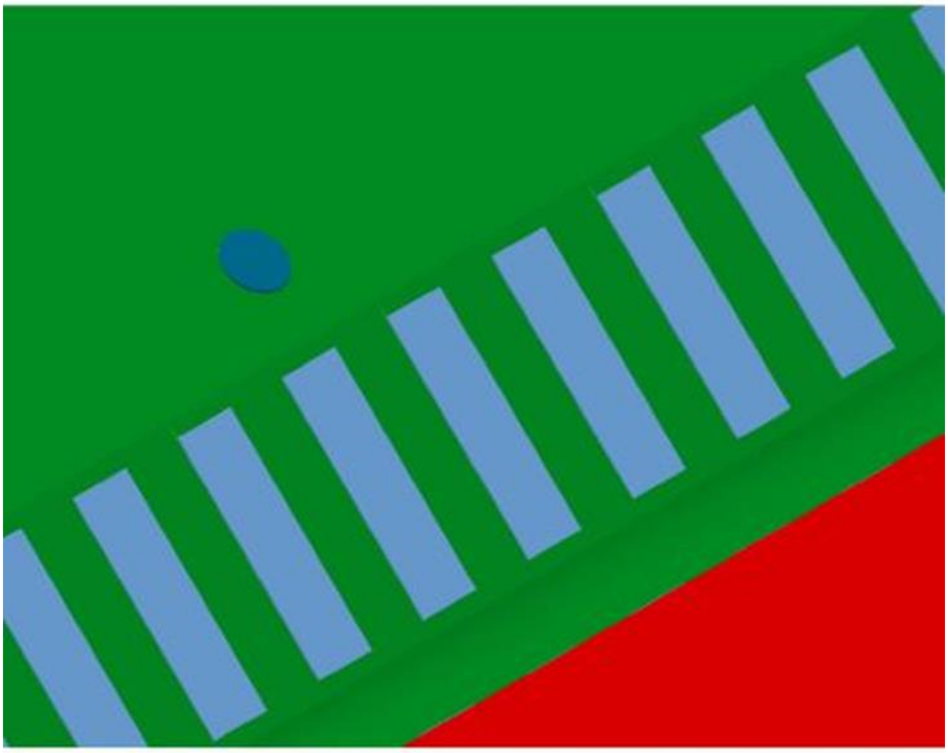
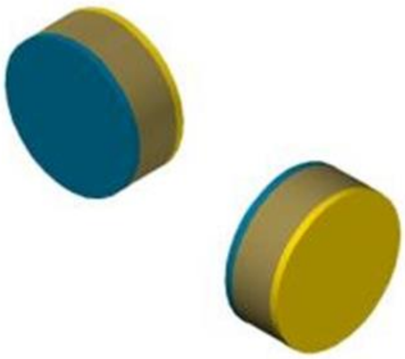


Figure XVI: Roof windows and roof extraction fans can be seen.



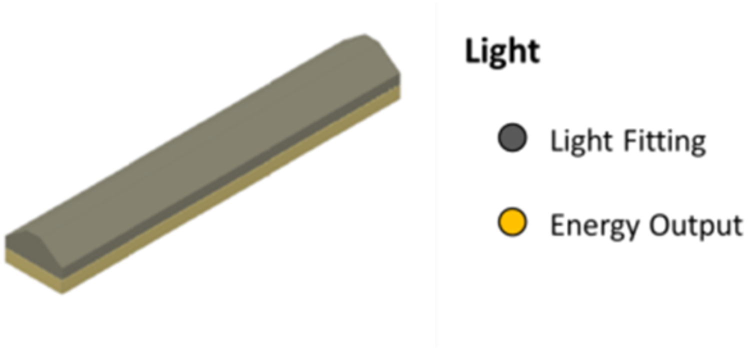


Figure XVII: Shows Fans within the building and the model for lights.

Appendix D

Appendix D shows the actual Autodesk Inventor model which was then simulated. This model is already converted and simplified so all simulated features can be seen. However, the first Figure XVIII shows the first AutoCAD to Inventor conversion attempt.

