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Thesis
Volume 1

Systematic Engineering of Industrial Ovens

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Abstract

This EngD research is aimed at improving low-grade industrial ovens (less than 250°C) in the manufacturing industry. Industrial ovens have a significant bearing on the environmental and economic impacts of a manufacturing factory due to their excessive fossil fuel consumption and influence on product quality. Therefore, this thesis’ research question is: How can manufacturers improve the environmental and economic performance of industrial ovens?

Research on industrial oven improvement is under-developed and there are significant improvement opportunities within many industrial-heating processes. Manufacturers traditionally prioritise economic assessment when evaluating capital investment projects and it is important that systematic engineering of industrial ovens align energy saving and process enhancement with key business interests. Furthermore, there is a need to incorporate stakeholder perspectives when improving oven processes.

This thesis consists of three bodies of research, which all develop ways to improve the environmental and economic performance of industrial ovens:

1. Energy saving through process optimisation
2. Process enhancement considering both energy consumption and product quality
3. Developing sustainable industrial ovens

The key research outputs from this thesis are shown below:

- There are two options to reduce energy consumption: a) Optimise the process by changing parameters, or b) Innovate the process by changing the way the heat is supplied to an oven.
- System airflow can often be reduced by up to 30%. This was demonstrated at two factories and three oven systems, and has reduced gas energy consumption by 4,536,000 kWh and cut carbon emissions by 836 tCO₂e per year. This has delivered a combined annual cost saving of £121,000.
- Installing sufficient control capability enables heating processes to be optimised throughout their life, to meet changing requirements.
- A novel approach of polymer cure characterisation has been developed that combines DMTA and a free phenol/CIE-Lch test. This demonstrated that temperature variation within a festoon oven results in dramatically different cure conversion (complete conversion time ranges from 73 to 40 minutes depending on location) and product quality.
- A novel multi-criteria analysis method incorporating sustainability indicators from stakeholder’s perspectives has been developed for oven optimisation.
- Retrofitting gas-fuelled processes with biomass technology is not economically viable. Alternative schemes that negate capital cost from the business would significantly enhance biomass viability.
- Biomass technology is more viable in newly-built processes than retrofit scenarios.
- EU Emission Trading Scheme (ETS) is an effective tool to encourage uptake of biomass heating technology in the manufacturing industry.

This study demonstrates that there is opportunity to improve low-grade heating processes in the manufacturing industry. The environmental and economic performance of industrial ovens can, and should, be improved to help the manufacturing industry move towards a more sustainable future.
Readers’ Guide

This thesis consists of two volumes. Volume 1 presents the key research methods and findings, while Volume 2 presents the collated six-month reports showing the progression of research.

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### Appendix A
- Paper published in Journal of Applied Thermal Engineering

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### Appendix C
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- Paper published in the Journal for Clean Technologies and Environmental Policy.

### Appendix E

### Appendix F
- Paper published in the Journal of Cleaner Production.

### Bibliography

**Thesis**

Frederick Pask
Executive Summary

1. Introduction

Process heating within industrial ovens is a commonplace in the manufacturing industry. Industrial ovens consume a substantial amount of energy and have a large effect on the final product quality. Therefore, understanding the environmental and economic impact of oven operation is an important objective for manufacturers. The research question of this study is: How can manufacturers improve the environmental and economic performance of industrial ovens?

Greenhouse gas (GHG) emissions from fossil fuel combustion is the key environmental impact from industrial oven activity (Sahhukhan et al., 2014). Industrial CO₂ is responsible for 40% of total global GHG emissions, and it has been estimated that if the industrial sectors were to remain unchecked, total global CO₂ emissions would increase by 74-91% by 2050 compared to a 2007 baseline (IEA, 2010). Heating applications consume almost one fifth of all industrial energy (EERE, 2013) and therefore, ovens have a substantial energy footprint. Minimising energy consumption in ovens is important for manufacturers to help reduce their GHG emissions and to comply with environmental regulations.

Energy consumption and product quality are the two key factors that impact on the economic performance of industrial ovens. Minimising energy consumption reduces operational costs, while minimising process variation can impact on product quality, safety and operational efficiency. Process understanding leads to variation reduction and is critical for manufacturers to be competitive in their specific market (Thornton, 2004).

Research on industrial oven improvement is under-developed. This EngD research initially focused on energy reduction within industrial ovens. However, the project scope later expanded to incorporate process enhancement, which was necessary to overcome industrial barriers and maximise benefits. Furthermore, research was needed to justify sustainable decisions to business leaders in manufacturing environments. Due to the expanding scope, this thesis consists of three research bodies, as shown below:

1. Energy saving through process optimisation
2. Process enhancement considering both energy consumption and product quality
3. Developing sustainable industrial ovens

This EngD project developed feasible practices to reduce the environmental and economic impact of industrial ovens that operate below 250°C. This research was based within 3M and was conducted at two of their existing factories. Improvements to industrial ovens were implemented during the EngD project that reduced energy consumption, enhanced process performance and developed a better understanding of process heating applications.

2. First body of research: Energy saving in industrial ovens through process optimisation

The aim of the first body of research was to establish a methodology to reduce energy consumption in the gas-consuming ovens. The objectives of this research body were to:

- Identify the heating processes with the greatest improvement opportunity.
Executive summary

- Establish a methodology for energy saving which can be widely applicable across multiple ovens.
- Implement a project that delivers energy and cost saving for the site.

Energy savings can be achieved by process integration, which is a holistic approach to process design and considers interactions between different unit processes to reduce resource consumption (Friedler, 2010). Energy integration is a special case of process integration. It can be regarded as a follow up step after a basic process synthesis has been performed and is widely accepted as a strategy for process development and design to minimise energy consumption (Kemp, 2007). Process optimisation of individual thermal units should be completed before reducing or optimisation energy across an entire process, or multiple units in a process line. Within a factory environment, reducing energy consumption in process units instead of across an entire site offers a focused and practical approach to energy saving.

There has been a lack of overarching optimisation methodologies that could be replicated across a wide range of heating applications, with existing studies tending to lack industrial oven operability analysis and clear optimisation techniques that can be applied in practice (Cheng and Jaluria, 2005). Procedures have more recently been established for various individual oven scenarios, whether it is an optimisation algorithm for a paint cure oven (Ashrafizadeh et al., 2012), a multi-objective approach for CFD design (Khatir et al., 2013c), or an energy modelling approach that maximises production (Perez and Carvalho, 2007). Although these optimisation tools can be replicated in related scenarios, their field is narrow, thereby limiting their application potential. Furthermore, existing literature has tended not to address the link between product and process understanding with the physical engineering principles of an industrial oven. The research conducted within this body of work addressed oven parameter optimisation from a more effective and generic level than previously published work.

2.1 Methodology

A methodology was developed for energy saving in industrial ovens through process parameter optimisation. The methodology adapted Six Sigma’s general DMAIC method for oven optimisation as shown in Figure 1.

![Figure 1: Systematic approach to optimise ovens for energy saving](image)

The design phase develops background knowledge of the oven system by understanding its purpose and physical arrangement. During the measure phase, process streams are identified, and a mass balance as well as an energy balance of the system is developed. All the process variables are identified, by labelling X input factors, intermediate I variables and Y output variables. Analysis identifies Y outputs that fall within energy-and quality-related categories. Understanding the impact that each X has on output Y is developed through experimentation. The improvement phase identifies ways in which process parameters can be optimised for energy saving. Potential modifications are evaluated in terms of safety and financial benefits before a final modification plan is developed. The suggested control strategy permanently implemented monitors the process modification to verify there are no product quality and safety concerns.
2.2 Case study
The methodology was applied to an indirect-gas oven for adhesive curing at a 3M factory. The oven is controlled by lower explosive limit (LEL) analysers, which shut the system down if solvent levels are too high. The aim was to optimise process settings for energy saving while ensuring solvent levels remained below 35% LEL. Figure 2 displays a schematic of the oven with mass flow-rates of process streams.

![Figure 2: Oven system flows](image)

A theoretical minimum energy to heat this airflow of 169 kW was calculated. Allowing for inefficiencies in energy transfer, the actual energy consumed of 909 kW was determined from metered gas usage. Therefore, the theoretical maximum energy saving potential was 740 kW. Analysis of process variables identified fans and dampers as having the greatest impact on energy consumption. Therefore, three experiments were conducted to establish a suitable optimisation plan. Experiment 1 concluded that flow into the oven through the web entrance and exit slots was greater than expected, and that the main recirculation damper was not effective for process control. Experiment 2 identified the optimum oven pressure, while experiment 3 concluded that fresh air through the web slots alone was sufficient for safe operation. The experiments found that the most suitable optimisation option to minimise system airflow was identified to install variable speed drive (VSD) control on the exhaust fan. The optimisation was implemented and resulted in an energy saving of 28%, which equates to a saving of 1,658,000 kWh or £58,000 per year.

This body of research contributes to knowledge by developing and demonstrating a methodology to reduce energy consumption within industrial ovens through parameter optimisation, which predominantly covers the environmental dimension of sustainable oven improvement.

3. Second body of research: Process enhancement considering both energy consumption and product quality
The aim of the second body of research was to develop an approach to oven improvement that delivers benefits in terms of energy consumption and product quality. The objectives of this research body were to:

- Develop product understanding, and then use this to enable process improvements.
- Understand how process enhancement can lead to product quality advances, and frame this as an economic benefit.
- Implement a project that delivers energy and cost saving for the site.
Manufacturers generally prioritise product quality over energy consumption because high-quality products can generate market share and maintain customer satisfaction (Srinivasan, 2011), and therefore, a compromise between energy saving and product performance is inevitable (Myers et al., 2011). From reviewing literature, it was found that there was a lack of emphasis on industrial oven improvement that encompasses both energy reduction and product quality enhancement. Furthermore, the majority of existing techniques to develop product understanding of adhesive cure did not meet manufacturer’s needs. Therefore, the research conducted within this body addressed oven process performance in terms of energy saving and product quality, and in doing so developed a practical method of cure characterisation for use in the manufacturing industry.

3.1 Methodology

Figure 3 shows the iterative approach for oven improvement that was developed in the second research body, which involves product understanding, process improvement and process parameter optimisation.

![Iterative approach for oven improvement](image)

**Figure 3: Iterative approach for oven improvement**

3.2 Case study

The approach was applied to a 1MW direct-fired festoon curing oven at a 3M factory. Greater product understanding was required to minimise variability in product quality and reduce risks associated with process modifications. Previously at the site, it was not known to what extent process temperature variation impacted adhesive cure conversion, and therefore the product quality. Figure 4 shows the vertical web temperature deviation for one product above and below its set point, with Probe 1 being the highest point on the web, and Probe 4 being the lowest (numerical values have been removed due to confidentiality).
Advanced adhesive cure understanding was needed. Cure is represented on a scale of 0-1 and is a qualitative measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive (Sernek and Kamke, 2007). The resin was analysed using Differential Scanning Calorimetry (DSC), Dynamic Mechanical Thermal Analysis (DMTA) and free phenol/CIE-Lch colour test. DSC data indicated that heating rate had a significant impact on final cure conversion, while analysis using DMTA and free phenol/CIE-Lch colour test indicated that final cure temperature dramatically affected the time taken to reach full cure conversion.

As well as delivering a uniform temperature profile, it is also vital to develop a system that can quickly change to a new temperature profile. The influence of structural thermal mass results in long start-up periods and unnecessary downtime during breakdowns. A modification to install an insulation layer to the inside of the existing oven wall was proposed to reduce the impact of structural thermal mass. A model was developed that evaluated the effect of an insulation layer on process downtime. Figure 5a shows the cooling profile of oven air for the existing structure, while Figure 5b displays the cooling profile for an oven with 50mm of insulation on the oven walls and floor; both label the process temperature and the safe temperature for oven entry. The time taken to reach the safe temperature is 2h for the case without insulation, whereas the insulation reduces it to approximately 0.25h. This 88% reduction can save an estimated 202h/y downtime.
The final stage of the oven improvement was process optimisation. Optimal fan settings were determined that reduced energy consumption by 20-30%, resulting in a £28,000 per year saving. The approach was also used to improve the second festoon oven at the same 3M factory that will save a further £35,000 per year.

This research body contributes to knowledge by reporting a methodology that combines DMTA and the free phenol/CIE-Lch colour test, which is effective at linking lab-based DMTA findings to product quality on the actual manufacturing line. Furthermore, this research body also demonstrates an effective and practical approach for the manufacturing industry to reduce energy consumption and improve product quality.

4. Third body of research: Developing sustainable industrial ovens

The aim of the third body of research was to establish approaches that incorporate the important aspects of sustainability into industrial oven development. The objectives of this research body were to:

- Identify suitable sustainability indicators specifically for industrial ovens.
- Develop a suitable methodology to analyse sustainability indicators for a manufacturing process environment.
- Use case study examples to demonstrate the effectiveness of the indicator set and accompanying methodology on sustainability of oven systems.
- Evaluate the sustainability benefits of biomass process heating for the manufacturing industry.

This body was split into two parts. Part A developed a set of sustainability indicators for industrial ovens and a method of multi-criteria analysis for manufacturing oven applications. Part B used sustainability indicators to evaluate the industrial feasibility of biomass technology for process heating.
4.1 Part A: Sustainability indicators and multi-criteria analysis

Sustainability indicators can be used to compare potential process modifications. Although indicator sets have been established for many different industrial scenarios, such a set had not previously been developed for industrial ovens. Table 2 displays the set of sustainability indicators for industrial ovens that was developed through expert consultation and reviewing existing literature.

<table>
<thead>
<tr>
<th>Type of indicator</th>
<th>Name of indicator</th>
<th>Description</th>
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<tr>
<td>Environmental</td>
<td>System airflow</td>
<td>The mass flow rate through the system</td>
</tr>
<tr>
<td></td>
<td>Production Efficiency</td>
<td>The efficiency of the system to produce product compared to operation time</td>
</tr>
<tr>
<td>Economic</td>
<td>Operating costs</td>
<td>Cost of running the oven, including labour, energy, materials.</td>
</tr>
<tr>
<td></td>
<td>Quality</td>
<td>Quality improvement to product (high, medium, low, or no impact)</td>
</tr>
<tr>
<td></td>
<td>Capital investment</td>
<td>Capital investment needed to get project off the ground</td>
</tr>
<tr>
<td>Social</td>
<td>Toxicity</td>
<td>Residual monomer in formulation and exhaust used to assess the impact on humans and environment</td>
</tr>
<tr>
<td></td>
<td>Employment opportunity</td>
<td>The employment opportunities generated from an oven, job numbers and skill level required</td>
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Multi-criteria analysis using Fuzzy set theory can be used to analyse sustainability indicators. Fuzzy set theory is a current methodology that handles uncertainty of quantitative and qualitative criteria (Fu, 2008); however, it became clear that existing methodologies were unsuitable for oven technology assessment in a manufacturing environment. Established techniques did not incorporate uncertainty into the final study outcome, which is problematic as it presents an outcome that appears definite when in reality it is uncertain. Therefore, a new methodology was developed that combines Fuzzy set theory and Monte Carlo simulation. The new methodology that has been developed in this study uses Monte Carlo simulation to generate histogram plots of desirability from numerous probability distributions, which are provided by the triangular distributions generated in Fuzzy set theory. This technique successfully incorporates uncertainty into quantified risk assessment.

The sustainability indicator set and new methodology of multi-criteria decision analysis was applied to an industrial oven case study. The aim was to identify the most sustainable way to increase the adhesive cure within an oven. The three modification options were analysed. Option A1 increased the size of the oven, A2 increased oven temperature and A3 changed the product formulation. Figure 6 displays the final output of desirability level for each option; the higher the desirability, the more sustainable the option. The histogram plot also gives an indication of uncertainty, shown by the spread of data. The analysis identified that option A2, which was to increase oven temperature and keep process time the same, was the most sustainable modification option, but had the highest uncertainty.
4.2 Part B: Industrial feasibility of biomass process heating

Part B of this research body evaluated the industrial feasibility of biomass process heating. 80% of global CO₂ emissions are estimated to result from burning fossil fuels, and biomass offers the manufacturing industry a sustainable alternative fuel (Tripathi et al., 2016). Although other renewable fuel sources also offer sustainable alternatives to conventional fossil fuels, the use of biomass in convective oven processes is straightforward, and will not require radical changes to the fundamental product design or internal oven structure.

The UK has a renewables obligation (OFGEM, 2014) to help meet European Commission targets to reduce GHG emissions, which look to increase the share of renewable energy in the EU’s gross consumption from 12.5% in 2010 to 27% by 2030 (EU, 2016).

The industrial feasibility of biomass in two case study examples was investigated: a) retrofitting existing gas process with a biomass burner, and b) installing a biomass burner in a new-build process. For both case studies, analysis was conducted using sustainability indicators and multi-criteria analysis. Furthermore, a techno-economic analysis was performed to rationalise manufacturers’ decisions.

The first case study considered retrofitting a 2MW existing gas-fired heating process with biomass technology. Indirect biomass heating was found to be the most sustainable option, as it would significantly reduce net operational cost and GHG emissions. However, a 10-year payback period and high capital cost led manufacturers to judge biomass as unviable in retrofit scenarios. The current UK Renewable Heat Incentive (RHI) scheme does not successfully incentivise biomass in retrofit scenarios. The capital cost associated with changing technology is the main barrier affecting viability, as biomass is evaluated against the option of business as usual, which has no capital expenditure.

The second case study investigated the feasibility of biomass technology for newly-built processes. Here, biomass was the most sustainable option, and it was thought to be more viable than in retrofit scenarios as the economic evaluation is more favourable. Biomass is more viable in a new-build
process because project evaluation incorporates capital expenditure for both the biomass option and for conventional heating technology.

An alternative initiative scheme was proposed that mitigates high capital expenditure away from manufacturers by offering a government loan, while also lowering operational costs with a reduced RHI tariff. These factors would increase biomass viability for businesses. Additionally, the EU Emission Trading Scheme (ETS) was found to be an effective tool to encourage the uptake of biomass heating technology in the manufacturing industry. Part B of the third body of research concluded that biomass process heating would not significantly reduce the carbon footprint from existing manufacturing processes, but it could offer a viable and sustainable option for new-build heating processes.

This research body contributes to knowledge by demonstrating that all aspects of sustainability can be incorporated into investment appraisal in the manufacturing industry. A specific set of sustainability indicators is reported as well as a new method of multi-criteria analysis. Furthermore, the research body comments on the feasibility of biomass from an industrial perspective.