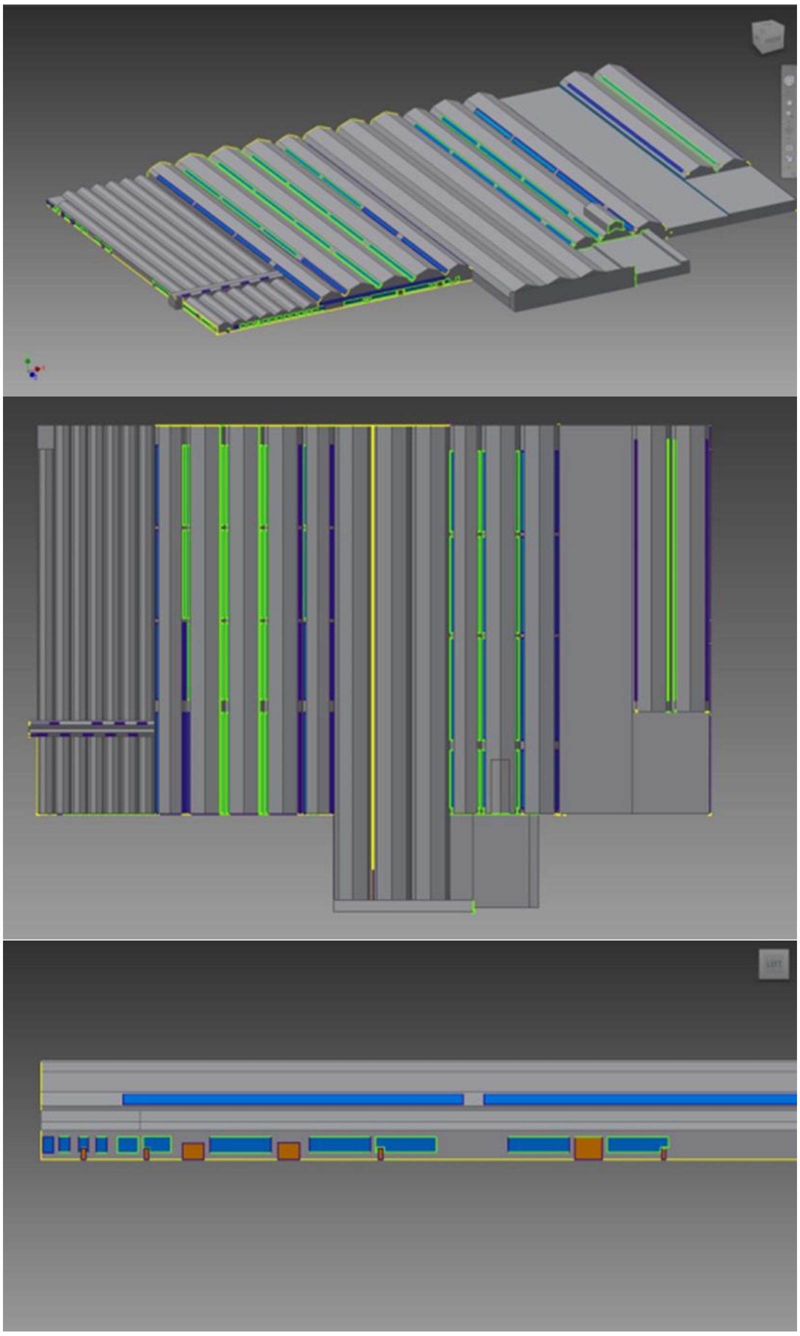


Figure XVIII: The external shell of the initial Inventor model is shown from 3 different angles.

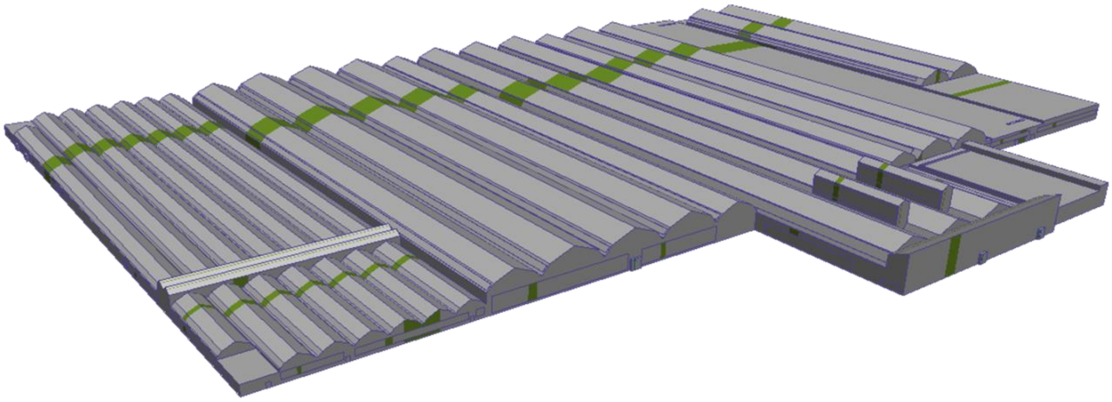


Figure XIX: Building shell of the Inventor model where the CFD simulation was performed. Some parts of the building had to be improved after the first conversion. Test runs also showed weaknesses in the first leakage approach, which was the reason that in evolved into the simulation which was explained in the main part of the report.

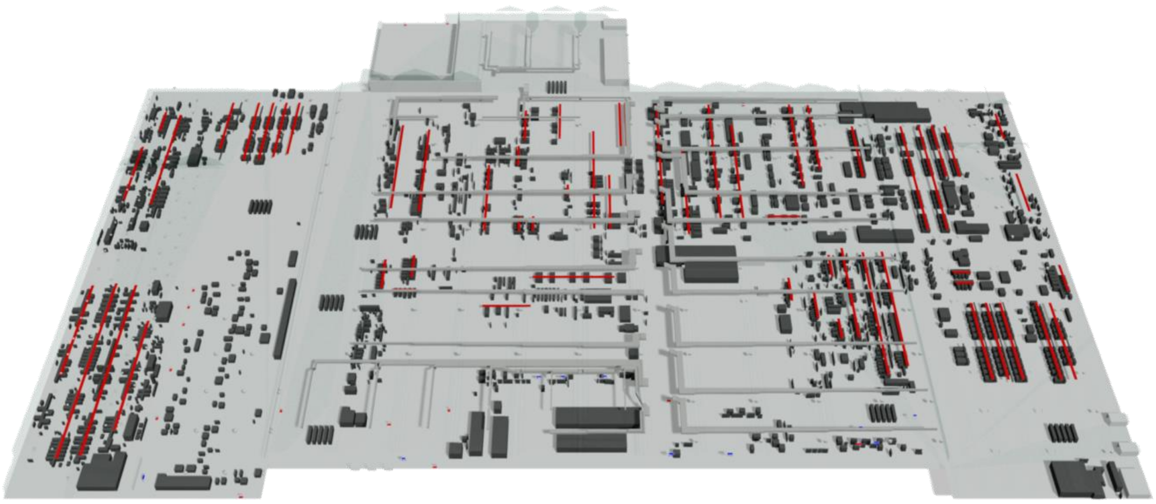


Figure XX: This was the interior of the final Inventor model and shows all parts of the simulation: Machines, extraction systems, restrooms, offices, some of the main duct works, diffusors additional heating units and stock of components in storage areas.

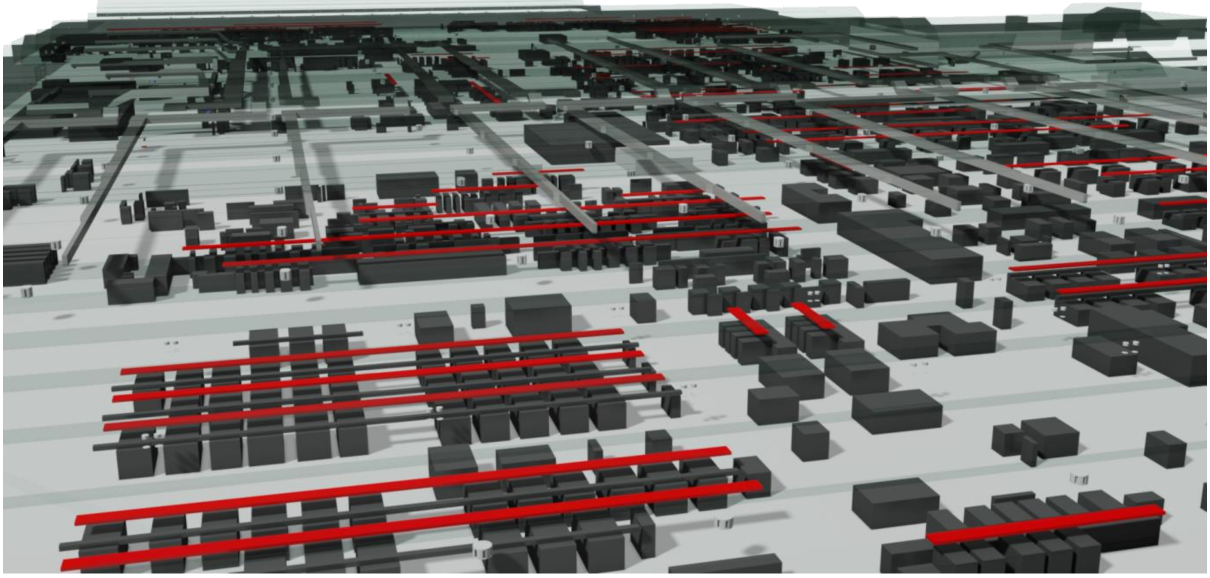


Figure XXI: Shows a zoomed view from a different angle to inspect the model interior more closely.

Appendix E

Before the actual simulation was approached various test simulations were done to understand multifarious aspects of the task. Appendix E shows some of these test simulations which were performed before the actual model was built. It was important to understand the behaviour of a modelled diffusor or the simplifications of lights to get some feeling how simplifications would affect the model. However it became clear that most simplifications had an effect on the immediate environment, but such effects where less significant if a larger area was observes as shown with the lights.