5. Key research outputs

Three bodies of research were conducted at two 3M manufacturing factories. Through oven improvement projects, this study has reduced energy costs to 3M by up to £121,000 per year. The key outputs from the thesis are shown below:

- There are two options to reduce energy consumption: a) Optimise the process by changing parameters, or b) Innovate the process by changing the way the heat is supplied to an oven.
- System airflow can often be reduced by up to 30%. This was demonstrated at two factories and three oven systems, and has reduced gas energy consumption by 4,536,000 kWh and cut carbon emissions by 836 tCO₂e per year. This has delivered a combined annual cost saving of £121,000.
- Installing sufficient control capability enables heating processes to be optimised throughout their life, to meet changing requirements.
- A novel approach of polymer cure characterisation has been developed that combines DMTA and a free phenol/CIE-Lch test. This demonstrated that temperature variation within a festoon oven results in dramatically different cure conversion (complete conversion time ranges from 73 to 40 minutes depending on location) and product quality.
- A novel multi-criteria analysis method incorporating sustainability indicators from stakeholder’s perspectives has been developed for oven optimisation.
- Retrofitting gas-fuelled processes with biomass technology is not economically viable. Alternative schemes that negate capital cost from the business would significantly enhance biomass viability.
- Biomass technology is more viable in newly-built processes than retrofit scenarios.
- EU Emission Trading Scheme (ETS) is an effective tool to encourage uptake of biomass heating technology in the manufacturing industry.
6. List of publications and conferences

**Publications**


**Publications in review**


**Conferences**

**PRES 2014 - Prague, Czech Republic.** 17th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction.

Poster presentation (shortlisted for best poster presentation, shown in Volume 2).


**SDM 2016 – Chania, Greece.** 3rd International Conference on Sustainable Design and Manufacturing.

Oral presentation.

“Manufacturing is more than just putting parts together. It’s coming up with ideas, testing principles and perfecting the engineering....”

Anon
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<tbody>
<tr>
<td>3M</td>
<td>Sponsor Company</td>
</tr>
<tr>
<td>BAU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital expenditure</td>
</tr>
<tr>
<td>CES</td>
<td>Centre of Environmental Strategy</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>CIE-Lch</td>
<td>Colour test</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>Cp</td>
<td>Constant heat capacity</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiment</td>
</tr>
<tr>
<td>DSC</td>
<td>Differential Scanning Calorimetry</td>
</tr>
<tr>
<td>DMTA</td>
<td>Dynamic Mechanical Thermal Analysis</td>
</tr>
<tr>
<td>DMAIC</td>
<td>Design, measure, analyse, improve, control</td>
</tr>
<tr>
<td>DCF</td>
<td>Discounted Cash Flow</td>
</tr>
<tr>
<td>EngD</td>
<td>Engineering Doctorate</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>EU ETS</td>
<td>European Union Emission Trading System</td>
</tr>
<tr>
<td>EIO</td>
<td>Environmental Input-Output</td>
</tr>
<tr>
<td>EJ</td>
<td>Exa-joule</td>
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<tr>
<td>GCC</td>
<td>Grand composite curve</td>
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<tr>
<td>GCV</td>
<td>Gross calorific value</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>h</td>
<td>Hour</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
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<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
</tr>
<tr>
<td>LCA</td>
<td>Life-cycle assessment</td>
</tr>
<tr>
<td>LEL</td>
<td>Lower Explosion Limit</td>
</tr>
<tr>
<td>m</td>
<td>Million</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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<td>--------------------------------------</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>MER</td>
<td>Minimum energy requirements</td>
</tr>
<tr>
<td>MJ</td>
<td>Mega-joule</td>
</tr>
<tr>
<td>NOX</td>
<td>Nitrous oxides</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>RE</td>
<td>Research engineer</td>
</tr>
<tr>
<td>RHI</td>
<td>Renewable Heat Incentive</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and data acquisition</td>
</tr>
<tr>
<td>SCC</td>
<td>Shifted composite curve</td>
</tr>
<tr>
<td>SP</td>
<td>Set Point</td>
</tr>
<tr>
<td>Surrey</td>
<td>University of Surrey</td>
</tr>
<tr>
<td>tCO₂e</td>
<td>Tonnes equivalent of carbon dioxide</td>
</tr>
<tr>
<td>VSD</td>
<td>Variable speed drive</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compound</td>
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Nomenclature

\( A \) - Alternative option
\( \alpha \) - Conversion of cure
\( c \) - Sustainability indicator
\( C_p \) - Specific heat
\( \bar{c}_{mn} \) - Normalised weighted score for each indicator
\( D \) - Desirability
\( E_a \) - Activation energy
\( f_1, f_2, f_3 \) - Triangular fuzzy number
\( h_t \) - Heat transfer coefficient
\( k \) - Thermal conductivity
\( M \) - Mass
\( \dot{m} \) - Mass flowrate
\( m \) - Alternative option number
\( n \) - Number
\( \rho \) - Density
\( Q \) - Energy
\( R \) - Gas constant
\( \bar{r}_{mn} \) - Randomly generate number
\( s \) - Second
\( t \) - Time
\( T \) - Absolute temperature
\( w \) - Weight factor
\( w_n \) - Weighted Fuzzy number
\( x \) - Score of indicator
\( \bar{x}_{mn} \) - Normalised score for each indicator
\( \gamma \) - Layer thickness
\( Z \) - Reaction constant
Glossary

CIE-Lch: Colour model encompasses the entire spectrum, including colours outside of human vision. It is extensively used in many industries and measures ‘l’ lightness, ‘c’ chroma and ‘h’ hue values.

Cure: The change in physical properties of an adhesive by chemical reaction, which may be condensation, polymerisation, or vulcanisation; usually accomplished by the action of heat and/or catalyst.

DMAIC: An acronym for Design, Measure, Analyse, Improve and Control. It is a tool used for specific Six Sigma improvement projects.

Exergy: Maximum useful work that is possible in a system during a process that brings the system into equilibrium with a reference environment.

Fuzzy set theory: A branch of set theory mathematics, in which the characteristic function of an object in a set is determined on a scale between 0-1, and not limited to two values of 0 and 1.

Monte Carlo Simulation: A statistical technique used for numerical approximation of a mathematical problem by studying the distribution(s) of random data.

Multi-criteria analysis: A method of research and decision-making analysis that is applied to complex problems where a single criterion approach is insufficient and it necessary to include a larger range of factors.

Process enhancement: The discipline of developing an existing manufacturing process through a series of actions to identify, analyse and improve the process to meet new goals and objectives, such as increased performance.

Process optimisation: The discipline of adjusting a process so as to optimise a specified set of parameters without violating certain constraints.

Retrofitting: To modify existing equipment that is already in use with upgraded or additional parts.

Six Sigma: A disciplined, data-driven approach and methodology for eliminating defects in any process. It drives toward six standard deviations between the mean and the nearest specification limit.

Sustainability indicator: A statistical measure that gives an indication on the sustainability of social, environmental and economic development.

Tan D peak: A key parameter from DMTA analysis. Tan D is a measure of storage modulus and a sample’s elastic behaviour. It is the ratio of the loss to the storage and is often called damping.
Chapter 1: Introduction

This chapter provides an introduction to thesis by presenting the research background, research question, aims and objectives and thesis structure. This gives a broad context to this EngD thesis and is used to identify the research area and justify the need for this study. The outline of thesis structure assists navigation through the thesis.

1.1 Research background

In order to limit the environmental impact of the manufacturing industry, actions must be taken to minimise the use of energy, raw material and water resources. Furthermore, lasting prosperity of businesses must be ensured to protect the livelihood of employees. To meet these challenges, professionals across industries and academia need to collaborate to help create a sustainable manufacturing industry. This thesis aims to play a part in this multi-disciplinary response by developing the sustainability of industrial ovens in the manufacturing industry.

1.1.1 Sustainable manufacturing

Sustainability is famously defined in the Bruntland report as ‘meeting our needs, without compromising the needs of future generations’ (WCED, 1987). The three pillars of sustainability are: environmental, economic and social. The challenge has been set through Our Common Future (WCED, 1987) for new approaches to encourage wider adoption of sustainable development throughout society.

It is important for the manufacturing industry to understand the role it can play in moving society towards a more sustainable future. Unsustainable manufacturing does not only transfer waste and emissions to the environment, but can also have negative economic and social implications (Yuan et al., 2012). Multinational manufacturing companies are responding to pressures from customers, legislative requirements and political influence. Industry can experience transcending positive impacts if sustainability principles are embedded within their businesses. Multinational organisations operate across national boundaries and they have significant influence when implementing sustainable policy.

Many manufacturers are aware that unsustainable practices can damage their own future, and an increasing number of companies are taking positive steps to improve the way they do business. Companies who have strongly adopted sustainability in their business models care about the long term (15+ years) prosperity of their business and workforce. There are generally three motivations to adopt sustainability principles within a business model: to deliver economic saving, to mitigate risks and to enhance business reputation. Wider adoption of sustainability will be experienced in the future due to increased value associated with each of these motivations (Despeisse et al., 2012).

All manufacturing operations require energy to convert raw materials into useable products, and as a result, manufacturing factories have an impact on the environment. Potential environmental harm within a manufacturing supply chain can arise from raw material sourcing, processing within a factory, consumption of products and disposal to landfill. Manufacturing is traditionally an energy intensive industry and relies heavily on fossil fuels, particularly during material sourcing and processing (IEA, 2007). Consequently, the industry emits pollutants and releases wastes into its surroundings. Mitigating harmful environment impacts is necessary to help minimise global warming and protect the ecosystem.
Incorporating sustainability into a manufacturing business’s core values can help to eradicate damaging industrial practices that affect some of the world’s poorest people and most sensitive ecosystems (Duflou et al., 2012). Over the past few decades, the more energy intensive manufacturing sectors have moved away from the developed world due to raw material-rich locality, cheap labour and the large emerging markets found in the developing world. This shift in location of heavy industry is responsible for the 5-21% reduction in manufacturing energy consumed in developed countries between 1973 and 1994 (Unander et al., 1999). Interestingly, global CO₂ emissions resulting from manufacturing has fallen during the same period as technological advances and political pressures have led to the industry becoming more aware of their impact on the environment and humans (Unander et al., 1999). However, the high concentration in the developing world of heavy industry has led to local social and ecological issues. Regulations in the developing world are generally less stringent than in the developed world, and it is therefore important for large multinationals to act responsibly across national boundaries to limit environmental damage from their manufacturing operations.

The manufacturing industry supports the livelihood of many people through employment, and also has an impact on the people who consume its products. The industry is being ever more challenged by governments and the public to act responsibly to ensure the long term prosperity of its employees and stakeholders. Customers have played a key role in sustainable development by demanding more sustainable products and for manufacturers to be environmentally and socially responsible in sourcing and processing materials. Increased consumer awareness and challenging international legislation and targets are the main drivers behind manufacturers acting more sustainably. Finally, it is vitally important for manufacturers to ensure safe working environments for their employees. This is because accidents not only affect employees, but can damage a company’s reputation and can have significant costs if the company breaches health and safety regulations.

Manufacturing helps to drive the global economy and its financial and physical output has steadily increased since the beginning of the industrial revolution (Unander et al., 1999). Without a strong manufacturing industry, the global economy would struggle. Therefore, the economic performance of manufacturing operations are vitally important to industry leaders, employees, politicians and consumers. Sustainable manufacturing can help to ensure a secure and stable economy.

Building sustainability into a business model helps to maintain and develop strategic market position. It is argued that the challenge of sustainability offers innovative businesses with a significant opportunity for sustainable growth, and companies that ignore these pressures will do so at their own peril (Senge and Carstedt, 2001, Hart, 1995). Although investing in innovation can improve the environmental and economic performance of a business, there are still relatively few businesses who adopt truly sustainability principles within their business models. The reason for this is the practical barriers and paradoxes that make implementing sustainability difficult (Hall and Vredenburg, 2003). It is important to emphasise the link between a company’s environmental and financial performances, as organisations who are incorporating sustainable principles into their business models and deliver good financial performances can lead the way for others to follow (Yang et al., 2011).

1.1.2 Industrial ovens

Figure 1.1 displays five levels of the manufacturing industry where sustainability principles can be applied: at the product design phase, unit process, process line, factory and supply chain level. The
scope of improvement project increases with subsequent levels, as does the time to implement changes. Each level can be explored for potential improvements. As summarised in biannual reports compiled in volume 2 of the thesis, the key focus of this EngD research is on energy consuming units with the highest energy saving potential, as detailed further in the study scope, Section 1.4. Figure 1.1 illustrates where this EngD research fits into the larger picture to develop a sustainable manufacturing industry.

Figure 1.1: Sustainability applied at different levels in the manufacturing industry

Within manufacturing facilities there are often a variety of unit processes and process lines. This EngD research focuses specifically on heating processes. An example of a heating process can be seen in Figure 1.2. Heating processes require an energy source and a heat containment device. The energy source is used to generate heat that is transferred to a product for thermal processing. Heat recovery devices can reduce energy consumption while emissions, which can be subjected to treatment, are exhausted to the atmosphere. Heating processes are an important component in many manufacturing factories, and are thought to consume almost one fifth of all industrial energy (EERE, 2013).

Figure 1.2: Process heating system

Thesis
Frederick Pask
Oven systems represent the most significant process heating application in the manufacturing industry. Ovens have very obvious impacts on the environment and economics of a manufacturing process. As well as having an energy footprint, industrial ovens also significantly affect the quality of product that is produced and the safety of operators. Systematically improving industrial oven units is a feasible way for a manufacturer to make significant sustainability improvements to their operations.

1.1.3 Industrial sponsor
3M are a large international manufacturing company with over 88,000 employees operating in 29 countries. The company manufactures more than 55,000 products in various businesses ranging from healthcare, industrial, safety, graphics, electronics and consumer products. The UK division of 3M commissioned this research project to help the company move towards a sustainable future. High energy costs and the constant need to manufacture better quality products were the key motivations of this EngD research.

There are significant opportunities to improve the sustainability performance within 3M manufacturing factories. Over the past decade, work to reduce the energy consumption in areas such as lighting or turning off redundant machinery has been largely completed, while focused efforts to minimise process energy were overlooked. Process changes result from modifying the manufacturing process itself, rather than ancillary services etc. This requires greater resource to identify and implement successful improvement projects.

Prior to this EngD, there was a lack of knowledge within 3M UK on best practices to systematically improve the heating processes within their industrial ovens. Many different types of industrial ovens are used in 3M factories such as air floatation ovens for drying, direct gas fired ovens for curing or festoon ovens for both drying and curing. The desire to improve the sustainability of these ovens resulted in 3M collaborating with the University of Surrey (Surrey) and commissioning this project.

1.1.4 Industrial collaboration with academia
This EngD research project embarks upon the need for collaboration between 3M and Surrey. Surrey has a long history of delivering EngD projects that have had a positive impact within industrial settings. The Centre of Environmental Strategy (CES) at Surrey supports the Research Engineer (RE) to ensure the EngD project meets its industrial expectations. This EngD project was scoped out to play a role in 3M’s energy reduction strategy, and will help to deliver valuable industrial benefits as well as an important contribution to knowledge.

1.1.5 Research scope
This research aims to systematically improve existing industrial heating processes at two factories; Factory A and Factory B. It focuses on the environmental and economic performance enhancement of industrial ovens, and thereby enhancing health and safety of workers due to mitigation of environmental emissions. The project must deliver a tangible benefit to 3M within the four years that the RE is within the company on this assignment. In order to do this, the research will not focus on large capital expenditure (CAPEX) projects, which tend to take a considerable amount of time to justify and implement, but instead on smaller projects that deliver short to medium term benefits. Table 1.1 displays activities that are in and out of scope for this project.
Chapter 1: Introduction

Table 1.1: Project scope

<table>
<thead>
<tr>
<th>In Scope</th>
<th>Out of scope</th>
</tr>
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<tbody>
<tr>
<td>➢ Energy saving process modifications.</td>
<td>➢ High CAPEX projects.</td>
</tr>
<tr>
<td>➢ Low to mid-range CAPEX projects.</td>
<td>➢ Significant product redesign.</td>
</tr>
<tr>
<td>➢ Oven processes at Factory A and Factory B.</td>
<td>➢ Electrical ancillary energy consumption.</td>
</tr>
<tr>
<td>➢ Long term process improvement plan.</td>
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1.2 Research question

For manufacturers to have sustainable growth they need to be innovative and adopt sustainability principles within their business models (Hall and Vredenburg, 2003). Interpreting this to have specific relevance to this EngD research, the manufacturing industry must develop innovative strategies to:

- Reduce CO₂
- Reduce overhead and production costs
- Reduce waste
- Reduce raw material consumption
- Manufacture higher quality product
- Manufacture more efficiently, in terms of specific energy consumption per product output
- Manufacture greater quantity of products created

This EngD research intends to establish strategies on how these points can be feasibly achieved in respect to industrial ovens. The academic field looking to improve industrial ovens is under-developed, especially considering the impact that industrial heating processes can have on a business, its employees and the environment. While there is a considerable amount of research looking to improve the sustainability of multiple processes or across a whole factory, there is a lack of specific research looking at sustainability improvements in an oven unit or system. Focussing on improvements at a unit level is often more feasible and can be achieved in the short to medium term as major multi-process changes have far greater complexity and less flexibility due to infrastructure or space limitations.

In both literature and industry, there is insufficient knowledge (see Section 2.5 for the knowledge gap) and practical guidance for engineers to improve the sustainability of industrial ovens. Furthermore, there is no awareness of the impact industrial oven improvement could have on creating a more sustainable manufacturing industry. Therefore, the research question for this EngD is:

*How can manufacturers improve the environmental and economic performance of industrial ovens?*

1.3 Aims and objectives

The research activities during all four years of the EngD programme have the same overarching objectives as follows:

- Identify oven improvement opportunities in 3M factories.
- Develop methods that will reduce energy, improve product quality and increase safety of industrial oven systems.
- Implement oven improvement projects in at multiple factories.
Investigate the opportunity to use renewable fuel sources for process heating.

Three oven systems have been investigated during this EngD project. Each system presented a specific problem that required a bespoke solution. In light of this, three research bodies have been developed for bespoke solutions within the overarching aims of the EngD research. The bodies of the research all work towards a unifying purpose of improving the environmental and economic performance of industrial ovens. The three research bodies are:

1. Energy saving through process optimisation
2. Process enhancement considering both energy consumption and product quality
3. Developing sustainable industrial ovens

The aims and objectives for each research body are presented below.

1.3.1 First body of research aims and objectives
The first body of research is entitled ‘Energy saving through process optimisation’. Details of this work can be found in Chapter 3. The research was conducted at Factory A during the first 14 months of the EngD program. The aim of research activities for the first body of research is to establish a methodology to reduce energy consumption in the gas consuming ovens at Factory A. The objectives of this research body are to:

- Identify heating processes with the greatest improvement opportunity.
- Establish a methodology for energy saving which can be widely applicable across multiple ovens.
- Implement a project that delivers energy and cost saving for the site.

1.3.2 Second body of research aims and objectives
The second body of research is entitled ‘Process enhancement considering both energy consumption and product quality’. Details of this work can be found in Chapter 4. The research was conducted at Factory B during months 15 to 35 of the EngD program. The aim of research activities associated with the second body of research is to develop an approach to oven improvement that delivers benefits in terms of energy consumption and product quality. The objectives of this research body are to:

- Develop product understanding, and then use this to enable process improvements.
- Incorporate the output from the first research body to deliver energy saving in ovens.
- Understand how product understanding can lead to product quality advances, and frame this as an economic benefit.
- Implement a project that delivers energy and cost saving for the site.