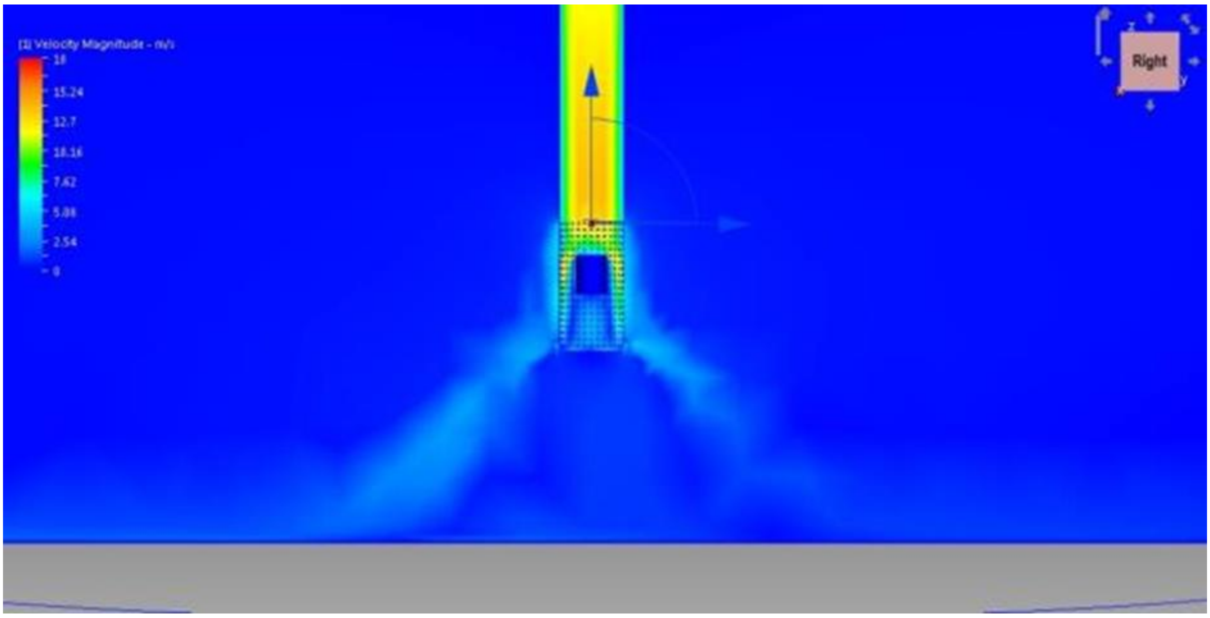


Figure XXII: Test simulation of one of the diffusor heads (Krantz diffusor).