1.3.3 Third body of research aims and objectives
The third and final body of research is entitled ‘Developing sustainable industrial ovens’. Details of this work can be found in Chapters 5 and 6. The research was conducted at Factory B from month 36 to the end of the EngD program. The aim of research activities associated with the third body of research is to establish approaches that incorporate important and relevant aspects of sustainability into industrial oven development. The objectives of this research body are to:

- Identify suitable sustainability indicators specifically for industrial ovens.
Chapter 1: Introduction

- Develop a suitable methodology to analyse sustainability indicators for a manufacturing process environment.
- Use case study examples to demonstrate the indicator set and accompanying methodology.
- Evaluate the sustainability benefits of renewable-fuel process heating for the manufacturing industry.

1.4 Thesis structure

Chapter 1 describes the background of the research, defines its aims and objectives and discusses the scope of the research. It also briefly indicates the study approach and outlines how the thesis is structured.

Chapter 2 introduces industrial ovens in greater detail. A selection of supporting literature related to industrial ovens is presented. Then, specific literature relating to each of the three research bodies is provided. The research gap that this EngD research responds to is also identified.

Chapter 3 presents the first of three bodies of research in this EngD: Energy saving through process optimisation. The chapter gives background context to how this research has been developed and justifies the need for it. The key research output is presented, which is a methodology to optimise oven process parameters. A case study is used to demonstrate the methodology created in this research body, before concluding remarks are given.

Chapter 4 presents the second body of research in this EngD: Process enhancement considering both energy consumption and product quality. Background context is given to explain how and why the research body has been developed. An approach for energy saving and process enhancement in ovens is presented, with a case study to demonstrate how the approach can be applied in industry. Concluding remarks on research findings are then given.

Chapter 5 presents Part A of the third body of research: Developing sustainable industrial ovens. It develops a set of sustainability indicators and accompanying multi-criteria analysis method. Background context is given to explain how and why the research body has been developed. Seven sustainability indicators are presented along with a method of multi-criteria decision making designed for this application. Two case study examples of industrial application are provided; one looking at traditional oven improvement and the second evaluating the benefits of biomass burners. Concluding remarks are given with key findings and research communications.

Chapter 6 presents Part B of the third body of research: Developing sustainable industrial ovens. It is a detailed application example of the sustainability indicators and methodology developed in Part A to evaluate industrial feasibility of biomass process heating for retrofit and new-build industrial scenarios. The study comments on policy effectiveness and the future of biomass technology in the manufacturing industry.

Chapter 7 highlights the impacts and implications of the research to the project sponsor, academia and wider audiences. The chapter also suggests possible avenues application as well as giving a critical review of the research in terms of validity and limitations. Final conclusions are then given.

The Appendices contains five supporting documents that should be read in conjunction with the research bodies in Chapters 3 and 4. Table 1.2 displays a summary of the paper and reports in the appendices.
Figure 1.3 shows a thesis road map with the structure of this thesis that the reader could follow whilst progressing through the document.
# Chapter 1: Introduction

## Research background

## Research question

## Aims and objectives

## Thesis structure

## Research gap

## Summary

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## Chapter 2: Literature review

- Background literature
- Literature review for 1st body of research
- Literature review for 2nd body of research
- Literature review for 3rd body of research

## Chapter 3: Energy saving through process optimisation

- Background
- Methodology
- Case study
- Recommendations
- Key findings
- Communicating the findings

## Chapter 4: Process enhancement considering energy consumption and product quality

- Background
- Methodology
- Case Study
- Recommendations
- Key findings
- Communicating the findings

## Chapter 5: Developing sustainable industrial ovens (Part A)

- Background
- Methodology
- Sustainable indicators for ovens
- Case study
- Recommendations
- Key findings
- Communication of findings

## Chapter 6: Developing sustainable industrial ovens (Part B)

- Background
- Methodology
- Case Study A
- Case Study B
- Discussion
- Key findings
- Communication of findings

## Chapter 7: Conclusion

- Research overview
- Main findings
- Generalised implications
- Broad applicability
- Critical review of the research
- Overall conclusion

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**Figure 1.3: Thesis roadmap**

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Thesis Frederick Pask
<table>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Journal/conference/report</th>
<th>Status</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Systematic approach to industrial oven optimisation for energy saving</td>
<td>Journal of Applied Thermal Engineering</td>
<td>Published</td>
<td>The journal paper that resulted from the first research body. A systematic approach for process parameter optimisation for energy saving is presented with a supporting case study.</td>
</tr>
<tr>
<td>B</td>
<td>Practical approach for engineers to optimise industrial ovens for energy saving</td>
<td>PRES 2014, Czech Republic. Published in journal of Chemical Engineering Transactions.</td>
<td>Published</td>
<td>The research from the first research body was presented at an esteemed international conference. This double peer reviewed conference paper summarises the research body and journal paper found in Appendix A.</td>
</tr>
<tr>
<td>C</td>
<td>Pinch Analysis for Factory A</td>
<td>Internal report</td>
<td>n/a</td>
<td>An internal report that assessed Factory A’s heating and cooling processes. The report presents a heat exchanger network and calculates minimum utility energy requirement for the site.</td>
</tr>
<tr>
<td>D</td>
<td>Industrial oven improvement for energy reduction and enhanced process performance</td>
<td>Journal of Clean Technologies and Environmental Policy</td>
<td>Published</td>
<td>A journal paper from the second body of research. A generic improvement approach is presented.</td>
</tr>
<tr>
<td>E</td>
<td>Generic approach to sustainability improvements in manufacturing ovens</td>
<td>Sustainable Design and Manufacturing 2016, Chania, Greece. Springer, Smart Innovation, Systems and Technologies 52.</td>
<td>Published</td>
<td>A conference paper on the second research body that presents a generic approach to oven improvement.</td>
</tr>
</tbody>
</table>
### 1.5 Summary

This chapter has provided the reader with an overview of the thesis by presenting background and motivation to the research, information about the industrial sponsor, context of the research, the research problem and justification for the research. The chapter has also introduced the study methodology describing how and why three bodies of research have been developed. The overall EngD aims and objectives have been presented along with the aims and objectives of each research body. Finally, an overview of the overall thesis structure has been given to assist the reader in navigating through this document. Chapter 2 offers a review of the literature related to the research undertaken.

| Appendix F | Sustainability indicators for industrial ovens and assessment using Fuzzy set theory and Monte Carlo simulation | Journal of Cleaner Production | Published | A journal paper from the third body of research. A method of multi-criteria decision analysis and case study are presented. |
2. Literature Review

This chapter provides an introduction to industrial ovens and reviews relevant literature. Figure 2.1 gives a structural overview of the literature review. The chapter presents background information on industrial ovens in the manufacturing industry with a supporting literature review describing the types of ovens and how they impact on sustainability performance of a factory. Energy reduction through process integration was then reviewed for a focused and feasible approach for energy savings in manufacturing industry. Thereafter, literature review for each research body is presented, along with the knowledge gaps that Chapters 3, 4, 5 and 6 aim to address. The chapter then finishes by highlighting the overall research gap for this thesis.

| Backround literature | • Types of ovens  
|                      | • Sustainability and industrial ovens  
|                      | • Process integration  
| Lit. review 1st body | • Process optimisation for energy saving  
| Lit. review 2nd body | • Process enhancement and energy saving  
| Lit. review 3rd body | • Sustainability indicators  
|                      | • Multi-criteria decision analysis  
|                      | • Biomass process heating  

Figure 2.1: Literature review structure

2.1 Background literature

Manufacturing processes are diverse in nature, and often require heating applications to change material properties, to drive off water and solvents or to cure adhesives. Heating applications involve devices that generate or supply heat, devices that transfer heat from sources to product, heat containing devices and heat recovery devices. This EngD focuses on heat containing devices, and in particular industrial ovens. Industrial ovens must aim to achieve a consistent and reliable heating regime. There are numerous types of ovens, with design specifications dependent on product type, process function, fuel type, available technology, cost and the process operating window. Improving an industrial oven will significantly improve a manufacturing process, and therefore developing a thorough understanding of oven processes is important.

2.1.1 Types of industrial ovens and processes

Ovens can be operated as continuous or batch processes. Continuous ovens have a constant stream of product moving through the oven, either on conveyor belts, hung by attachments to a moving chain or in the form of a continuous webbed product. Continuous processes are used for high volume operations where one type of product will be in production for an extended period of time. Alternatively, batch operations can involve a single-batch thermal process for a specific set of products, where one batch of products is removed from the oven after being exposed to the thermal regime before being replaced by another batch (Andresen et al., 2013). Batch ovens are generally used for unique products at a lower volume and particularly within smaller scale manufacturing applications. de Soete et al. (2013) noted that changing from batch to continuous processes for
pharmaceutical tablet manufacturing can reduce the energy consumption at the process level by 34%. However, this is not possible for all batch-manufacturing processes.

The way that energy is supplied to an oven can vary depending on many factors; process sensitivity, costs, temperature requirement, geographical location, technology acceptance, age of the oven system, etc. (DOE, 2015). Natural gas is the most common fuel type in industrial ovens due to its relatively low cost, versatility, accessibility and the fact that it can be used in processes with tight operating windows. In 2010, natural gas was the most prominent fuel source for in US industry and manufacturing accounted for 29% of energy use (U.S. Energy Information Administration, 2010). Alternatively, ovens can be heated by electricity or by biomass and other renewable sources. The heat energy can be supplied to an oven either directly or indirectly. Direct heating has the advantage of high conversion efficiency from fuel to useful energy; however, the combustion process can add moisture to the process air that negatively impacts drying capability. Indirect-heating requires a fluid to transfer energy from the primary fuel source to the oven. Indirect heating offers advantages when dealing with volatile environments; however, energy losses can be higher than in direct-heating scenarios due to heat exchanger inefficiencies.

This EngD study focuses on drying and curing ovens, which can be used in either continuous or batch processes. Drying is a mass transfer process to remove water or solvents through evaporation. For drying processes, the oven must maintain the necessary drying force at the surface of a material. The majority of drying of wet materials is done using convective ovens, which work by the moving of liquid or gas atoms in response to the heat (Kittisupakorn and Lipikanjanakul, 2015). In these ovens, drying is achieved through suspension of particles within hot air, blowing hot air through wet granular material, or by contacting a continuous solid wet material. Radiation ovens transfers heat through a direct path and do not need physical contact between materials. Radiation can offer advantages over convection in terms of energy efficiency, safety and process control. Assessing the energy performance of different drying ovens is relatively common throughout literature. For instance, it is known that 100% of the energy within the fuel is passed to drying air in direct heating dryers, whereas the figure for indirect dryers it is closer to 70% (Kudra, 2012).

Curing ovens, which can be either convective or radiative, are common in many industrial processes. The curing process refers to the hardening of a polymer material brought about by cross-linking of polymer chains. The level of cure achieved is determined by time and temperature exposure that a polymer material is subjected to. Therefore, curing ovens must deliver a consistent and reliable heating regime to a product.

An oven’s performance, compared to the best available practice, decreases over time due to structural/mechanical degradation, technology advancements or changing process requirements. There is almost always potential for functionality improvement in existing industrial ovens. Any change to an existing oven process must be justifiable to the manufacturing business either by resulting in an economic saving or by increasing the performance capability of the oven. The research conducted within this EngD aims to develop feasible improvement techniques and approaches for existing manufacturing ovens that are justifiable to a business.
2.1.2 Sustainability and industrial ovens

This subsection presents the environmental, economic and social impacts from oven activity in the manufacturing industry.

**Environmental impacts**

Greenhouse gas (GHG) emissions that result from fossil fuel consumption are key environmental impact from industrial oven activity. Many industrial processes require heat energy that is supplied to an oven through the combustion of fossil fuels. When fossil fuels are burnt they release harmful gases to the environment, such as carbon dioxide, carbon monoxide and volatile organic compounds (VOCs) etc., the latter two may result from incomplete combustion of fuel in the oven system. CO\(_2\) from fossil fuel combustion constitutes the main GHG emission. CO is a toxic gas and greater than 100 ppm concentration is dangerous to humans. VOCs contribute to photochemical oxidant creation or urban smog potential (Sahhukhan et al., 2014). GHG emissions are high on the global political agenda, and there are pressing needs for manufacturing companies to mitigate their emissions. As a result, minimising energy consumption is a key activity for manufacturers as they attempt to reduce utility costs and meet increasingly stringent environmental regulations.

Limiting CO\(_2\) from industry is important in creating a sustainable future. Industrial CO\(_2\) emissions are responsible for 40% of total emissions worldwide. It has been estimated that if emissions from the industrial sectors were to remain unchecked the global CO\(_2\) emissions would increase by 74-91% by 2050 compared to 2007 (IEA, 2010). Napp et al. (2014) suggested that there needs to be a focussed industry-wide effort to improve emission measurements and benchmarking, through which all industrial activities should have as much best available technology as possible. They also suggest that barriers of adoption for energy efficiency improvements are often social as organisations lack the required knowledge, rather than being financially constrained. Policy should also focus on demonstration of carbon reducing activities to enhance their commercial deployment by early 2020s.

Within a factory environment, reducing the energy consumption of oven units offers a focused and feasible approach to energy saving. Heating applications consume almost one fifth of all industrial energy (EERE, 2013). As ovens are a significant heating application, they have a substantial energy footprint. Energy saving within heating processes is relatively common throughout the literature. Linnhoff and Hindmarsh (1983b) developed the concept of pinch technology to systematically reduce utility consumption across processes. Dörr et al. (2013) presented a methodology for energy efficiency at a process level for everyday organisational practices. Duflou et al. (2012) presented a systematic overview of state of the art methods and techniques to reduce energy and increase resource efficiency in the domain of discrete part manufacturing. The majority of existing research focuses on minimising energy across an entire manufacturing process rather than within a unit. However, site wide heat integration via retrofitting is often unfeasible and impractical due to limitations in existing technologies, space availability, layout restrictions, heat losses, disruption on production, financial viability etc. (CanmetENERGY, 2013). The improvement from site-wide heat integration can also be marginal for already energy efficient sites. The pinch analysis study detailed in Appendix C led to this EngD’s focus to be on industrial oven units, where the greatest energy and environmental impact saving potentials were identified.
Renewable energy is an obvious way for a manufacturer to reduce its environmental impact from fossil-fuel powered manufacturing processes. Alternative energy sources should be considered when developing industrial processes within a factory. Biomass, a naturally available biological or organic solid fuel product, offers the manufacturing industry a sustainable alternative but it is still rarely used in heating processes (Tripathi et al., 2016). The feasibility of changing a fossil-fuelled process to one that is powered by renewable energy sources is dependent on many factors. Evaluation of renewable energy substitution is incorporated in the third research body, with relevant literature presented in Section 2.4.

The waste generation from an industrial process can also be impacted by the oven’s performance. Oven function impacts on production downtime and the amount of product that has to be scrapped due to poor quality, which both can result in excessive waste generation. There might be an option to re-work scrapped product; however, much of it will be land-filled.

**Economic Impacts**

The link between environmental and economic impacts of an oven is significant and can help justify energy reduction projects. In competitive markets, businesses must continually push to increase profit margins from products that are manufactured in oven systems. Therefore, ensuring an oven generates a positive economic impact is important for sustainable production. The economic performance can be improved by reducing production costs, increasing sales or reducing overhead costs. Production costs include the cost of raw materials, fuel and the labour. For industrial ovens, this involves the energy utility costs, the product raw materials and the salary of employees who are responsible for the oven operation. The opportunity to deliver increased sales and reduce overhead costs from improving industrial ovens is not as great as the opportunity to decrease production costs within oven processes.

Increasing energy efficiency reduces energy utility costs. Fuel costs are a considerable expenditure for manufacturing businesses and they significantly impact on production costs and profit margins. In order to try to reduce production costs associated with thermal processing, manufacturers should aim to increase the energy efficiency of ovens, which has a combined positive environmental and economic benefits. Depending on the manufacturing scenario, energy costs within an oven can represent a large proportion of a site’s overall utility bill and can therefore significantly affect the production costs.

The cost of fossil fuel energy fluctuates depending on a complex combination of factors including: supply, demand, taxation, political stability, infrastructure and competition from renewable energy sectors. The cost of a barrel of oil peaked in 2008 at a cost of $140, while at the same time the cost of natural gas was $12.67 per million BTU. In April 2016, the cost of both oil ($50 per barrel) and natural gas ($1.92 per million BTU) was relatively low when compared to their 2008 peaks (MacroTrends, 2016). This decrease in fossil fuel energy prices since 2008, has effectively reduced the economic impact associated with industrial oven activity by decreasing production costs. Despite this, manufacturing companies still attempt to minimise energy consumption for further reduction in production costs, increased profits and to maintain strategic market position.

Decreasing scrap and minimising material waste can reduce the costs associated on product raw materials. Moreover, improving an oven’s ability to manufacture good quality product can have a
positive effect on marketing and sales. Process variation impacts on product quality, running costs, safety and operational efficiency. Therefore, understanding a process is critical for manufacturers to be competitive in their specific market. It can be used to develop better products, avoid excess precision in certain aspects of a process, minimise defects, allow for faster transition from one product to another, deliver cost reduction, and to reduce scrap (Thornton, 2004).

Social Impacts
There are also social impacts that result from industrial oven processes. All ovens have a degree of human interaction for operation. Those who work with oven systems are subjected to potentially hazardous environments, either from excessive heat exposure or toxic materials, and their safety must be considered. An industrial oven through atmospheric pollutants can also impact human receptors outside of a manufacturing facility.

Manhart and Grießhammer (2006) conducted a study analysing the positive and negative social impacts of notebook manufacturing. The important social impacts that are relevant to most manufacturing scenarios were found to be:

- Manufacturing provides an important source of employment, especially for less qualified workers and help alleviate unemployment issues.
- Fair payments fair throughout the manufacturing supply chain is difficult to ensure, and can create poor working conditions, inequality and poverty.
- Poor working conditions can represent a threat to political and social stability.
- Certain supply structures pose risk to health and safety of employees’ and local communities.

The social dimension has been a driver of oven improvement objectives throughout the research and this aspect has been embedded explicitly in the sustainability analysis of an oven system. Reductions of environmental impacts that result from oven activity lead to enhanced health and safety of stakeholders. This is taken into account in the third research body, which aims to incorporate all three dimensions of sustainability by developing a sustainability indicator set that evaluates the sustainability performance of oven systems. The indicator set takes into consideration the energy consumption, product quality as well as safety and employment opportunity.

2.1.3 Process integration and exergy analysis
A number of research fields relating to process energy reduction were investigated. This supporting literature review looks at energy consumption in heating processes, process integration and exergy analysis, which are useful in eliminating infeasible options or options with incremental improvements. Process integration is probably the most common method of addressing energy consumption in process industries throughout the literature. Considerable research and improvements in industrial process energy analysis have been made over the past few decades, especially since the energy crisis of the 1970s (Khalil et al., 2007). Process integration aims to set optimum process configuration and operating conditions for a manufacturing process. Process integration can include heat integration, value analysis, system integration, process intensification and conceptual thermodynamic optimisation (Sahhukhan et al., 2014, Smith, 2005). Heat integration, which is the most relevant research area to this EngD, employs methods such as pinch analysis and mathematical programming. Pinch analysis, by being graphical and conceptual, is more
effective for larger scale industrial applications, while mathematical programming is a more statistical approach used in smaller-scale industrial activities (Mardan and Klahr, 2012).

Pinch analysis determines the minimum thermodynamic requirement of a process and allows for an engineer to design heat recovery systems, alter energy supply methods and optimise process operating conditions so that the energy consumed is as close to the thermodynamic minimum as possible. Early work by Linnhoff and Hindmarsh (1983a) designed a process in which the minimum hot and cold utility demands were met, for a given set of hot and cold process streams. Pinch analysis identifies how best to redistribute the heat loads within the existing thermal streams. It is a cost optimisation process to recover thermal energy from process lines and is one of the founding research areas in energy saving in process environments. However, it has been described as an expensive and heavy tool for companies as it requires a significant amount of data and knowledge when it is applied in practice (IPPC, 2006). Furthermore, retrofitting an existing process by installing a heat exchanger network is expensive and complex due to geographical locations of energy streams leading to unfavourable economic assessments and high energy losses.

There are certain aspects of pinch analysis which have been consistently adopted by subsequent energy reduction methods, such as identifying the minimum energy requirement of a process. Identifying the minimum energy required helps identify energy management opportunities in heating processes. Any method of process energy analysis to determine the minimum energy requirement to transform a raw material into a saleable product is beneficial for a manufacturer. Frazier (2006) proposed a systematic method of identifying energy management opportunities in manufacturing plants. By calculating the minimum energy required, an engineer can then make informed judgements on how the energy consumption can be reduced.

A critique of pinch analysis is that its practical application in retrofit scenarios is limited. This became evident after applying the analysis technique at Factory A during the initial phase of this EngD; further information can be found in Chapter 3 and Appendix C. Pinch analysis is not incorporated in any of the three research bodies; however, the technique was important to direct to the energy and environmental impact hotspot, which is the oven system for 3M factories.

Exergy analysis is an alternative tool for designing and analysing energy systems by combining energy and mass analysis with the second law of thermodynamics. It helps to achieve greater energy efficiency by using resources more effectively and quantifying effective efficiency calculations (Rosen and Dincer, 2003). Taner (2015) utilised exergy analysis to determine the optimum energy efficiency for a drying plant. Their study optimised the mass flowrates and temperature of the drying process based on food processing guidelines. Uncertainty analysis and techno-economic analysis were also utilised. Exergy approaches can identify energy saving potentials; however, their applicability to existing industrial settings can be limited due to available data and physical layout as well as the fact that modifications can be very disruptive to a manufacturing process. This is why a more practicable approach to energy saving by oven optimisation has been adopted for 3M’s industrial settings.
2.2 Literature review for first body of research

The first body of research is entitled ‘Energy saving through process optimisation’. The objectives for the first body of research can be found in Sections 1.3.1 and the full body of work is presented in Chapter 3. This section presents existing literature related to process optimisation, while also identifying the gap in knowledge that Chapter 3 aims to address.

2.2.1 Process optimisation for energy saving

The first body of research uses process optimisation techniques to reduce energy consumption within industrial ovens. Process optimisation falls under the umbrella term of process synthesis, which is closely related to process integration, as described in Section 2.1.3, to describe a family of methodologies that reduce resource consumption (Friedler, 2010). Process synthesis is widely accepted as the strategy for process development and design to minimise energy consumption. It should be approached in a logical sequence of redesigning the product, followed by optimising the process, exploring heat recovery options and by finally considering alternative site heat and power systems (Kemp, 2007). Figure 2.2 (adapted from Kemp, 2007) displays where process optimisation fits into the process synthesis approach.

![Figure 2.2: Process synthesis approach (Kemp, 2007)](image)

Process optimisation analyses an existing process and establishes ways for the process function to remain unchanged, or improved, while the energy consumption is reduced. A process parameter is a changeable quantity necessary to control a process, for instance the status of a fan, damper or valve. Process parameter optimisation, which is achieved by fully understanding the process and energy flows, has been demonstrated to deliver to a 10% energy reduction (Duflou et al., 2012). As true energy flows are difficult to determine, establishing accurate metering is one of the first steps when attempting to reduce process energy.

Process optimisation of individual thermal units should be completed before energy reduction or optimisation across an entire process, or multiple units in a process line (as shown in Figure 2.1). Meyers et al. (2016) argue that the primary recommended energy saving measure for industry should be process optimisation and heat recovery due to their low payback period. A fundamental approach to energy optimisation of an oven is modelling. A variety of modelling tools have been suggested with the aim to improve energy efficiency. Empirical models correlating overall performance with simple parameters such as space volume, box temperature and inlet air...
properties have been used to optimise ovens. This has since progressed to a model based on numerical solutions using equations such as the conservation of momentum, mass, chemical species (Carvalho and Nogueira, 1997).

Linking product and process understanding with the physical engineering principles should be fundamental for optimisation of commercial ovens in order to reduce risk to safety and product performance. Optimisation frameworks have been developed for specific oven scenarios. Frameworks have been developed and applied to commercial bread-baking ovens that demonstrate technically sound applications of process optimisation. A conceptual optimisation framework has been constructed that utilises experimentation, models and an understanding of the required energy to obtain an optimal design (Khatir et al., 2013a).

Energy losses within an optimisation framework are of great importance. Paton et al. (2013) accounted for the energy losses when optimising baking ovens, and found that calculating losses was a crucial component of the overall oven optimisation methodology. Furthermore, the most useful objective for an oven optimisation is often the specific energy consumption, i.e. consumption per unit mass of product, rather than simply the energy consumption.

Heat transfer models can be a useful tool to highlight energy saving opportunities and areas of oven performance that can be improved. Williamson and Wilson (2009) conducted a study using computational fluid design (CFD) models to develop novel and efficient radiant burner design. Although incorporating CFD in the analysis can be beneficial, it might not be feasible for retrofit design in many facilities due to lack of available resources. However, complete analysis of a process is vital for appropriate selection of process parameters to be considered in optimisation (Apostolos et al., 2013). Overall system performance is characterised by thermal efficiency, energy efficiency, volumetric evaporation rate, specific heat consumption, surface heat losses, and unit steam generation (Kudra, 2012).

Despite the literature that has been presented, there is generally a lack of overarching optimisation methods that could be replicated across a wide range of heating applications, with studies tending to lack industrial oven operability analysis and clear optimisation techniques that can be applied in practice (Cheng and Jaluria, 2005). Procedures have more recently been established for various individual oven scenarios, whether it is an optimisation algorithm for a paint cure oven (Ashrafizadeh et al., 2012), a multi-objective approach for CFD design (Khatir et al., 2013c), or an energy modelling approach that maximises production (Perez and Carvalho, 2007). However, although these optimisation tools can be replicated in related scenarios, the ability to directly apply the same techniques across multiple process heating applications is limited.

Alternative strategies to reduce energy consumption in ovens include installing more energy efficient heating technology. Changing technology can be advantageous (Duflou et al., 2012) but often requires significant capital investment. In contrast, process optimisation can deliver energy saving without the need for excessive capital expenditure and can be performed on almost any heating application. Optimisation, therefore offers an achievable and beneficial target for many industrial processes.

Continual improvements of manufacturing processes is well established in the industry and offers a strategy to minimise costs and improve product quality over an extended period of time. Organisations tend to use a variety of methods to reduce variation such as continual process
improvement, Six Sigma and Total Quality Management (Thornton, 2004). Six Sigma’s DMAIC (Design, Measure, Analyse, Improve and Control) is a data driven strategy to deliver process improvements. It can be adapted to deliver both energy and functionality improvements. These tools can highlight areas of an oven process which need improving in terms of energy consumption and quality enhancement, but they can also establish modification plans. The same principles can also be effectively applied to increase the sustainability of an industrial oven (Espindle, 2011).

2.2.2 Knowledge gap for first research body
There are two specific knowledge gaps that the first research body aims to address:

- There is currently no overarching optimisation approach to reduce energy in any industrial oven, with existing oven optimisation frameworks only for individual oven scenarios.
- Existing literature tends not to address the link between product and process understanding with the physical engineering principles of an industrial oven.

Thermal process optimisation in manufacturing has not received a great deal of attention throughout the literature, hence the discipline has significant room for development (Duflou et al., 2012). The research conducted within this body of work addresses oven parameter optimisation from a more generic level than previously published work. Existing practices tend to only be applicable for one particular oven scenario whereas this body of research aims develop a method which is applicable to any oven, and one that incorporates product and process understanding into the analysis phase.

2.3 Literature review for second body of research
The second body of research is entitled ‘Process enhancement considering both energy consumption and product quality’. The aim and objectives for the second body of research can be found in Sections 1.3.2, while the research is presented in Chapter 4. This section presents existing literature related to the second research body and identifies the knowledge gap that Chapter 4 aims to address.

The literature presented in this subsection incorporates energy reduction and process enhancement, which is a development from the first body of research. Existing literature on adhesive cure characterisation is also presented, as product quality is to be considered in this research body. The product being manufactured at Factory B contains a polymer resin; therefore, existing literature on adhesive curing must be reviewed.

2.3.1 Energy saving and process enhancement
Industrial oven improvements can involve enhancing product quality, production efficiency and worker safety, as well as reducing energy consumption and waste. Manufacturers generally prioritise product quality over the energy consumption, which negatively impacts the energy reduction agenda within industry. High quality products can generate market share and maintain customer satisfaction. The cost reduction associated with lean manufacturing is important for businesses in increasingly competitive markets (Srinivasan, 2011).

Understanding the link between energy and product quality deserves attention in the research. Pathare and Roskilly (2016) evaluate quality and energy performance in the food manufacturing industry. However, there is little evidence of emphasis on both dimensions for heating processes in
Chapter 2: Literature review

Khalil et al. (2007) developed a four-stage methodology that aids rapid identification of potential energy savings and product quality improvements in manufacturing processes. The stages include process definition, energy and mass analysis of process lines, analysis of energy consumption and production volumes and finally efficiency assessment by identifying energy savings. The minimum energy requirement is determined by product requirements and is important when establishing methods to minimise energy consumption. This study highlights how product understanding should be incorporated into the energy reduction activities. A strong focus on process energy analysis is important when starting any energy reduction study. Nevertheless, the study fails to give guidance on how the energy should then be reduced or purposefully link energy and quality improvements under a broader sustainability improvement plan.

There is often a trade-off between energy saving and product performance. Over-processing is common in many ovens due to the desire to minimise quality risk associated with under-processing, however it results in unnecessarily high energy consumption (Myers et al., 2011). Lu et al. (2012) presented a dual objective framework for optimisation of energy saving and product quality for injection moulding processes. The study was completed at a laboratory scale to deliver a 10% energy reduction; however, the conclusion reached was that higher quality can result in higher energy consumption and that there must be a trade-off to satisfy the application needs.

Process variation has a significant impact on product quality, performance, cost, safety and operational efficiency. Understanding of process variation has many benefits and is critical for manufacturers to be competitive. It can be used to develop better products, avoid excess precision in certain aspects of a process, minimise defects, allow for a faster transition from one product to another, deliver cost reduction and reduce scrap (Thornton, 2004).

The baking industry spends a considerable resource ensuring that their heating processes are optimised for energy saving and to create a thermal regime to deliver high quality and consistent products. Khatir et al. (2015) conducted a study of the thermal management of bread baking ovens using CFD modelling to minimise energy consumption and maximise oven functionality. This research built on previous work (Khatir et al., 2013b, Paton et al., 2013, Khatir et al., 2013c), and highlights the important link between product quality and energy reduction, thus emphasising a dual approach to oven improvement. These studies incorporate laboratory scale investigations to develop product understanding and then combine this with industrial scale investigations to thoroughly understand oven performance. Ma et al. (2015) optimise an enamel baking oven in respect to process temperature and pressure drop. This study optimises structural parameters of air distribution devices to create an optimal thermal regime. Bhanot et al. (2016) presents a framework for industry to analyse the economic and environmental performance of a turning process to maximise benefits to the manufacturer. The existing research in the baking industry highlights the important link between product quality and energy reduction in industrial ovens. Manufacturers operating drying and curing ovens have the opportunity to learn from the baking industries and maximise benefits by emphasising a dual-focused approach to oven improvements.

2.3.2 Adhesive cure characterisation

The function of the oven system used in the second body of research is to cure adhesive resin. Curing adhesives has been studied extensively throughout literature and there have been numerous
studies on epoxy based resins that are used to affix abrasive mineral to a paper web. There are several stages to a chemical curing process:

- Resin viscosity drops initially when exposed to heat.
- Material passes through a region of maximum flow.
- Chemical reaction increases average length and degree of cross linking between oligomers.
- Process continues until 3 dimensional networks of oligomer chains are created.

The cure of a resin is represented on a scale of 0-1, and is a measure of the relative number of cross links which are formed to complete vitrification of a thermosetting adhesive (Sernek and Kamke, 2007). Applying chemical understanding of cross-linking processes, as well as heat transfer and chemical kinetic models, the most appropriate cure strategies can be ascertained (Dickie et al., 1997). Kinetic modelling of a curing process can be achieved by either mechanistic or semi-empirical methods. Mechanistic methods require detailed knowledge of the elemental reactions which take place, as well as the ability to write cure rate equations at each stage of the cure process, whereas using empirical data can enable easier modelling of complex processes without the need for the fundamental knowledge of the curing reaction.

Mechanistic kinetic modelling is relatively common throughout literature with most approaches based on first order rate equations and the Arrhenius equation, shown in Equation 2.1. The general rate law, where da/dt is the rate of cure, and k(T) is the temperature-dependent rate constant of the reaction and f(α) is a function of the concentration of reactants can be used to find the curing reaction:

\[
\frac{da}{dt} = k(T)f(\alpha) \quad \text{Eq. (2.1)}
\]

The empirical Arrhenius equation is fundamental to cure kinetic modelling, and is used to define k(T):

\[
k(T) = A \exp \left( -\frac{E}{RT} \right) \quad \text{Eq. (2.2)}
\]

Where A is the pre-exponential factor, E is the activation energy (kJ.mole\(^{-1}\)), R is the gas constant (J.K\(^{-1}\).mol\(^{-1}\)) and T is the absolute temperature (K). Combining Equations 2.1 and 2.2 gives:

\[
\frac{da}{dt} = A \exp \left( -\frac{E}{RT} \right) f(\alpha) \quad \text{Eq. (2.3)}
\]

Equation 2.3 shows a common equation for data fitting and regression. These equations are deemed to be among the most reliable for modelling cure kinetics (Sbirrazzuoli et al., 2009), and have been commonly used to understand the kinetics of chemical or physical processes and lead to understanding of the mechanisms involved in various chemical reactions, cross linking etc.

Measuring cure is not an easy task, and although there are a number of techniques developed to monitor the cure of thermoset adhesives, very few have been successfully applied within industry. Differential scanning calorimetry (DSC), torsional braid analysis, dynamic mechanical thermal analysis (DMTA), dynamic mechanical analysis (DMA), and solid-state nuclear magnetic resonance, work in a laboratory but are unsuitable for in situ continual analysis. However, techniques such as infrared spectroscopy using optical fibres, dielectric spectroscopy, and acoustics have the potential to be used in situ within industrial processes (Sernek and Kamke, 2007). For many industrial
environments it may not be financially feasible to use these techniques to determine the optimum cure conditions for a given material, and therefore an alternative approach must be adopted.

Differential Scanning Calorimetry (DSC) is an established technique for the modelling of curing kinetics of epoxy based resin formulations. There are a number of kinetic curing models that can be used to interpret DSC data (Geipel and Eitner, 2013). However, it is thought that DSC is limited when scaling up from lab based experiments to predicting what happens on a manufacturing line; an issue which will be common for many ‘real life’ adhesive formulations. There is a lack of sufficiently detailed chemical formulations of product mixes for many industrial processes. As curing processes are extremely complex and influenced by many factors, it can be difficult to understand the cure kinetics using a modelling approach. Optimum cure conditions are often determined through laboratory experiments of physical properties, chemical resistance and durability rather than direct measurement of the chemical conversion.

It is thought that Dynamic Mechanical Thermal Analysis (DMTA) provides a better representation of actual cure conversion compared to DSC analysis for the type of adhesive used at Factory B. It is used to develop understanding of products containing polymer composites (Saba et al., 2016). DMTA is a versatile technique that can provide information on the physical changes of a resin that is subjected to a thermal regime. It measures the modulus of an adhesive sample, which increases as cure conversion increases; experiments can be used to determine which process variation (heating rate, temperature, time etc.) has the largest impact on modulus, and therefore cure conversion. However, it is important to link lab based DMTA findings to product quality on an actual manufacturing line.

2.3.3 Knowledge gap for second research body

There are two specific knowledge gaps that the second research body aims to address:

- There is a lack of emphasis on industrial oven improvement that encompasses both energy reduction and product quality enhancement.
- The majority of existing laboratory based cure characterisation techniques do not meet the needs of manufacturers.

This body of research aims to demonstrate that projects are easier to justify if they deliver energy saving while also improving product quality. There is a lack of sufficient focus on industrial oven improvements that encompass both of these dimensions. Furthermore, existing literature fails to link product and process understanding with physical engineering principles of an oven, which is important to reduce risk to safety and product performance. Finally, there is a lack of analysis and clear improvement techniques that can be applied in practice (Cheng and Jaluria, 2005).

2.4 Literature review for third body of research

The third and final body of research is entitled ‘Developing sustainable industrial ovens’. The aim and objectives for the third body of research can be found in Section 1.3.3, while the research is presented in Chapters 5 and 6. This section presents existing literature related to the third research body and identifies the knowledge gap that Chapters 5 and 6 aim to address. The literature presented in this subsection is in the field of sustainability indicators, multi-criteria decision making analysis and biomass process heating in the manufacturing industry.
2.4.1 Sustainability indicators

Sustainability indicators can be used to inform decisions and provide insight into complex issues by balancing the three sustainability dimensions (Kwatra et al., 2016). They can be used to compare differences between potential oven improvements and therefore help to develop a sustainable manufacturing industry. Application of indicators for technology assessment can be used in two ways; a) to assess the overall performance of a particular technology system, or b) to compare at least two technology systems. Indicators should be applied using ‘fit for purpose’ approach rather than making a generic set of indicators fit for all applications (Dewulf and Van Langenhove, 2005). Indicators can be quantitative or qualitative, and can fall within the categories of descriptive, performance or efficiency indicators (Hallstedt, 2015). A UN report (Nations, 2007) sets a number of guidelines when selecting appropriate indicators. In summary, they should be clear, unambiguous and provide basis for comparison without a large number of sub sets. Furthermore, they should be responsive to changes in the environment and related human activities.

Environmental indicators may include greenhouse gas emission, energy consumption, renewability of resources, toxicity of emissions, re-use of materials, recoverability of waste materials and efficiency (Dewulf and Van Langenhove, 2005). Proposed economic indicators relevant to industrial ovens involve net sales, operational production costs, gross margin and overhead costs (Pannell and Glenn, 2000). And finally, social indicators tend to be toxicology or safety related (Al-Sharrah et al., 2007, Al-Sharrah et al., 2010).