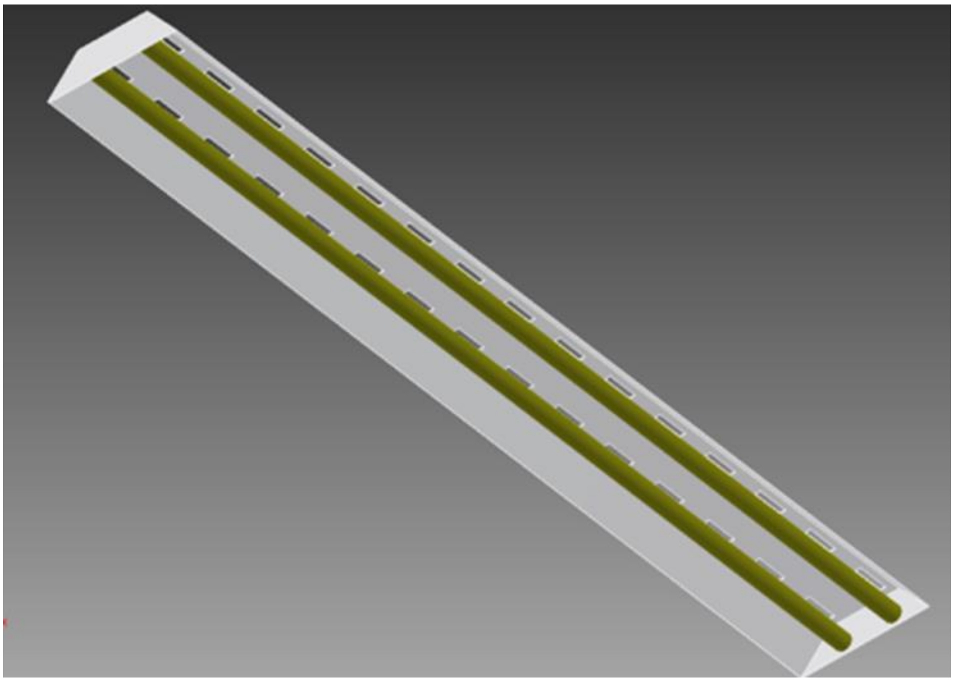


Abbildung XXIII: ***Inventor model of a detailed double light fitting***

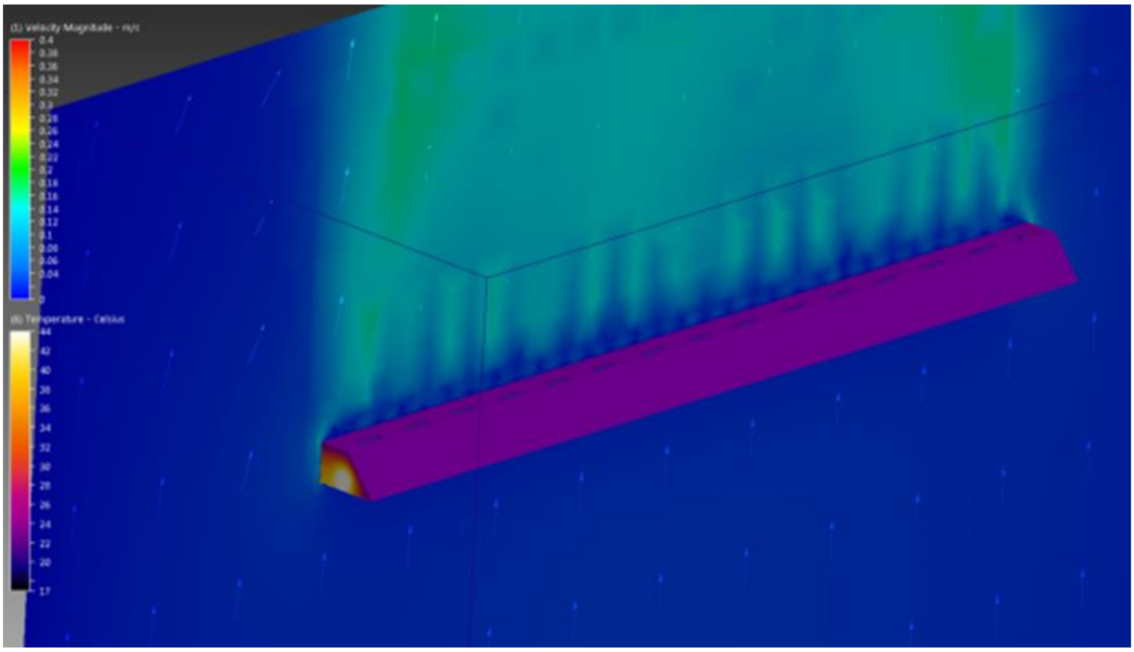
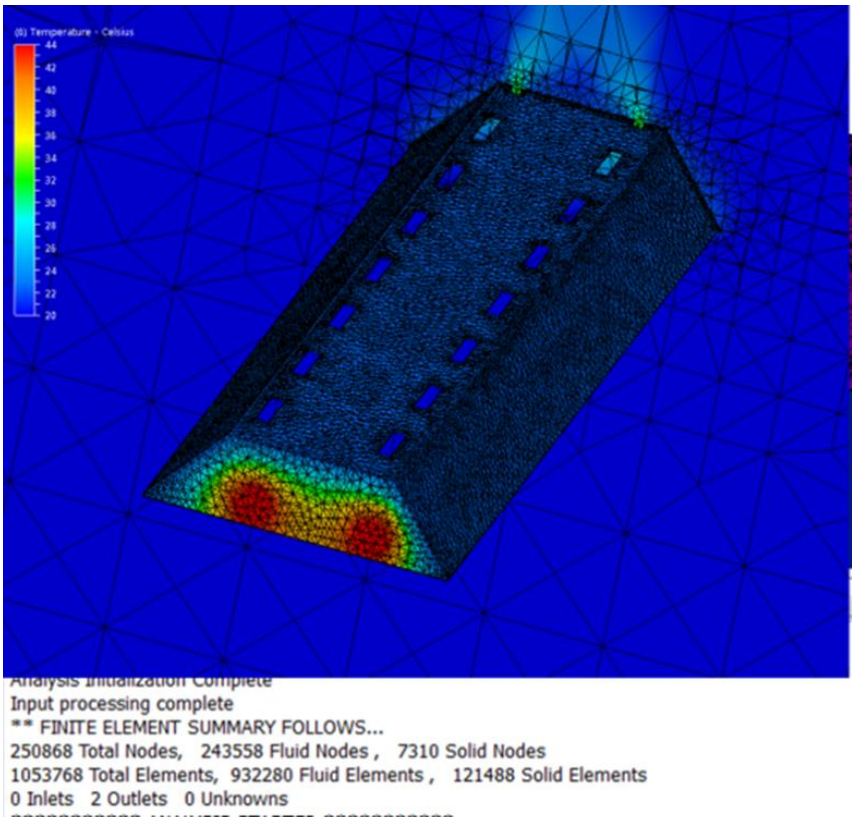


Figure XXIV: Simulation of a detailed double light fitting



```
Analysis Initialization Complete
Input processing complete
** FINITE ELEMENT SUMMARY FOLLOWS...
250868 Total Nodes,   243558 Fluid Nodes ,   7310 Solid Nodes
1053768 Total Elements,  932280 Fluid Elements ,   121488 Solid Elements
0 Inlets   2 Outlets   0 Unknowns
```

Figure XXV: Trial runs with different meshes to find acceptable accuracies.

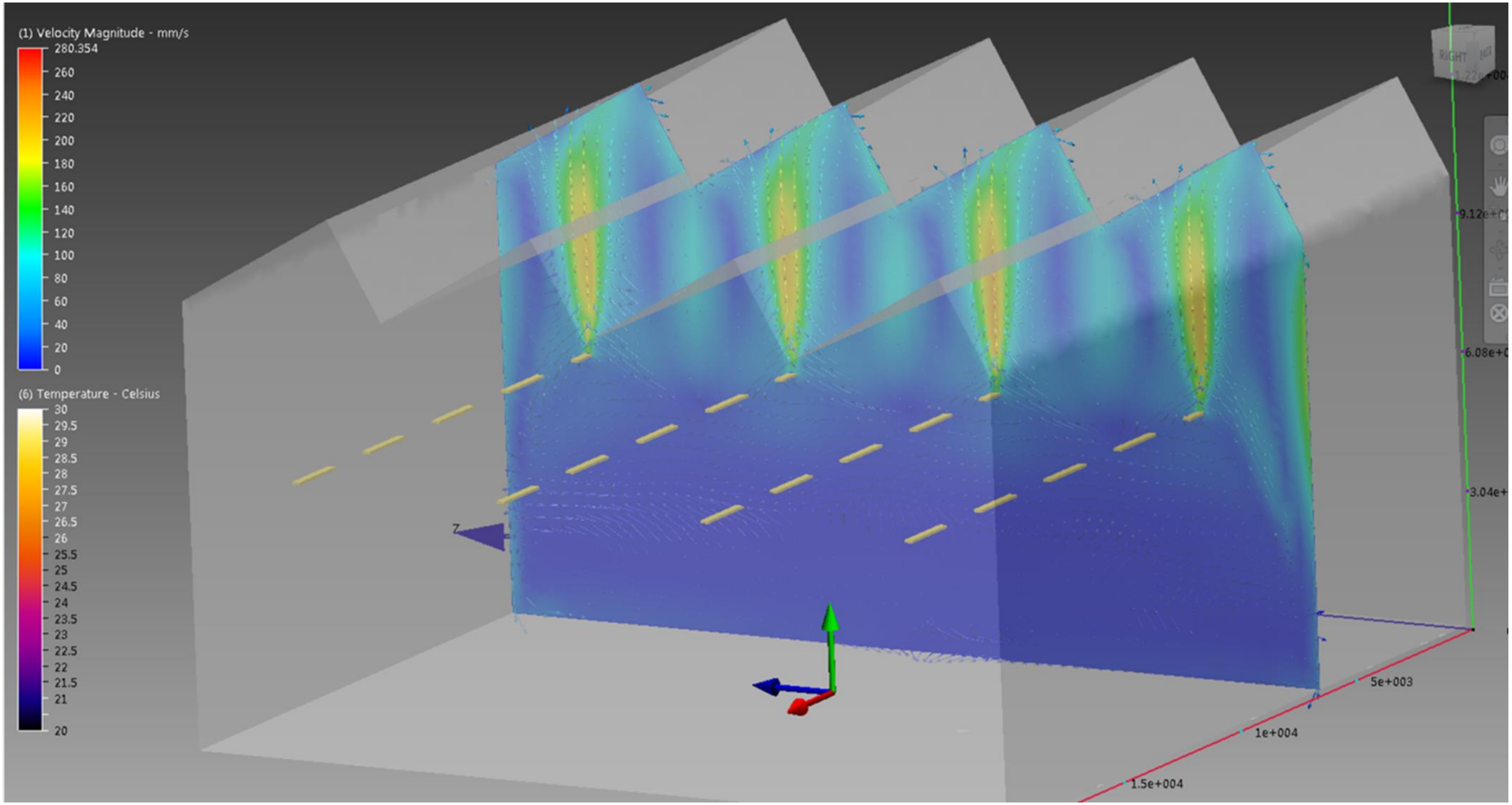
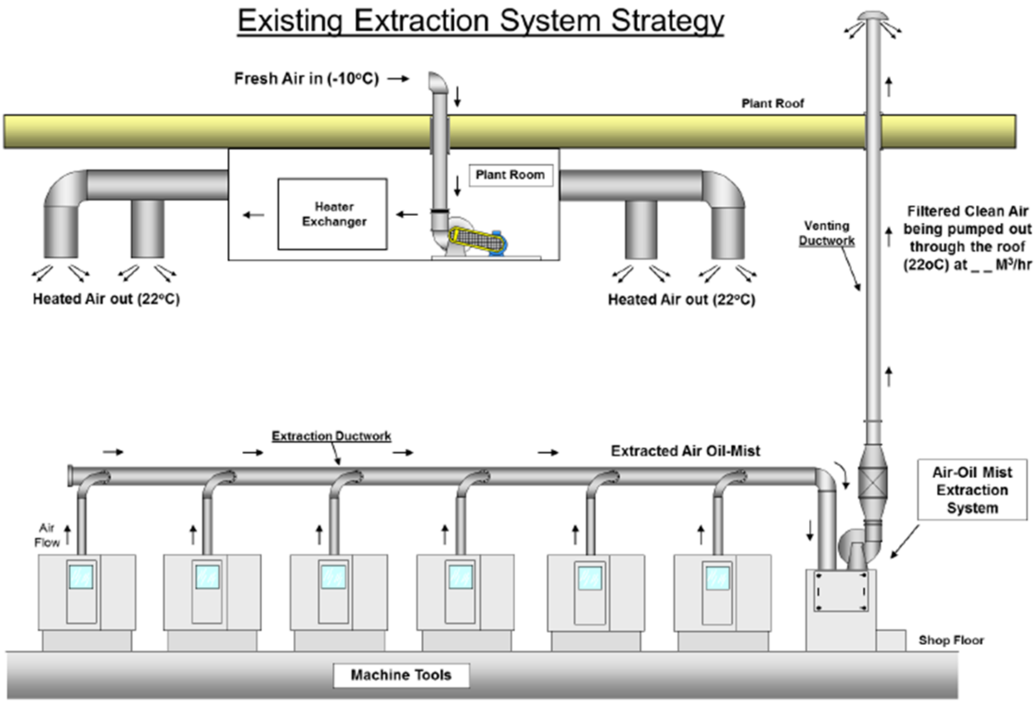