Many different sets of sustainability indicators have been established for different scenarios. Indicators have been used to assess the sustainability of renewable technologies. The indicators used were price of generated electricity, greenhouse gas emissions during full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts (Evans et al., 2009). Based on these multi-criteria, the study was able to establish that wind power is the most sustainable technology, followed by hydropower, photovoltaic and then geothermal. Sustainability indicators have also been developed for the construction of industrial buildings in the petrochemical industry. Heravi et al. (2015) concluded that economic considerations are the most important dimension in construction phase, while environmental considerations are of great importance to operation and maintenance phase. This study used questionnaires to help identify suitably indicators, and to aid the modelling approach to analyse the multiple indicators.

Social responsibility of a manufacturing operation addresses a company’s impact (either at a global or local level) on human beings, with efforts focussed on supply chain networks, local communities and actions to maintain product safety (Koskela, 2014). An oven process is a part of a manufacturing supply chain and human interaction with ovens must be treated with care. Occupational health and safety comprises the conditions and factors that affect the health and safety of any person in the workplace. A company must anticipate, recognise, evaluate and control hazards that could affect employee wellbeing and should go beyond the legal obligation of the manufacturer (Alli, 2008).

Heating processes are potentially hazardous working environment due to exposure to excessive heat, pollution and toxic materials. The health and safety of workers need to be considered during any improvement project. Furthermore, factories are seldom isolated from local pollution receptors, and therefore manufacturers must be stringent with pollution control measures from a heating
process. Not only can nearby humans be affected by toxic airborne pollutants, but the secondary effects of damage to local watercourses, flora and fauna can also result in negative social impacts (Ashmore, 2013). It is a business’s responsibility to ensure that workers, local populations and ecosystems are not harmed during the operation of an industrial oven. The negative impacts of an unsafe oven are serious enough to shut down a manufacturing operation.

Mukherjee et al. (2015) used the sustainability footprint method to identify the most sustainable process for methanol production. The sustainability footprint method attempts to provide a methodology which is usable in real world applications. However, the results from this method were different from analysis using more traditional process synthesis through superstructure formulation. Therefore, the potential of the sustainability footprint method as a tool for the manufacturing industry requires further investigation.

Keirstead and Leach (2008) studied urban sustainability indicators, and evaluated their use in helping to create sustainable cities. The study found that developing meaningful metrics can be difficult when trying to grapple with overly ambitious versions of sustainable development. Instead, a service niche approach was used to select indicators, which provided a more focused method. When selecting sustainability indicators, it is important to ensure they can be properly analysed and that their role is meaningful for multiple stakeholders. This is true for industrial ovens as much as it is for urban environments.

2.4.2 Multi-criteria decision making analysis

Multi-criteria analysis can be used to assess sustainability indicators by gathering information on a variety of criteria to understand how multiple objectives can best be achieved (Cutz et al., 2016). The method allows indicators with different units to be assessed in tandem. There are various established techniques to analyse multiple criteria and sustainability indicators. One of the most prominent analytical techniques for multi-criteria analysis is Fuzzy set theory, which forms the basis of the multiple criteria analysis in this research body. Monte Carlo simulation is another analytical technique applied in this research body. This technique has seldom been used with Fuzzy set theory for the analysis of sustainability indicators, but could offer worthwhile benefits for multi-criteria analysis.

Multi-criteria analysis is used to aid decision making by gathering information on a variety of criteria, or indicators, to understand how multiple objectives can best be achieved. The method enables indicators with different units to be assessed alongside each other. There are various methods of multi-criteria analysis depending on whether there are a finite number of alternative solutions or an infinite number. Decision matrices are used to assess $m$ alternatives based on $n$ attributes. Although the problems are different, all multi-criteria analysis has common features: multiple criteria often forming a hierarchy, conflict among criteria, a hybrid nature of criteria (in terms of units, qualitative/quantitative, deterministic/probabilistic), uncertainty throughout the analysis and assessment may not be conclusive (Xu and Yang, 2001).

There are two types of multi-criteria decision making methods; compensatory and non-compensatory. Non-compensatory methods are simpler due to methods not allowing for tradeoffs between different attributes. Examples of non-compensatory methods are dominance, maxim, conjunctive constraint, or disjunctive constraint method. On the other hand compensatory methods
allow tradeoffs between attributes, with examples being scoring, compromising, or concordance methods (Hwang and Yoon, 1981).

Fuzzy set theory is a long established field within multi-criteria analysis which presents a way to deal with problems which had previously been unsolvable by traditional multi-criteria analysis. It deals with approximation rather than exact reasoning (Zadeh, 1965), allowing for uncertainty to be assessed rationally by associating a grade of desirability to quantitative and qualitative data (Begić and Afgan, 2007, Niekamp et al., 2015, Fu, 2008). Fuzzy optimisation is seen to be more robust than crisp optimisation with Pareto optimum analysis as no iterative steps are required (Tay et al., 2011). The aim of applying methods such as Fuzzy set theory is to assist decision makers by incorporating uncertainty into a final desirability level; thus providing information so that investments can be aligned with risk strategies.

Fuzzy indicator sets including both qualitative and quantitative indicators have more recently been demonstrated as a method to assess sustainability indicators (Mendoza and Prabhu, 2004, Ducey and Larson, 1999), by enabling objective decision making of indicators, which may themselves be subjective. Uncertainty can result from imprecise measurements, average or outdated data using proxies and incomplete data, approximations in modelling, normalisation and weighting (Sadhukhan et al., 2014) assessment and linguistic descriptors by experts and their assigned values, in case of qualitative indicators. Uncertainty in the assessment of sustainable development causes issues when trying to solve problems using conventional multi-criteria analysis. Probabilistic theory is based on classical set theory which is defined by yes or no statements and requires hard thresholds. Whereas Fuzzy theory is based on multi-valued logic and relates to events which have no well-defined meaning, allowing for the fuzziness to describe a degree to which an event occurs (soft thresholds) (Cornelissen et al., 2001). Fuzzy sets do not have to be in or out, but are rather given a degree of membership. Fuzzy methods are useful when assessing complex or ill-defined problems, and can therefore be very useful for sustainability indicators. Fuzzy indicator uncertainty is not due to error or randomness, but attributed to generality, ambiguity or vagueness.

Many multi-criteria decision making methods for indicator analysis have just used Fuzzy set theory to collate information into a meaningful outcome. However some studies have indicated that Fuzzy set theory alone is insufficient in providing decision with a suitable level of information. Monte Carlo simulation is a sampling technique used for result generation that depends on parameters given from probability distributions. Monte Carlo simulation requires the generation of random values to input into the model, where the model variables have a known range (as determined from a distribution type) but uncertain values in a particular event. Model variables can be provided by the triangular distributions generated in Fuzzy set theory. This technique is used as a way to incorporate uncertainty into quantified risk assessment. Additionally there are guidelines for uncertainty analysis using Monte Carlo simulation for estimation and mitigation of uncertainty during environmental impact assessment (Hammonds et al., 1994).

Studies have been conducted that utilise both Monte Carlo simulation and Fuzzy set theory to evaluate sustainability indicator sets. Loyd (2004) compared the results of using both Fuzzy theory and Monte Carlo simulation independently during a preliminary phase of a planning project. This study did not incorporate a combined approach. However, Sadeghi et al. (2010) created a Fuzzy
Monte Carlo Simulation framework for risk analysis of construction projects. This study was designed to estimate costs of construction projects along with the degree of uncertainty. The combined approach was advantageous because it provided the management of the construction projects with a greater awareness of the uncertainty associated with different construction projects. This approach was specifically intended for use in economic assessment of large capital expenditure products and would have to be adapted for technology sustainability assessment, such as for use in analysing industrial ovens. Abdo and Flaus (2016) applied Monte Carlo Simulation to calculate the fuzzy failure distribution and evaluate the reliability of dynamic systems modelled by dynamic fault tree. They concluded that uncertainty affects the analysis and results and needs to be quantified. The method proposed uses Monte Carlo analysis to analyse triangular fuzzy numbers and the midpoint distances are used to represent uncertainty and compare the fuzzy times respectively. The simulation gave accurate results and was able to calculate the reliability of systems whatever the complexity. These studies demonstrate the potential use of combining Monte Carlo Simulation and Fuzzy set theory, but they do not present methods that are used in technology and sustainability assessment.

2.4.3 Biomass process heating

Natural gas is the conventional fuel used in many industrial heating processes due to its convenience, safety and reliability. About 80% of global CO₂ emissions result from burning fossil fuels, and biomass represents one of the most important sources of renewable energy that could help solve the carbon emission crisis by reducing industrial CO₂ emissions. Biomass, a naturally available biological or organic solid fuel product, offers the manufacturing industry a sustainable alternative but its use is still rarely used in heating processes (Tripathi et al., 2016). Alternatively, technologies such as microwave and radio-frequency heating have the potential to provide a step change improvement to heating processes, especially if renewable electric power is used. Microwave and radio-frequency can result in benefits in terms of energy, emissions, process variation, work in progress and factory space. Studies have been conducted to demonstrate that microwave synthesis can reduce the curing time for adhesive resins, while still creating an end product with similar chemical characteristics to conventional heating (Britten et al., 2007). Buttress et al. (2015) evaluated the use of microwave processing in cement and concrete manufacturing. They found that the technology was still in its infancy and economic feasibility barriers must be overcome before the technology can be widely used in industry. Compared to radiative heating from microwaves and radio-frequency heating, biomass can be used in conventional convective heating processes, which enables for easier industrial application.

Biomass accounted for 8 EJ global industrial heating supply in 2011, up from 7 EJ in 2000 (IEA, 2014). As with many types of renewable energy, political support is needed to encourage the uptake of biomass process heating. In January 2014, the European Commission announced new energy and climate change targets for 2030. The targets state that the share of renewable energy in the EU’s gross consumption should increase from 12.5% in 2010 to 27% by 2030, and the global warming emissions should decrease by 40% (EU, 2016). These targets are a development of the EU Directive 2009/28/EC (Parliment, 2009). At a UK national level there are also supports in place to encourage renewable technology uptake (Ofgem, 2015). It is evident that policy is moving in the right direction to increase the uptake of renewable technologies, however politicians are always challenged to further reduce CO₂ emissions without crippling important industries that support economies and societies.

Policy is used to promote the use of bioenergy through fixed prices, taxation, investment subsidies and green certificates. Thornley and Cooper (2008) found that subsidies are not particularly effective
in developing bioenergy industry, while taxation is generally more effective. Policy design is needed to devise effective policy that evaluates the optimum balance between cost control, incentive intensity, planning security and adaptive efficiency (Purkus et al., 2015). The UK government implemented a renewables obligation to help meet EU targets for reduced greenhouse gas emissions (OFGEM, 2014).

Financial incentives are used to encourage businesses in the UK to install biomass process heating. The UK government offer a financial renewable heat incentive (RHI) for commercial heating processes for 20 years after a biomass burner is commissioned. The RHI tariff from 1st October 2015 will pay businesses 2.03p/kWh of energy output from commercial biomass burners over 1000kW (Ofgem, 2015). The cost of wood pellets varies depending on market prices, transportation costs, location, quantity ordered etc. However, it is generally accepted that wood pellets are slightly cheaper than natural gas per kWh based on energy output: 4.4p/kWh for wood pellets compared to 4.9p/kWh for natural gas (BiomassEnergyCentre, 2013). Therefore, the income generated by the RHI results in wood pellet use costing less than natural gas. The RHI aims to encourage the uptake of biomass heating technology by making it considerably cheaper than conventional fossil fuels. Financial incentives have been successful in kick-starting the solar panel industry in the UK, to get it to a point where it can hopefully support itself without the need for government intervention.

Much has been learnt about the potential of biomass in remedying the energy crisis, mitigating global warming potential impact due to fossil energy use and providing energy security. An analysis by Welfle et al. (2014a) found that the UK’s resources with greatest primary bioenergy potential are household wastes (>115 TWh), energy crops (>100 TWh) and agricultural residues (>80 TWh), by 2050. In spite of biomass availability, according to their work and earlier work by Deloitte (2012), the energy sector has not been able to employ much of biomass as renewable fuel and is facing its greatest challenge for at least a generation. To date, however, there is no perspective and feedback on these problems from industry. The barriers and drivers have been analysed from long term availability perspectives. Alexander et al. (2015) evaluate the cost-effectiveness in providing a source of low carbon renewable electricity, while Welfle et al. (2014b) analyse biomass resource availability and energy generation potential within different contexts. Even if biomass could be made available at the plant gate, there are feasibility issues that could prevent successful deployment of biomass process heating that must be understood from an industrial perspective. Such feasibility issues could make the policy incentives, including the UK’s RHI, less effective in successful uptake of biomass heating technologies. This thesis analyses sustainability of biomass heating in an industrial setting, from the perspectives of industrial practitioners.

Biomass can be used as a solid fuel or can be used to create other fuel products such as biogas. Solid biomass, such as wood pellets, are the most common biomass product used in process industries. It can be fed into a biomass burner to transfer energy to a fluid (steam or oil) that can be distributed to where it is needed. Wood pellets are made from dry sawdust or shavings from the timber market’s residues. Wood pellet manufacturing has increased dramatically over recent years, with the industry producing 1.8 million tonnes in 2000, and 24.5 million tonnes in 2013. Wood pellet demand in Europe is inelastic and pellet supply is unit elastic, meaning that customers can be exposed to price changes resulting from supply shocks (Kristöfel et al., 2016).

Biomass generally has a lower calorific value compared to conventional fossil fuels. Therefore, biomass burners have a higher fuel throughput for the same energy output of conventional burners.
Everard et al. (2012) used infra-red (IR) spectroscopy to determine the mean gross calorific value (GCV) of three varieties of solid based biomass to be 17.07 MJ/kg. Other studies have also demonstrated that the GCV of biomass such as cotton waste, bamboo leaves, wheat straw and rice straw is between 14-19 MJ/kg (Motghare et al., 2016). Amin et al. (2016) observed that the GCV of biodiesel is between 39.00 and 43.33 MJ/kg, while for conventional diesel is 49.65 MJ/kg. As a comparison to fossil fuels, the GCV of coal can range from 17-34 MJ/kg depending on the whether it is anthracite, meagre, stone coking or lignite coal (Feng et al., 2015).

The environmental impact of biomass for electricity generation is better understood than for the process industry. Manufacturers can learn from studies on biomass for electricity generation to indicate the potential environmental benefits of biomass in the process industry. Judl et al. (2014) conducted a life cycle assessment (LCA) study that has proven that wood pellet co-combustion (biomass with coal) in combined heat and power (CHP) plants leads to net environmental impact reduction in terms of fossil fuel depletion, climate change, acidification and deteriorating air quality in urban environments. Best case scenarios for biomass electricity generation have shown an 83% reduction in GHG emissions compared to coal based production. However, due to large uncertainties associated with supply chain, the emissions from biomass energy generation can be up to 70% higher than that of coal based generation. The large variation is caused by uncertainty of parameter such as drying, storage and feedstock market changes cause (Röder et al., 2015). Other LCA based studies have also found that biomass electricity generation reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16–38 years depending on biomass source (McKechnie et al., 2011). These LCA studies have quantified impacts on the environment in the following categories: global warming potential, land use, resource use, ozone layer depletion, acidification potential, photochemical oxidant creation potential, aquatic eco-toxicity, eutrophication potential and biodiversity.

LCA approaches offer a way to evaluate the sustainability advantages of renewable energy over fossil fuels. Sustainability indicators offer an alternative method of assessment of renewable energy and have been used to evaluate wind, hydro, PV and geothermal technology. The indicators used to assess each technology were price of generated electricity, greenhouse gas emissions during full life-cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts (Evans et al., 2009). Stupak et al. (2011) explore options to improve sustainable forest management standards for the production of biomass. Pelkmans et al. (2014) developed guidelines and indicators to evaluate resource efficient biomass value chains, while Fritsche (2012) use sustainability indicator sets to assess whole supply chain impacts of bioenergy production. Indicators should be chosen using a fit for purpose approach rather than making a generic set of indicators fit for all applications (Dewulf and Van Langenhove, 2005).

Techno-economic feasibility and environmental performance studies of biomass CHP have been conducted. They evaluate a number of different options that vary process configurations and fuel types using Fuzzy set theory, which considers multiple techno-economic and environmental criteria and determines the best way to achieve an optimum CHP system. The study also found that existence of pre-treatment, variations in feedstock cost, boiler efficiency, and biomass feedstock have a significant effect on the technical and economic performance of CHP system (Wan et al., 2015).
However, to the best knowledge of the author there has been limited use of sustainability indicators to assess biomass heating technology in the process industry. Evaluation of biomass process heating compared to conventional natural gas powered processes would be a useful addition to understanding the potential of biomass providing a realistic alternative to natural gas.

2.4.4 Knowledge gap for third research body
There are three specific knowledge gaps that the third research body aims to address:

- A sustainability indicator set for industrial ovens has not previously been developed in existing literature.
- There is a need for an appropriate multi-criteria analysis method of sustainability indicators to evaluate technology investment in a manufacturing environment. Current methods do not incorporate risk into the final outcome.
- There has not previously been a study analysing sustainability of biomass heating in an industrial setting, from the perspectives of industrial practitioners.

A sustainability indicator set to assess overall oven sustainability has not previously been developed. Such a set to inform investment decisions associated with oven improvement would be a useful tool for manufacturing and process industries. An indicator set for industrial ovens is particularly useful for other oven scenarios, but can also be interpreted for other technology applications. There is also a gap in knowledge on how sustainability indicators are analysed within the manufacturing industry. A method of multi-criteria analysis that incorporates risk into the final analysis outcome would be useful for manufacturing decision makers and a worthwhile addition to literature.

Biomass presents an alternative heating technology for the manufacturing industry. There are very limited examples within literature that investigate the use of biomass in process industries. There is a need to understand whether current policy incentives are effectively encouraging the uptake of biomass process heating. Investigating the viability of biomass process heating from a manufacturer’s perspective will help comment on the future of biomass use in this industry sector.

2.5 Research gap for thesis
The academic field that surrounds industrial ovens is under-developed. There is a need for greater research focus to systematically improve industrial oven, especially due to the significant impact that heating processes have on the environment, a manufacturing business and its employees. Although there has been a considerable amount of research to reduce energy and increase sustainability within the process industry, there is a lack of research focusing specifically on industrial oven units. Moreover, there are not enough industrial based case studies in the existing literature that demonstrate the positive effect of academic research in the manufacturing industry.

This EngD project intends to make a valuable contribution to knowledge by developing novel techniques that improve the environmental and economic impact of industrial ovens, and also by developing an approach that justifies sustainable investment decisions in a factory environment. This thesis will validate the proposed techniques and approaches by providing data from real industrial projects, as well as identifying and remedying barriers that prevent successful implementation of improvement projects. This thesis tackles a problem that industry has identified itself to be addressed. Therefore, this study is a worthwhile addition to literature and can be used by industry and academia to further improve industrial heating processes.
The specific knowledge gap being addressed by each research body is slightly different. Table 2.1 summarises the key points from this chapter and displays the particular knowledge gap that each research body aims to address.