Figure XXVI: Test simulation with simplified light bulbs in a larger environment, to understand the impact of simplification. Especially observations from greater distances on this image differences had less impact than in the immediate environment such in Figure XXIV.

Appendix F

Appendix F shows an example how the extraction values were collected and stored for boundary conditions within the simulation. Additionally a drawing of such an extraction system show how extraction is performed.

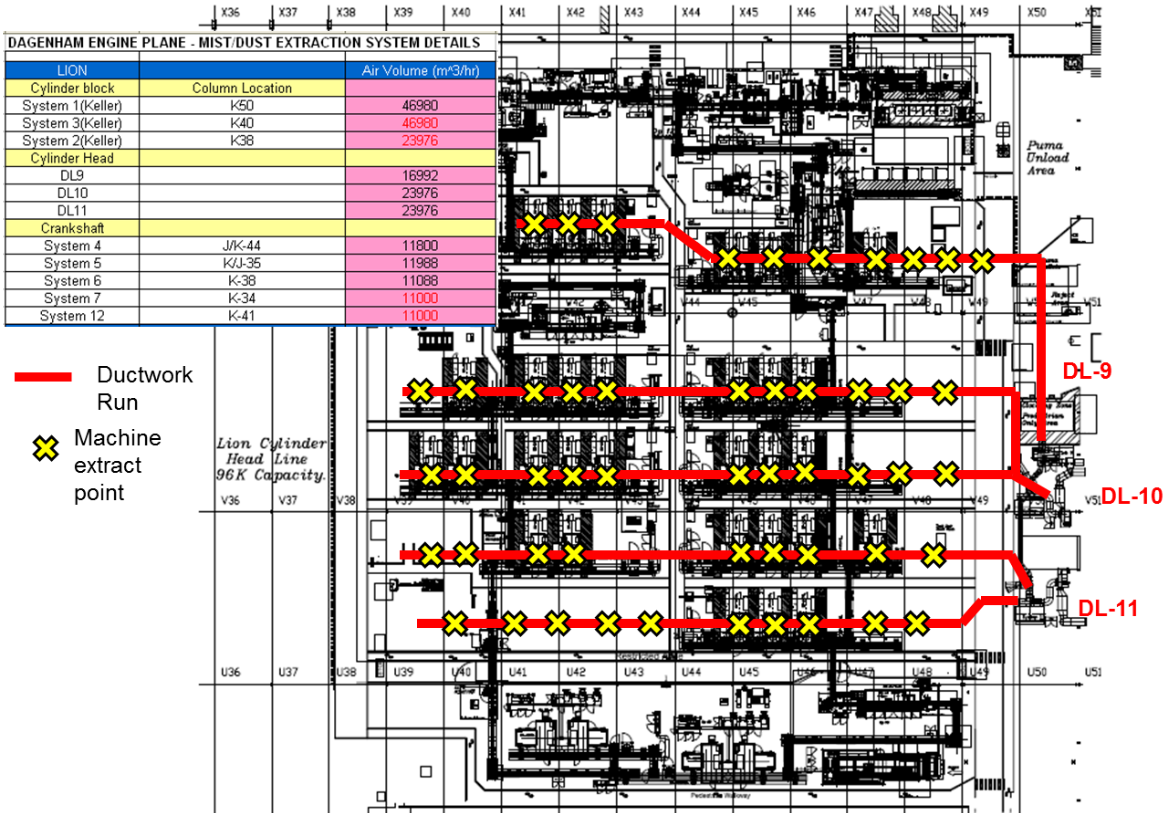


1) The ductwork of the system has mechanical dampers, which are adjusted and fixed in position at the commissioning stage. Whether all machine tools are running, or not, the extraction system still runs at the same speed and uses energy.

2) The Plant Rooms have no EMS system in working operation to control the on/off of the motors and once turned on, they will continue to run, irrespective of whether the plant has reached working temperature.

Figure XXVII: Extraction systems as they are used in the DEP (Ford 2013b)

Lion Systems – Cylinder Head Line



DAGENHAM ENGINE PLANE - MIST/DUST EXTRACTION SYSTEM DETAILS

LION		Air Volume (m^3/hr)
Cylinder block	Column Location	
System 1(Keller)	K50	46980
System 3(Keller)	K40	46980
System 2(Keller)	K38	23976
Cylinder Head		
DL9		16992
DL10		23976
DL11		23976
Crankshaft		
System 4	J/K-44	11800
System 5	K/J-35	11988
System 6	K-38	11088
System 7	K-34	11000
System 12	K-41	11000

Figure XXVIII: This image shows an example for the extraction of one of the observed machining lines. In this case the cylinder head line for the Lion engine is shown.

Appendix G

Appendix G shows an example how thermography was used applied next to a surface thermometer to understand the heat output of machines.

Lion Systems – Cylinder Block

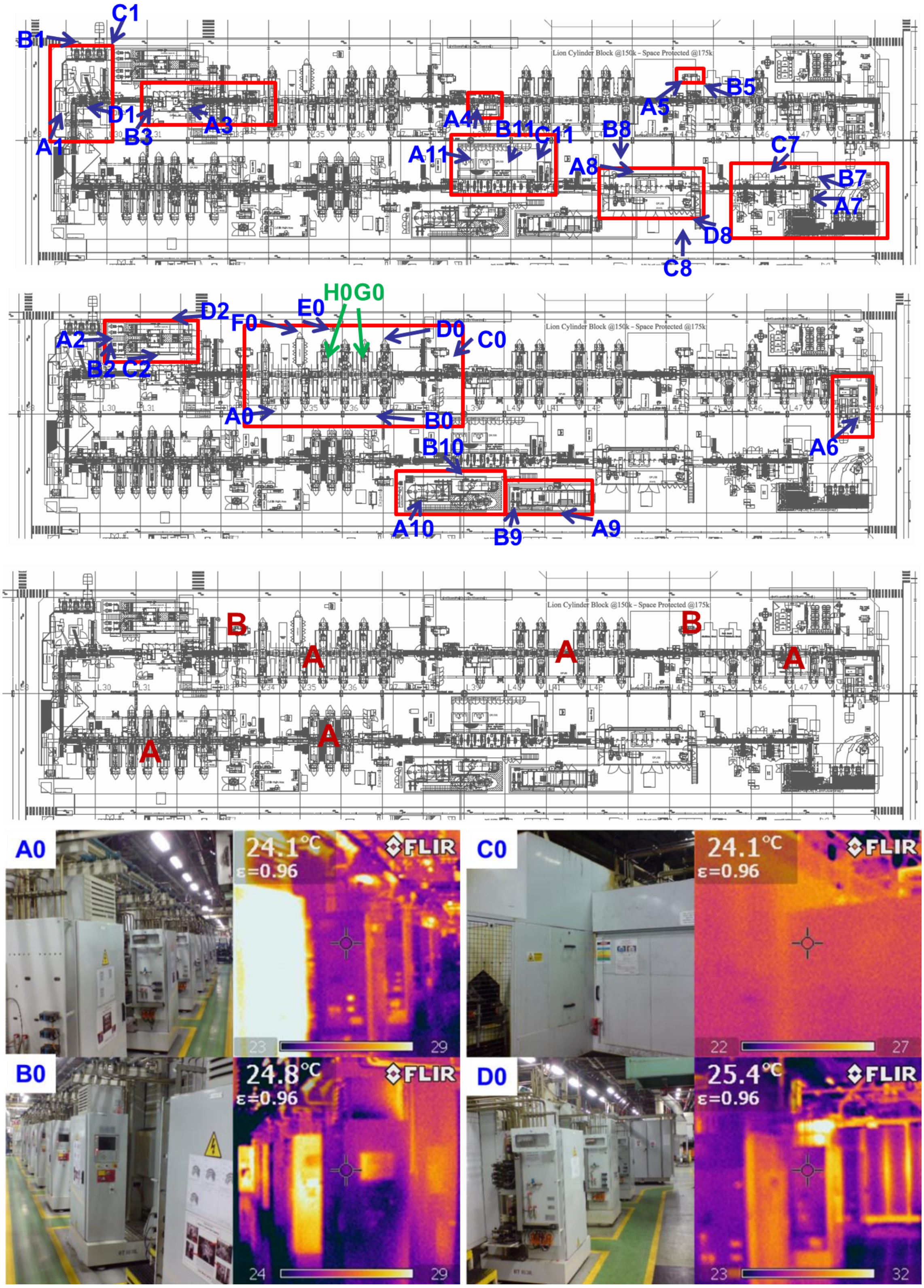


Figure XXIX: Shows one example on how thermography was used to support the CFD simulation. In this case the cylinder block line for the Lion engine is shown.