Table 2.1 Knowledge gaps for each body of research

<table>
<thead>
<tr>
<th>First body of research: Energy saving through process optimisation</th>
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<tbody>
<tr>
<td>- There is currently no overarching optimisation approach to reduce energy in any industrial oven, with existing oven optimisation frameworks only for individual oven scenarios.</td>
</tr>
<tr>
<td>- Existing literature tends not to address the link between product and process understanding with the physical engineering principles of an industrial oven.</td>
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<th>Second body of research: Process enhancement considering both energy consumption and product quality</th>
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<tr>
<td>- There is a lack of emphasis on industrial oven improvement that encompasses both energy reduction and product quality enhancement.</td>
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<tr>
<td>- The majority of existing laboratory based cure characterisation techniques do not meet the needs of manufacturers.</td>
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<th>Third body of research: Developing a sustainable industrial oven</th>
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</thead>
<tbody>
<tr>
<td>- A sustainability indicator set for industrial ovens has not been previously been developed in existing literature.</td>
</tr>
<tr>
<td>- There is a need for an appropriate multi-criteria analysis method of sustainability indicators to evaluate technology investment in a manufacturing environment. Current methods do not incorporate risk into the final outcome.</td>
</tr>
<tr>
<td>- Biomass technology has been extensively investigated for electricity generation and transportation. However, there are far fewer studies investigating the use of biomass in the process industry.</td>
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2.6 Summary of the literature review

This chapter has presented a literature review on industrial ovens. The chapter begins by providing background information and explains how all three dimensions of sustainability can be applied to have specific relevance for ovens. Supporting literature, that has been important in shaping the EngD research direction, is then presented. Next, a review of literature closely related to each of the three research bodies is provided, along with identifying the knowledge gap that each body of work aims to address. A summary of the research gap that the whole thesis will address is then given with a concise account of how this EngD will make a valuable contribution to knowledge. There is opportunity for this research to have a positive impact on the manufacturing industry. Industrial ovens have a significant impact on the environment, a manufacturing business and its employees and the research field is currently underdeveloped. This thesis aims to create an overarching oven optimisation framework for energy saving, develop a strategy of holistic oven improvement and establish a sustainability indicator set and accompanying methodology for industrial ovens.
3. First Body of Research: Energy Saving Through Process Optimisation

This chapter discusses the first body of research, which focusses on energy savings within ovens through process optimisation. The chapter provides background information of how this body of research has been developed. The associated literature review can be found in Chapter 2, Section 2.2. A novel methodology for energy saving through process optimisation in ovens is then presented with an accompanying industrial case study to demonstrate the intended use of the optimisation approach. The chapter should be read in conjunction with the published papers found in Appendix A and B.

3.1 Background

During the initial stages of the EngD project, time was spent understanding the manufacturing process at Factory A. This factory manufactures masking tape product and is one of 3M UK’s largest energy consuming factories due to intensive industrial ovens used for drying and curing. A total of six ovens are heated indirectly by thermal oil and a natural-gas burner. Process heating requirements of these ovens were evaluated and this investigation included a full Pinch analysis for the site and its processes.

The Pinch analysis report, completed in April 2013, included in Appendix C, shows composite curves and identifies a pinch point temperature of 116°C. The minimum energy requirement for the process and the maximum reduction in utility consumption were also determined. Theoretically, the process required less than 20% of the hot utility being supplied, which signifies an opportunity to reduce and/or recover energy. A heat exchanger network for the existing process was designed that could recover 1100 kW of heat energy. A financial assessment of the network determined that the total estimated cost would be £513,000 with a payback period of 2.2 years. However, when considering individual heat exchangers, the feasibility is reduced due to the difficulties in re-directing preheated air back into ovens, and the condensation of exhaust streams fouling heat exchanger plates.

Pinch analysis of Factory A’s manufacturing process indicated that there was potential for process energy saving across the factory. However, it also highlighted the practical difficulties associated with heat exchanger networks and that many ovens were un-optimised. Process synthesis gives direction on how a process should be designed or redesigned. It provides a systematic approach that progresses from product design to process optimisation, to heat recovery before assessing site heat and power systems (Kemp 2007) (see Figure 2.2). The energy being consumed within all of Factory A’s ovens is considerably greater than the energy required by the product. Much of this inefficiency may well be due to heating technology; however, there will undoubtedly be a degree of ‘over processing’ that could be reduced.

Process optimisation is therefore seen as a more cost effective and feasible way to decrease energy consumption at Factory A than installing a heat exchanger network. The report in Appendix C highlighted specific oven units that had the greatest opportunity for energy saving. It became evident that existing practices of oven optimisation, shown in Section 2.2, tend to only be applicable for one particular oven scenario. There is a need for a methodology that is applicable to any oven, and that incorporates product and process understanding into the analysis phase. This gap in oven optimisation research is addressed by developing a new methodology to optimise process
parameters for energy saving. This body of research provides a systematic methodology for engineers to optimise industrial ovens for energy saving.

As mentioned in Section 1.3.1, the aim of research activities associated with the first body of research is to establish a methodology to reduce energy consumption in the gas consuming ovens at Factory A. The associated objectives for this body of research are to:

- Identify heating processes with the greatest improvement opportunity.
- Establish a methodology for energy saving which can be widely applicable across multiple ovens.
- Implement a project that delivers energy and cost saving for the site.

The remainder of this chapter presents an overview of the methodology for oven optimisation and a detailed description of each stage. An application example on a cure oven at Factory A is presented to demonstrate the intended use. Recommendations for project replication are given and also how the research findings have been communicated is discussed. Finally, the chapter concludes with a summary of what the research body has achieved.

3.2 Methodology for parameter optimisation

The methodology that has been developed for energy saving in industrial ovens through process parameter optimisation is presented in this section. The methodology displayed in Figure 3.1 is comprised of five stages: Define, Measure, Analyse, Improve and Control. The methodology adapts Six Sigma’s general DMAIC method for problem solving specifically for oven optimisation. As this is a well-known approach within industry (de Mast and Lokkerbol, 2012), it is in a language that many engineers will be familiar with and can thus be applied with greater ease. The sequence starts at the top left of the figure and moves through the stages to the bottom right. Although the methodology follows a logical sequence, in certain instances an engineer should approach the optimisation problem with greater flexibility to make best use of their time. A description of each stage is provided below.

3.2.1 Define

Background knowledge of the oven system forms the foundation for oven optimisation. In stage 1, the purpose and physical arrangement of the oven must be understood. Process or product constraints must be identified early on. System boundaries have to be drawn so the project scope can be defined. A problem statement gives clarity to the ultimate purpose of the optimisation project, and will most likely involve comments referring to safe reduction in energy consumption while retaining product quality.

3.2.2 Measure

During stage 2, it is necessary to identify all process streams within the system boundaries. Once all process streams and components are identified, a mass balance can be developed. Streams into the system may include wet product, air or other drying agents, and the streams leaving the system may include exhaust gases, water vapour and dry product. The mass balance can be calculated theoretically or empirically.

The energy streams must be identified. The energy into the system will be from the heating supply system, and the energy leaving the system will be in the exhaust gases, radiation from the body of
the oven and in the product. The theoretical energy required for the process is calculated. Actual consumption is determined through measurement or metering. Discrepancies between ideal and actual energy use will give an indication of saving potential. Energy losses within an optimisation framework are of great importance and should be calculated. Furthermore, determining the specific energy consumption, i.e. consumption per unit mass of product, rather than simply the energy consumption should also be completed during this phase.

The final task in this stage is to identify all the process variables. X input factors are variables which can be directly controlled (e.g. damper position). Intermediate I variables are directly affected by altering Xs (e.g. humidity within the oven). Finally, Y variables are the outputs of the process (e.g. product performance). Evaluation of all variables can be conducted to identify which variables require further investigation.

3.2.3 Analyse
Stage 3 improves process and product understanding. The Y outputs considered should fall within energy and quality related categories, and the engineer must have a good understanding of both dimensions. Initially, the quality baseline for the product must be established, and any critical safety constraints must also be considered.

The stage then looks to understand the impact each X has on the output Ys. In many instances, this knowledge can only be ascertained through experimentation. Conventional experiment can be conducted, or design of experiments (DOEs) can be constructed in order to assess multiple inputs simultaneously. Xs are analysed for sensitivity on energy saving with the aim to identify input variables that influence Is, which ultimately influence critical Ys. Input variables are labelled as XE, XQ or XEQ depending on whether they either influence energy (YE) or quality (YQ) related outputs, or both (YEQ).

Sensitivity and controllability of the equipment must also be assessed to be able to determine which variables can be altered to successfully obtain energy saving. The outcome from this stage is to identify which, and to what extent, variables can be altered while still ensuring the oven performs its primary purpose.

3.2.4 Improve
Stage 4 develops options which can deliver energy savings. Identifying several ways in which process parameters can be changed is useful to determine the most appropriate modification plan. A process hazard analysis evaluates the safety implication of making modifications. A business case must be made to evaluate financial benefits of the project by calculating capital expenditure, savings and payback periods. Only then can a final modification plan be developed. The final task in this stage is to complete a trial period to prove the product quality is not diminished.

3.2.5 Control
The final stage looks to permanently implement the plan from Stage 4. Implementation includes a validation period, where the optimised process is monitored to verify there are no product quality and safety concerns. Once the optimisation is proven then it can be implemented in full. The final task is to confirm the project’s energy saving and to replicate across additional ovens as necessary.
Figure 3.1: Methodology to optimise industrial oven for energy saving

Where:
- X - Input
- Y - Output
- I - Intermediate
- E - Energy
- Q - Quality

Define
- Understand oven purpose
- Identify system boundaries
- Develop problem statement

Measure
- Process stream identification
- Measurements taken
- Inflow/outflow mass balance
- Theoretical energy required
- Actual energy consumed
- Energy saving calculations

Analyse
- Identify all variables
- Variable evaluation
- Group factors by response effect X, X, or X.
- X can be modified to reduce Y
- X can be modified to reduce energy but will impact on Y
- X cannot be modified as it will damage Y
- Process sensitivity evaluation
- Determine process parameters which can be changed that reduce Y whilst retaining Y

Improve
- Identify options to change process parameters
- Safety and risk evaluations
- Calculate savings, costs and payback period
- Develop modification plan
- Trials to test quality and safety

Control
- Full Implementation
- Validation period
- Project Evaluation
- (Replicate)
3.3  Case study: cure oven optimisation

3.3.1  Define

The methodology was applied to one oven that is used to cure adhesive on a masking tape web at Factory A. Figure 3.2 shows process flows and the system boundaries. Thermal oil, heated with natural gas, provides energy to the oven. Figure 3.3 displays a photograph of an air-floatation curing oven. A small amount of solvent residue that is left over from previous unit operations is also driven off within the oven. The system is controlled by lower explosive limit (LEL) analysers, which shut the system down if too much solvent is present in the system and a 35% LEL is exceeded. The problem is stated as to determine a way to optimise the cure oven for energy saving improvements while ensuring the oven’s primary purpose does not diminish.

Figure 3.2: Oven system flows

Figure 3.3: Photograph of an air-floatation curing oven for webbed product
3.3.2 Measure
3.3.2.1 Mass Balance
The process streams into and out of the oven system, as well as the mass flow rate of each stream, are displayed in Figure 3.2. The flow rates shown were determined empirically and theoretically. The mass into the system equals the mass out of the system. All water is driven off from the product in previous unit processes.

3.3.2.2 Energy Analysis
The theoretical minimum energy is determined by the minimum safe airflow through the system. The shutdown LEL of 35% determines minimum dilution air required. For the average solvent flow, the air into the system must be above 3,500 kg/h to ensure % LEL remains at a safe level. Equation 3.1 and the parameters in Table 3.1 are used to calculate the heat energy required for a given temperature change. The theoretical minimum energy to heat this airflow has been calculated as 169 kW.

\[ Q = \dot{m} c_p \Delta T \quad Eq. (3.1) \]

Where \( Q \) is the energy (kW), \( \dot{m} \) is the mass flowrate (kg/s), \( c_p \) is the specific heat capacity (kJ/kg.K) and \( T \) is the temperature (K).

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter value for theoretical energy required</th>
<th>Parameter value for actual energy consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{m} )</td>
<td>( 0.987 \frac{kg}{s} )</td>
<td>( 3.606 \frac{kg}{s} )</td>
</tr>
<tr>
<td>( c_p )</td>
<td>( 1.009 \frac{kJ}{kg.K} )</td>
<td>( 1.009 \frac{kJ}{kg.K} )</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>(190°C – 20°C)</td>
<td>(190°C – 20°C)</td>
</tr>
</tbody>
</table>

Within this industrial scenarios, metered data is insufficient to determine the actual energy consumption because the site’s metering does not isolate this oven unit processes. Therefore the actual energy consumed within the oven is calculated using the exhaust flow. Using Equation 3.1 and Table 1, the actual energy consumed to heat the exhaust flow is 619 kW. Allowing for inefficiencies in energy transfer from natural gas to thermal oil, the actual energy consumed is estimated to be 909 kW. Therefore the theoretical maximum energy saving potential is 740 kW.

3.3.2.3 Process Variables
X input variables can be changed in order to impact upon the intermediate I variables and ultimately on process output Ys. Table 3.2 presents X input factors, I intermediate variables and Y output variables. A cause and effect analysis was conducted for X variables to indicate which variables must be investigated further. The matrix highlighted that fan speeds and damper positions had the greatest impact on both energy and quality outputs.
Table 3.2: Process variables

<table>
<thead>
<tr>
<th>X Variables</th>
<th>I Variables</th>
<th>Y Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply fan speed</td>
<td>Web slot flow</td>
<td>Gas consumption in burner</td>
</tr>
<tr>
<td>Exhaust fan speed</td>
<td>Oven leakage</td>
<td>Adhesive cure</td>
</tr>
<tr>
<td>Supply air damper</td>
<td>Fresh air inlet flow</td>
<td>Moisture content of masking tape</td>
</tr>
<tr>
<td>Recirculation damper</td>
<td>Recirculation flow</td>
<td>Tackiness of adhesive</td>
</tr>
<tr>
<td>Exhaust damper</td>
<td>Oven exhaust flow</td>
<td>Solvent level in adhesive</td>
</tr>
<tr>
<td>Atmospheric Conditions</td>
<td>Thermal oxidiser flow</td>
<td>Masking tape adhesion</td>
</tr>
<tr>
<td>Line speed</td>
<td>Oven pressure</td>
<td></td>
</tr>
<tr>
<td>Heat exchangers condition</td>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Oven insulation</td>
<td>Oven temperature</td>
<td></td>
</tr>
<tr>
<td>Thermal oil temperature</td>
<td>Internal flows within oven</td>
<td></td>
</tr>
<tr>
<td>Residence time</td>
<td>LEL analyser reading</td>
<td></td>
</tr>
</tbody>
</table>

3.3.3 Analyse

Product quality is determined by cure conversion, which is influenced by oven temperature and residence time. Therefore, to minimise risk to product quality, the intermediate I variables that could be modified were % LEL and the oven pressure negativity. Figure 3.4 displays the important X variables considered, with dampers labelled with ‘D’ and fans with ‘F’. The main fresh air supply to the oven is via D2, F4 draws the system exhaust to a thermal oxidiser, and F3 provides flow to an air flotation roller. As variable speed drives were not installed on the fans, dampers were used to replicate this effect and three experiments were conducted in order to determine the impact of X variables.

Figure 3.4: Oven schematic including key dampers and fans X variables
3.3.3.1 Experiment 1

A Design of Experiment (DOE) was constructed and run without product, but with heat and airflow systems on. Minitab software was used to generate a DOE that analyses the impact of input variables (factors) and output variables (responses) at the same time. DOEs consist of runs, or tests, in which purposeful changes are made to the input variables. Data is collected at each run and the DOE can help identify optimum process conditions. A DOE fractional factorial design has been used in this scenario and is an appropriate method due to the multiple input variables being analysed, and the fact that DOE makes effective use of available experimental time on the oven. It generates a significant amount of information from fewer runs than other conventional experimental methods. Fractional factorial designs have lower resolution than full factorial designs but enable for useful information to be obtained from far fewer experiment runs (Gunst and Mason 2009).

Table 3.3 shows which variables were considered for all three experiments: X variables are the input factors, while I variables are the responses. For experiment 1, four factors were considered and a factorial design was generated using 9 runs (see page 29 of the 12 month report in volume 2). These four factors were selected following a cause and effect analysis of all X variables in Table 3.3, to shortlist the variables that could have had the most significant impact on key responses, and also the variables which could be practically controlled. For a full factorial design with four factors, a 16 run DOE is recommended. For a full factorial design with four factors, a 16 run DOE is recommended. However, due to time constraints when an experiment could be conducted between production runs on the oven, it was decided that 9 runs were more realistic. This would mean that the experiment would not have full resolution, but still manage to have 1 centre point per block and 1 replication per corner point. Although this is not ideal, it was deemed suitable given the circumstances.

Experiment 1 concluded that flow into the oven through the web entrance and exit slots was greater than expected, and that changes to D3 did not significantly impact recirculation flow. The recirculation flow through D5 was restricted due to a permanent blockage. Additionally, Figure 3.5 shows that D2 had the greatest effect on oven pressure, and therefore was effective at controlling the fresh supply air.

<table>
<thead>
<tr>
<th>Table 3.3: Variables considered in experiment 1, 2 &amp; 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X’s considered</strong></td>
</tr>
<tr>
<td>D1, D2, D3 and D5</td>
</tr>
<tr>
<td><strong>Intermediate variables measured</strong></td>
</tr>
</tbody>
</table>
3.3.3.2 Experiment 2

Table 3.3 shows variables considered for experiment 2. Figure 3.6 shows that D3 was not effective at re-circulating flow. Even when the damper is set to 0% (i.e. supposedly fully closed to recirculation), over 2000 kg/h of flow was still reached F4 and the thermal oxidiser. Therefore future process modification should not rely on damper D3 for process control. The optimum oven pressure was found to be -0.3 mbar, as determined to ensure flow does not exit the web slots.

3.3.3.3 Experiment 3

Experiment 3 was conducted with product to understand how the % LEL responds to reducing airflow through the system. Table 3.3 shows the variables that were considered. The experiment concluded that D2 did reduce flow into the system, but not significantly until closed to 20%. D6 controlled the exhaust flow effectively. Therefore altering D2 and D6 can balance the system so that optimum pressure and minimum flow through the system (9,347 kg/h) is obtained. To achieve this, D2 is closed fully at 0% and D6 is closed to 46°. This 28% reduction in flow results an average % LEL increase of 4.8%. There is still a sufficient amount of fresh air drawn into the oven via the web slots because the oven is negative.
Table 3.4 shows an overview of I and X variables considered in the three experiments and whether they affect quality or energy related outputs. Through analysis, the intermediate variables to be altered for process optimisation include reducing the supply air inlet flow and the oven exhaust flow. The X input factors which would impact on these I variables include D2, D6, F1 and F2.

<table>
<thead>
<tr>
<th>Output: Y variables</th>
<th>Energy</th>
<th>Energy and Quality</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate: I variables</td>
<td>oven pressure, web slot flows</td>
<td>Oven exhaust flow, recirculation flow, LEL analyser reading</td>
<td>-</td>
</tr>
<tr>
<td>Input: X variables</td>
<td>D2, D3, D4, D6</td>
<td>D1, D5</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3.4 Improve

The analysis stage identified the most appropriate X variables that can be changed to reduce airflow. Two options were put forward. Option A involved blanking off D2 permanently, setting D6 to 46° and turning off F1 permanently. Option B upgraded D2 to be closed when in production but open during emergency shutdown and for maintenance. A variable speed drive would be installed to F2 which would operate at a reduced fan speed during production but fully on during emergency shutdown. F1 would be off during production, but switched on for emergency shutdown to flush system with fresh air. D6 would be unchanged. A Process Hazard Assessment concluded that option B was favourable due to the added safety dimension from the ability to flush air though the system during an emergency shutdown.

Experiment 3 determined that the airflow through the system could be reduced by 28%. Figure 3.7 shows the percentage of total volume for each product as well as the % LEL that would be reached if the oven were optimised. Additionally, the cumulative energy saving is displayed and it can be seen that the optimisation would result in a 1,658,000 kWh per year saving in natural gas. Trials were conducted to verify that the optimisation did not diminish product quality; with results from laboratory testing proving quality is not diminished. This optimisation modification was installed in autumn 2014.
Figure 3.7: Cumulative energy saving taking into account of product volumes. The % LEL post-modification for each product is also displayed.

3.3.5 Control
After the implementation, a two month validation period was conducted to verify that the modification was stable and performed as expected. Following this, documents such as start-up/shutdown procedures and process standards were updated. Monitoring of actual savings showed that the optimisation reduced energy consumption in line with predictions, reduced oven energy consumption by 28% saving 1,658,000 kWh or 306 tCO$_2$e per year. This has resulted in a gas costs saving of £58,000 per year. Following this, the project was closed and deemed a success.

Additional ovens were then assessed to understand whether project replication was possible. At Factory A, an additional drying oven was identified as having optimisation potential; however the RE relocated to Factory B before the project could develop significantly. At Factory B, the RE identified opportunity to optimise additional ovens. Optimisation projects, following the same methodology, on two festoon ovens at Factory B have been conducted during this EngD project, delivering annual cost saving of £72,000 to the sponsor company. The first optimisation project at Factory B led to a 29% reduction in energy consumption within the festoon oven, while the second project delivered a 20% reduction in oven energy consumption. Details of these projects can be found in the second research body, Section 4.3.3.

3.4 Recommendations
An intention of the EngD program is to have a positive effect on industry. Therefore, recommendations are provided to aid further project replication in similar industrial scenarios. Reducing the total airflow through the system has been demonstrated as an important way to reduce energy consumption. Below are a number of general recommendations in how to reduce total airflow:
• Determine the limiting variable for reducing the total inlet flow (% LEL, relative humidity, etc).
• Define a baseline of the limiting variable for all products. Identify the most sensitive product.
• Calculate acceptable inlet airflow rate and validate with on-line experiments measuring the limiting variable levels.
• Determine optimum oven pressure. Design experiment to understanding airflow through slot and balancing inlet and exhaust flows. Conduct with and without product running.

Although the case study presented aims to reduce overall airflow, there are alternative methods that the systematic approach developed in this research could be applied to, such as the following:

• Increase heat transfer coefficient of the oven, so faster drying rates can be attained (higher product output).
• Optimise the temperature and residence time based on drying or cure simulation.
• Balance internal airflows to ensure there are no dead spots within the oven.
• Ensure uniform oven temperature profile.
• Maintain heat exchangers to ensure heat transfer remains effective.
• Insulate oven walls to minimise energy losses to the surrounding environment.

3.5 Key findings
Below are the key research findings from the first body of research.

• Oven parameter optimisation is a cost effective way to reduce energy consumption.
• Site wide process integration is difficult to implement in many manufacturing facilities due to high capital costs and process constraints.
• A methodology based on Six Sigma approach has been developed specifically to reduce energy consumption in ovens.
• Airflow minimisation is effective at reducing energy consumption; the percentage of airflow reduction is directly proportional to that of energy reduction. A 28% energy reduction is achievable.
• Many industrial oven processes have significant opportunity to be optimised.

3.6 Communication of findings
The research has been communicated within the sponsor company through quarterly EngD review meetings and internal technology forum presentations. Furthermore, the research led to production of paper publications for a conference and academic journal.

A paper based on this research body was published in the journal of Applied Thermal Engineering in June 2014. The paper can be found in Appendix A. In August 2014, the research was presented at PRES conference in Prague, Czech Republic; an international conference on process integration, modelling and optimisation for energy saving and pollution reduction. The aim of the PRES conference is to review the latest development and applications of process integration for energy conservation, pollution reduction and related topics. Industrial experience of the application of any available method is also welcome. A conference paper (see Appendix B) was written based on the original journal paper. A poster of this research body was presented and shortlisted for the best poster presentation. A copy of this poster can be found in Volume 2 of this thesis as supplementary material.
3.7 Summary of the first body of research

The research presented in this chapter addresses the energy consumption of industrial ovens, which use a considerable proportion of energy associated within manufacturing. A thorough assessment of Factory A’s manufacturing process highlighted that many of the industrial ovens consumed excessive amounts of energy compared to what the product required. For Factory A, the most feasible method to reduce energy consumption was to squeeze, or optimise, the process.

This body of research developed and demonstrated a methodology to reduce energy consumption within industrial ovens through parameter optimisation, which predominantly covers the environmental dimension of sustainable oven improvement. The systematic methodology guides an engineer from the basic understanding of an oven to optimisation for energy saving. The stages include define, measure, analyse, improve and control. Combining process and product understanding with consideration of physical and engineering constraints is a powerful tool that can deliver significant energy savings.

This body of research has made an important contribution to answering the original research question and helped to achieve the project aim to establish the most appropriate and feasible practices to sustainably improve industrial ovens in the manufacturing industry. This study has identified an opportunity to oven improvement that can be achieved in many manufacturing facilities. A methodology to optimise process parameters for energy saving has been developed, and an optimisation project at Factory A has been implemented. The optimisation consisted of reducing airflow through the system by altering process parameters, resulting in annual gas savings. This project has reduced oven energy consumption by 28%, saving 1,658,000 kWh or 306 tCO₂e per year. Factory A has seen a £58,000 per year reduction in gas utility costs.

The oven optimisation project at Factory A demonstrates the industrial applicability of this research body. Further opportunities for oven improvement have been identified at Factory A, and are to be completed when engineering resource is available. The methodology has also been applied to additional ovens at Factory B, delivering further cost and energy savings for the sponsor company. This systematic approach can be tailored to accommodate individual optimisation options, while still providing a clear pathway. As such, there is potential for such a methodology to reduce energy consumption within other 3M facilities and the wider manufacturing industry.

This chapter discusses the second body of research, which aims to build on the first research body by focussing on oven improvements that involve energy saving and process enhancement. The background to this body of work is presented, as well as identifying how it fits into the overall EngD research objective. The associated literature review can be found in Chapter 2, Section 2.3. The main research output presented in this chapter is a three-phase methodology for oven improvement. An industrial case study is used to demonstrate the intended use of the approach. The chapter should be read in conjunction with the journal and conference papers found in Appendix D and E.

4.1 Background

The objective of this research has been to develop process and product improvement strategies for manufacturing industry and apply the tools to Factory B. The gas-fired festoon ovens at Factory B, which are large corridors constructed of thermal blockwork heated to a set temperature, are used to cure and dry an adhesive layer in coated abrasive products. After attempts to minimise energy consumption in the festoon ovens at Factory B, it became evident that eliminating risks to product quality was vitally important in energy reduction projects. Therefore, in order to implement energy savings projects at Factory B, an approach was needed that placed emphasis on both energy saving and product quality enhancements.

Product understanding can quantify the effect of a process modification on product quality. Developing knowledge of how the materials behave during the production process and final use is always beneficial to a manufacturer. In the context of this research, product understanding involves knowledge of how heat energy affects the product quality within the ovens. This involves determining the minimum energy requirement and evaluating the effect that a heating process can have on final product performance characteristics. The obstacles that had to be overcome at Factory B, namely the concern that process changes would affect product quality, ultimately resulted in the work outlined in this chapter.

There has not previously been a general methodology to oven improvement that encompasses energy saving and product quality enhancement, as highlighted in Section 2.3. Furthermore, existing methods of adhesive cure characterisation were unsuitable to generate sufficient product understanding in real manufacturing environments. Therefore, this second body of research develops an iterative approach to oven improvement for energy reduction and enhanced process performance, which has the potential to deliver greater benefits in terms of holistic process improvement and economic saving. Additionally, a new approach to adhesive cure understanding is also presented that takes lab-based cure characterisation and relates it to product understanding.

As mentioned in Section 1.3.2, the aim of research activities associated with the second body of research is to develop an approach to oven improvement that delivers benefits in terms of energy consumption and product quality. The objectives of this body of research are:

- Develop product understanding, and then use this to enable process improvements.
- Incorporate the output from the first research body to deliver energy saving in ovens.
- Understand how product understanding can lead to product quality advances, and frame this as an economic benefit.
Implement a project that delivers energy and cost saving for the site.

This chapter presents an iterative approach for oven improvement, followed by a description of each stage. An application example is presented to demonstrate the intended use. This case study of how the approach has been applied to an oven system at Factory B is useful for academia and industry as it demonstrates the intended use and barriers for such projects. Recommendation and key findings are presented before concluding on the research body and its implications in industry and academia.

4.2 Methodology

The proposed approach to improving industrial ovens is shown in Figure 4.1. The method starts with product understanding before moving to process improvement and then finally looking at process optimisation. Incorporating product quality considerations throughout the improvement process helps to develop process capability, which results in economic benefits for a manufacturer in terms of energy saving and process performance. Ideally, activities should be completed sequentially so that changes are made at the correct time during the improvement process. For instance, product understanding can highlight an aspect of oven performance which is under-performing and needs to be improved. Optimisation should be completed once manufacturers are confident in the process hardware; optimising process settings before the hardware is changed is not efficient. That being said, in practice the approach is likely to be an iterative process. This is because the understanding gained from one phase can highlight areas of improvement that were previously overlooked. Developing knowledge of both the process and product can be done in parallel, and oven improvement should be a continuous process. This section details the methodology and the techniques used in the industrial oven case study.

![Proposed approach for oven improvement](image)

**Figure 4.1: Proposed approach for oven improvement**

Figure 4.2 presents a flowchart that interprets the high level methodology (Figure 4.1) for industrial oven application. The flowchart starts by evaluating an existing oven system before using this insight to direct product understanding. The understanding of how process temperature variation affects product quality is used to direct the process improvements that are required. The next step is then to reduce oven pressure negativity and reduce system airflow through process optimisation.
4.2.1 Product understanding
The aim of this phase is to understand what affects product quality, which can be the determining factor for many modification projects. It establishes what is required from the process to deliver a product that performs to specification. This work, generally performed at a laboratory scale using experimental approaches, acts as an enabler for future projects by understanding risks associated with projects or by quantifying potential quality improvements. Establishing this knowledge at the beginning of the improvement approach is beneficial because it enables the right decisions for process improvement and optimisation to be made quickly.

For the industrial application presented in this chapter, a number of different techniques is used to develop product understanding. Temperature logging of a product through the oven identifies the actual thermal regime the product is subjected to and highlights areas of process temperature variation. DMTA is used to understand the physical dynamic properties of an adhesive over a thermal process. The CIE-Lch colour test and accompanying free phenol analytical technique are used to give an indication of what the DMTA data means in terms of product quality. Further information on product understanding for the industrial application can be found in Section 4.3.2.

4.2.2 Process improvement
Process improvement addresses three aspects of the oven system: system controllability, process variation and energy consumption. This activity looks to develop operability and maximise an oven’s capability under its current process settings. Analysis of the system, through a combination of experimental and computational techniques, evaluates how close to its original specification the current process performs. This can then be developed to establish a way to exceed and enhance the oven’s original capability. Improvements in this section are likely to be physical changes to the oven system, which can be in the form of upgrading equipment or installing additional hardware. Product understanding can be used to help identify constraints in an existing process and can therefore highlight potential process improvement.
For the industrial application presented in this chapter, process improvement takes the form of installing insulation on the inside of the oven walls to reduce the impact of structural thermal mass on temperature responsiveness. Modelling heat transfer through the existing oven structure can determine the potential advantages in terms of energy saving and reduced process variation. Process improvement can involve installing additional sensors to assist with process control and understanding, which can then generate understanding of product quality, resulting in an iterative approach.

4.2.3 Process parameter optimisation

Process parameter optimisation is the final step in the oven improvement approach. The optimisation procedure questions whether the existing process settings can be altered in order to give benefits to process variability, product quality as well as energy consumption. Optimisation involves detailed analysis of process variables through empirical or theoretical approaches. Energy reduction is a key target in this stage, with the optimisation of process variables often being cost effective. This is the final stage because optimisation of a process should ideally be completed once the manufacturer is satisfied with the physical set-up of the system.

Chapter 3 outlines an optimisation methodology for industrial ovens which is applied in the industrial case study. The systematic approach follows Six Sigma principles and applies them to an oven scenario. The approach involves five stages: Define, Measure, Analyse, Improve and Control. The optimisation objective is to establish process settings that minimise energy consumption and improve product quality. All process variables affecting energy consumption and product quality are identified and analysed, such as fans or dampers. Performance data energy consumption and product quality are analysed for different variables to identify optimal settings that best achieve the objective. The oven is then improved to its optimised state and closely monitored.

4.3 Case study: Industrial oven improvement using a holistic approach

In order to demonstrate the intended use, the approach is applied to an industrial sized festoon oven that cures a layer of adhesive resin to a backing. Energy is supplied to the oven by direct-fired gas burners with fumes exhausted to atmosphere. The 1MW oven performs its task reliably, however it was identified as an area of process improvement and energy saving during initial energy targeting. Figure 4.3 displays a photograph of the inside of the oven with webbed product hanging from sticks. Greater understanding of the product is required to minimise variability in quality, as well as reducing risks associated with process modifications. The rest of this section details how the approach has been applied to this one oven.

Aspects of the process enhancement have been implemented during the time of this EngD, while others were not completed before the RE left Factory B. The product understanding, described in Section 4.3.1, has been conducted and has provided the factory with greater understanding of how temperature affects product quality. The analysis phase of the process improvement (Section 4.3.2) has been completed during the EngD, but the recommended changes have not yet been implemented. However, Factory B is intending to implement these improvements in 2017. The process parameter optimisation, described in Section 4.3.3, has been implemented during this EngD.
4.3.1 Product understanding

A key gap in product understanding is the knowledge of how temperature variation affects adhesive resin curing. Below is the narrative that describes the product-understanding phase of this project. It provides an overview of the purpose, analysis methods and outcomes in a logical sequence that mirrors Section 4.3.1.

- Establish the purpose of product, and cure, understanding:
  - Identify impact of temperature variation on cure conversion ($\alpha$).
  - How does cure conversion affect product quality?
- Temperature variation analysis within the oven.
- Cure analysis using DSC (analysis method A):
  - Existing models were unable to accurately predict cure.
  - Concluded that DSC is not suitable for this application, as it could not cope with complex product formation.
- Cure analysis using DMTA (analysis method B):
  - Found that DMTA is a more practical method of cure characterisation.
  - Identified that Tan D peak consistently changed depending on time and temperature exposure of product.
  - Used CIE-Lch and free phenol tests to establish the relevance of Tan D peak on the actual manufacturing line.
- Product understanding outcomes:
  - Unable to state how cure conversion ($\alpha$) varies at different points in the oven due to DSC inadequacies for this application.
Was able to identify that final cure time varies by 40 minutes depending on location within the oven. Thus, justifying the need to ensure more consistent heating regime.

4.3.1.1 Temperature variation analysis

Temperature profiling within the industrial oven should be conducted to understand existing process variation. In the given example, this is investigated by additional measurement through four probes attached to the webbed product at periodic vertical intervals. Figure 4.4 shows the vertical web temperature deviation for one product above and below its set point, with Probe 1 being the highest point on the web, and Probe 4 being the lowest (numerical values have been removed due to confidentiality). It highlights that temperature variation is particularly problematic at the beginning and end of the process, and less so during the middle of the process when the product is farthest away from the product slots where cold air can ingress into the oven. It highlights that temperature variation is particularly problematic at the beginning and end of the process.

![Figure 4.4: Vertical web temperature profiling](image)

Figure 4.5 shows the average cross web temperature difference from set point temperature. The plot demonstrated that variation above and below the set point is ± 4°C, with the top right exposed to the highest temperature, and the lower left exposed to the lowest temperature. The x and y axis on Figure 4.5 are dimensionless and refer to the physical position on the vertical webbed product that is hung from sticks.
Cure characterisation is also required to understand the impact of temperature variation on product quality. The cure of a resin is represented on a scale of 0-1, and is a qualitative measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive (Sernek and Kamke, 2007). Understanding the cross-linking of polymers can help identify the most appropriate cure strategies (Dickie et al., 1997). In this particular case, the level of cure achieved in the process has not been known and the level of cure to be targeted has also been unclear. Two methods of analysis were used to develop cure understanding.

4.3.1.2 Analysis method A
The resin was analysed using Differential Scanning Calorimetry (DSC); an established technique for the modelling of curing kinetics of epoxy based resin formulations. Details of cure characterisation using DSC can be found on pages 18-27 of the 24-month dissertation in Volume 2. The Arrhenius \( n \)th order equation is one of the most common kinetic curing equations; shown in Equation 4.1.

\[
\frac{d\alpha}{dt} = Z \cdot e^{\left(\frac{-Ea}{RT}\right)}(1 - \alpha)^n \quad Eq. \ (4.1)
\]

Where \( \alpha \) is the conversion of cure, \( t \) is the time, \( Z \) is the reaction constant, \( Ea \) the activation energy, \( R \) the gas constant, \( T \) is the absolute temperature, and \( n \) is the order of reaction. Equation 4.1 is used for data fitting and regression, and is deemed to be generic for modelling cure kinetics (Sbirrazzuoli et al., 2009). Figure 4.6 displays the exothermic region of heat flow from DSC plots for different heating rates, which can be used to determine parameters for the Arrhenius \( n \)th order kinetic model (numerical values have been removed due to confidentiality). The total enthalpy of the curing reactions (area under the curve) for each heating rate would be the same if the reactions were identical; Figure 4.6 shows this is not the case. This study highlights how heating rate variation can result in different final cure levels; important for product quality.
Alternative kinetic curing models were considered (Zhao and Hu, 2010, Nawab et al., 2012, Zvetkov et al., 2010), but given the complex nature of the adhesive formulation being analysed, it was determined that Arrhenius is the most robust model, and provided sufficient information for this study. As the heating rates A, B and C represent a feasible variation in the oven, this study has demonstrated process temperature variation can significantly affect product cured when exiting the oven, and thus significantly impacting quality.

Although DSC analysis indicated that heating rate variation would impact cure conversion, there are concerns that DSC is limited when scaling up from lab based experiments to predicting what happens on a manufacturing line (concern arose from talking to 3M product developers with many years of experience developing cure understanding). Cure analysis using alternative method of Dynamic Mechanical Analysis (DMTA) is thought to offer a better representation of actual cure conversion in manufacturing environments.

4.3.1.3 Analysis method B

The adhesive resin was also analysed off-line using a combination of two laboratory-scale analytical techniques, Dynamic Mechanical Thermal Analysis (DMTA) and free phenol/CIE-Lch colour test. DMTA provides information on how the physical property of the resin varies after being subjected to different temperature regimes, while the free phenol test is used to relate physical cure properties to the actual manufacturing process. The CIE-Lch colour test can be used to quantify the free phenol test results. Details of cure characterisation using DMTA can be found on pages 8-9 of the 30-month dissertation in Volume 2. Three temperatures have been used to replicate common temperature variation within the oven; x°C, y°C and z°C (actual temperatures omitted due to confidentiality). x°C is the average temperature at the bottom of the oven, y°C at the middle, and z°C at the top of the oven. Samples of adhesive coated film are prepared for both the DMTA and free phenol/CIE-Lch colour test. Standard isothermal DMTA procedures are followed on samples at each temperature over 180 minutes. The DMTA applies a sinusoidal force measuring the in-phase component (storage modulus), and out-of-phase component (loss modulus). The storage modulus is an indication of the material’s elastic behaviour, and the tan delta (tan D) is ratio of loss to stored energy i.e. ‘dampening’. These are commonly used for cure understanding as the hardening of a material changes the elasticity and dampening effects.

Simultaneously, adhesive coated samples are heated at matching temperatures in a separate laboratory oven. A free phenol test is conducted on these samples every 10 minutes. The free
phenol experiment involves submerging the coated sample in a 2% mixture of Sodium Phosphate. If the sample is under-cured, the solution removes the free phenol from the adhesive and a sodium hypochlorite indicator can be used as a visual indication of cure. In order to quantify the level of phenol in the solution, and thus imply the cure conversion, a CIE-Lch colour test is performed on the resulting solution. The CIE-Lch test measures three axis values; L axis is the lightness, c axis is the saturation, and h is the hue.

Figure 4.7 plots the hue data from the CIE-Lch colour test. Hue is measured in degrees, ranging from 0° (red) through 90° (yellow), 180° (green), 270° (blue) and back to 0°. The samples start yellow/orange before changing to green, and then to blue when a higher level of cure is established. Note that at each temperature (x°C, y°C and z°C) there is a strong correlation between the trend of the hue value and the time when the tan D peak occurred, which is indicated with the arrows under the main plot. The tan D peak for each temperature does not occur until a hue value has settled out above 250°. Therefore, the hue value can be used as a quick method to establish whether the tan D peak has been achieved during online testing.

![Figure 4.7: H value results from colour test with tan D values from DMTA test](image)

By investigating three different final temperatures, the study has shown the importance of achieving a uniform temperature profile within the industrial oven. The DMTA analysis shows that the tan D peak, and implied complete cure conversion, falls from 73 minutes at x°C, to 40 minutes when the oven is set at z°C. As the temperatures x°C, y°C and z°C represent a feasible variation in the oven, this study has demonstrated that process temperature variation can significantly affect how cured a product is when exiting the oven, and thus can have a significant impact on quality.

Analysis method A using DSC data indicated that heating rate has a significant impact on final cure conversion, while analysis method B indicated that final cure temperature dramatically affected the time taken to reach full cure conversion. The combination of using DMTA and free phenol/CIE-Lch colour test utilised in the analysis method B has not been presented in literature before. This
method is effective at linking lab based DMTA findings to product quality on the actual manufacturing line; a long standing issue in industrial settings attempting to characterise adhesive cure.

4.3.2 Process improvement

Product understanding highlights the importance of delivering a uniform temperature profile. As well as cross web variation, another constraint of the system is its inability to quickly change to a new temperature profile. As products with different temperature set points are run continuously after one another, the system’s inability to change temperature can result in different temperature profiles for products at the start and middle of a run.

The influence of structural thermal mass reduces the oven’s ability to change temperature. This results in long start-up periods and unnecessary downtime during breakdowns. The existing wall structure consists of thermal blockwork, insulated cavity, and an external skin. A modification to install an insulation layer to the inside of the oven wall is proposed to reduce the impact of structural thermal mass. Along with reducing oven pressure negativity to minimise cold air ingress, insulation would help to develop a tightly controlled repeatable process.

To assess the effect of adding an insulation layer on the heat fluxes across the dimension of the solid oven structure during the heating and the cooling process, a heat transfer model is adopted as shown in Equation 4.2. The boundary conditions assume a constant internal oven temperature during the heating process, and a constant external ambient air (for walls and the ceiling) or ground (for floor) temperature for both the heating and the cooling process. The initial condition adopted for a heating simulation is an oven wall temperature that is just above ambient air temperature. The heat transfer equation is solved for simulating the heating process first. Once a steady state temperature is reached, the structure’s temperature profile is taken as the initial condition to model the cooling process. For cooling, burners are turned off and the fans replace warm air with ambient air. As a preliminary analysis, the oven air temperature is first assumed to be constant at the ambient temperature throughout the cooling process, which in a second step is replaced by a more realistic treatment as presented later in this section.

$$\rho C_p \frac{dT}{dt} = k \frac{d^2T}{dy^2} \quad \text{Eq. (4.2)}$$

Where $\rho$ is the density (kg.m$^{-3}$), $C_p$ is the specific heat capacity (kJ.kg$^{-1}$.K$^{-1}$), $T$ is the temperature (K), $t$ is the time (s), $k$ is the thermal conductivity (W.m$^{-1}$.K$^{-1}$), and $y$ is the layer thickness (m). Figure 4.8 presents the model output showing the heating and cooling temperature profiles for an industrial festoon oven wall with, and without, an insulation facing (numerical values have been removed for the reasons of confidentiality). Figure 4.8a and Figure 4.8b show the cross-sectional wall temperature for the existing structure for heating and cooling regimes, whereas Figures 4.8c and 4.8d show the same for a wall structure with a layer of insulation on the inside surface. A comparison between Figures 4.8a to 4.8c demonstrates that the time taken for the structure to reach steady state reduces when insulation is installed: from 10 to 20h, there is still a considerable change in temperature profile for the existing wall structure, while the insulated system does not have a significant temperature change after 10h. Energy used to heat the wall structure results in higher supply temperatures to maintain the set point exhaust temperature. Higher supply temperature results in greater temperature variation within the oven and thus negatively affects
product quality variation. A comparison between Figures 4.8b to 4.8d, shows that the time taken for the wall structure to cool is reduced for the insulated system.

Encouraged by the positive effect of insulation suggested by the above preliminary analysis, a more realistic model was adopted to determine the cooling profile of a hot oven in a blow down operation, where the burner is off and the exhaust and supply fans are fully on. The model included a heat balance equation for the inner oven space, as shown in Equation 4.3.

\[
C_p M \frac{dT_a}{dt} = C_p m(T_0 - T_a) + Q \quad \text{Eq. (4.3)}
\]

Where \( T_a \) is the oven air temperature, \( T_0 \) is the inlet (i.e. ambient) air temperature, \( M \) is the mass of air in the oven, \( m \) is the mass flowrate of the air that flows through the oven, \( C_p \) is the heat capacity of air, and \( Q \) is the total heat flow into the oven from its solid structure. \( Q \) can be evaluated by Equation 4.4.

\[
Q = \sum h_i A_i (T_{s,i} - T_a) \quad \text{Eq. (4.4)}
\]

Where \( h_i \) is the heat transfer coefficient (W.m\(^2\).K\(^{-1}\)), \( A_i \) is the heat transfer area (m\(^2\)) and \( T_{s,i} \) is the temperature at the inner surface (K) of the oven’s structure component / such as the wall, ceiling or
Chaprer 4: Second body of research

Together with the heat transfer equation, Equation 4.2, which now includes Robin boundary conditions to connect the heat fluxes at the interface between the oven structure and external (ambient) or inner-oven environment, the blow-down cooling process is simulated, with results shown in Figure 4.9.

Note that long cooling periods have a negative effect on production efficiency as operators can only enter the oven after breakages once the temperature is below a safe limit. Figure 4.9a shows the cooling profile for the existing structure, while Figure 4.9b displays the cooling profile for an oven with 50mm of insulation on the oven walls and floor, both label the process temperature and the safe temperature for oven entry. As can be seen from Figure 4.9a and Figure 4.9b, the time taken to reach the safe temperature is 2h for the case without insulation, whereas the insulation reduces it to approximately 0.25h. This represents an 88% reduction, which can save an estimated 202h/y downtime.

![Figure 4.9: Air cooling for an oven with a) no insulation on inside surfaces, b) 50mm insulation on the floor and walls](image)

This analysis shows that the oven structure has a significant impact on oven temperature as heat retained within the structural thermal mass results in long cooling periods. Insulating the walls and floor benefits the operation and productivity of the oven system, and also helps to deliver a consistent thermal regime to the product, thus ensuring uniform cure and enhanced product quality. Process improvement enhances the process performance that has a positive economic impact as productivity is improved and superior quality products can be manufactured.

4.3.3 Process parameter optimisation

Process parameter optimisation is the final stage of the improvement approach. Chapter 3 presents a Six Sigma DMAIC (design, measure, analyse, improve, control) based methodology for parameter optimisation that is adapted for this application. When applying the DMAIC methodology to this oven, the aim identified is to establish optimal process parameters to reduce energy consumption by minimising system airflow, and to improve temperature uniformity by minimising cold air ingress through the oven slots. Figure 4.10 displays process variables within the oven system affecting energy consumption and temperature uniformity including a direct-fired gas burner/heater box,
three fans (F), five dampers (D), and the ducting/recirculation system. The dashed line passing through the oven represents the web path.

Fans and dampers offer the most reliable and practical way to reduce energy consumption and improve temperature uniformity in this oven system. Experimental analysis of the process highlights that the three fans (supply, recirculation and exhaust fans) have the largest impact on system airflow. Furthermore, fan control is the most practical option for parameter optimisation because variable speed drives (VSDs) are already installed. Minimising airflow by reducing fan VSD inverter setting (%) is straightforward; however, an optimum oven pressure negativity must also be maintained to ensure harmful fumes do not exit the oven and to limit the ingress of cold air into the oven, which has a detrimental effect on temperature uniformity. All three fans affect oven pressure negativity, which is determined by the supply and exhaust flowrates.

Figure 4.10: Oven system under considering; showing fans (F), dampers (D), ducting, and the oven chamber with web path (dashed line)

Detailed process optimisation using measurements and control experimentation has been performed for the fan settings to reduce energy consumption and improve temperature uniformity. It suggests to alter inverter settings on the supply, recirculation and exhaust fan while measuring the exhaust and slot flow. Figure 4.11 shows the resulting optimisation plot, which identifies the fan configuration that delivers the optimum combination of minimum exhaust flow of 0.22 m$^3$/s and a target slot flow of 1.28 m$^3$/s. This figure shows nine plots of fan speed against desirability, exhaust flow and slot flow, where $D$ is the desirability of the fan combination (desirability is the extent to which fan configuration reduces the exhaust and target slot flows), $y$ is the target exhaust/slot flow (identified in the charts for all three fans by the dashed blue line), and the red line identifies optimal fan speed. The optimum exhaust fan setting is 42% (previously set at 80%), the optimum supply fan setting is 100% (previously set at 100%) and the optimum recirculation fan setting 93% (previously
set at 85%). The optimum static settings decrease airflow through the system by 20-30%, which reduces fuel gas or energy consumption by 20-30%. In terms of energy cost saving, this optimisation reduces gas costs associated with this oven by approximately £18,000-£28,000 per year. Uncertainty with these findings exists due to the unpredictable nature of the oven pressure negativity, affected by local atmospheric conditions and process temperature.

Figure 4.11: Optimisation plot for fan speed configuration

After identifying that oven pressure negativity is a key parameter affecting potential energy savings, the project established automatic fan control to maintain an optimum oven pressure. A hot-wire anemometer flowmeter was installed at the web entrance slot, which is used as a proxy measurement for oven pressure negativity. This flowmeter provides values for temperature and flow velocity to the Programmable Logic Controller (PLC). Two modes of automatic fan control have been added to the PLC and Supervisory Control and Data Acquisition (SCADA) software.

Warm-Up Auto Negativity Mode

The following logic has been implemented to vary the recirculation fan speed set point (SP) and exhaust fan speed SP in order to maintain a constant flow velocity into the oven of 5m/min ± 5m/min.

- Initial supply fan speed to be set to 100%.
- Initial Recirculation fan speed to be set initially to 100%, and allowed to vary between 60% and 100%.
- Initial exhaust fan speed to be set to 30%, and allowed to vary between 30% and 40%.

If the temperature value from the negativity flow meter > 60°C, then this indicates that the oven pressure is positive. Every 15s the PLC system checks the oven pressure negativity; if the oven is positive or not negative enough, the PLC will automatically increase the exhaust fan speed SP by 0.5% providing that the SP speed is less than 40%. If the oven is too negative, the PLC will automatically decrease the exhaust fan speed SP by 0.5% providing the SP speed is greater than 30%. Once the exhaust fan speed SP has been reduced to 30% then the recirculation fan speed SP is reduced by 0.5%, providing that the SP speed is greater than 60%.
Production Auto Negativity Mode

The following logic has been implemented to vary the recirculation fan speed SP in order to maintain a constant flow velocity into the oven of 20m/min ± 5m/min.

- Initial supply fan speed to be set to 100%.
- Initial recirculation fan speed to be set initially to 100%, and allowed to vary between 60% and 100%.
- Initial exhaust fan speed to be set to 50%.

Every 15s the system will check the Oven Negativity. If the oven is positive or not negative enough, the PLC will automatically increase the recirculation fan speed SP by 0.5%, providing that the SP speed is less than 100%. If the oven is too negative it will automatically decrease the recirculation fan speed SP by 0.5%, providing that the SP speed is greater than 60%.

Additional alarms have been added to the PLC and SCADA software to indicate if the values from the flow meter are abnormal. Figure 4.12 displays the updated SCADA screen interface that displays the live negativity with a traffic light colour indication and buttons for each mode (highlight in the red box).

Figure 4.12: Updated SCADA screen interface with automatic negativity control

The automatic fan control has delivered a significant process enhancement. Not only does it save £28,000 per year as a result of reduced system flowrate, it minimises internal vertical temperature variation and reduces process warm-up time. Figure 4.13 displays two charts of supply (orange) and exhaust (blue) temperature during oven warm-up. Figure 4.13a shows that when using existing static fan speeds, the time taken for the exhaust temperature to reach SP is over 3 hours and the supply temperature is in excess of 40°C above exhaust temperature. While, Figure 4.13b shows that the automatic control of fan speeds reduces the time for warm-up and significantly reduced the supply temperature. This delivers benefits to process downtime and product quality, as a more consistent thermal profile is established.
Chapter 4: Second body of research

Thesis Frederick Pask

Process parameter optimisation is the final stage of the improvement approach. Along with process improvement and product understanding, an oven system has been developed that consumes less energy and produces higher quality product. Implementation of this optimisation project at Factory B has reduced oven energy consumption by 29%, saving 1,296,000 kWh or £28,000 per year. A similar optimisation project has been performed on a second festoon oven at Factory B, which has delivered a 20% energy reduction, saved 1,620,000 kWh of gas and £35,000 per year. The annual CO₂ emissions from both of these project has been reduced by 538 tCO₂e.

4.4 Recommendations

Understanding the interaction between heat energy and the product is necessary in oven improvement projects. Actual and ideal thermal regimes should be compared in the product understanding phase. This can help to evaluate the effectiveness of the oven and identify areas for potential process improvement. Furthermore, it is important for process engineers to interact with both product developers and operators during all phases of an improvement project. Developers have detailed knowledge of the product and its components, while operators have greatest familiarity with how the process behaves on a daily basis.

Product quality is often the limiting factor within energy reducing modifications. Therefore, establishing optimal thermal regimes from both quality and energy perspectives can indicate how oven improvements can be aligned to manufacturing strategy. Key opportunities for process improvement are often in the areas of temperature uniformity, effect of thermal mass and equipment reliability.
4.5 Key findings
Below are the key research findings from the second body of research:

- It is often difficult for energy saving projects to be implemented in industry because of unquantified fears over product quality that could arise from an energy reduction project.
- Incorporating product quality considerations from the start of all projects helps the energy reduction agenda.
- Iterative oven improvements approach involves
  - Product understanding
  - Process improvement
  - Process parameter optimisation
- This second research body gives context to where the first research body (process parameter optimisation) fits into the larger picture.
- In terms of energy cost saving, the oven case study from Section 4.3 reduced energy costs by approximately £28,000 per year.
- A similar optimisation project has been performed on the other festoon oven at Factory B. This project has been implemented and will save the factory an estimated £35,000 per year.
- A novel approach to cure understanding using Dynamic Mass Thermal Analysis (DMTA) and free phenol/CIE-Lch colour test was developed. This approach provides greater comprehension of how DMTA data relates to an actual manufacturing process line.

4.6 Communication of findings
A journal paper has been written based on the second body of research. This paper was accepted for publication in the journal of Clean Technologies and Environmental Policy in May 2016. This paper can be found in Appendix D. Furthermore, this body of research was presented at the international conference on Sustainable Design and Manufacturing 2016, Crete, Greece. The resulting conference paper can be found in Appendix E.
4.7 Summary of the second body of research

This chapter presents an approach for industrial manufacturing ovens to reduce energy consumption and enhance product quality, simultaneously. The methodology develops product understanding, process improvement and process parameter optimisation. An iterative approach is practical in industrial scenarios where the knowledge gained from each phase can impact on observations made previously. The link between product quality and energy consumption should have greater emphasis as it is a vital consideration for manufacturers when tackling their energy consumption. A manufacturer places greater emphasis on generating a profit by creating superior quality products rather than reducing energy consumption; therefore, emphasising the link between energy and product performance can help to implement more energy reducing activity within industry.

The iterative approach has been applied to a 1MW industrial festoon oven that cures a layer of adhesive resin to a backing. Generating product understanding identifies the process conditions necessary to create the desired product, thus highlighting areas of quality improvement. A method of cure characterisation for adhesive resin has been presented which combines DMTA and a free phenol/CIE-Lch test. This novel approach gives greater meaning, in terms of product quality, to the lab-based DMTA data. The data has shown that a feasible temperature variation within the oven can result in dramatically different cure conversion when material exits the oven; complete cure conversion time falls from 73 to 40 minutes depending on whether material is at the top or bottom of the oven. Process improvement ensures system hardware performs as expected and shows ways to enhance the process capability. It also identifies that the oven can be improved by installing an insulation layer to the inside of the oven wall. The effect of insulation has been modelled and found to improve temperature responsiveness, resulting in an 88% reduction in cooling time and an annual downtime saving of 202 hours. Process parameter optimisation looks to alter the process settings to maximise system performance. Optimal fan settings can be established that can reduce energy consumption by minimising system airflow, and minimise oven pressure negativity for better temperature uniformity. Automatic fan control to maintain optimum oven pressure negativity has been introduced and reduces energy consumption by 29% and delivers a gas costs saving of £28,000 per year.

The approach was also used to improve the second festoon oven at Factory B. This reduced system airflow through 7 bays which will deliver an annual cost saving of £35,000. The work on this project has not been included in this thesis because it does not expand on the research; however, it is worth commenting on as it further demonstrates that the proposed approach is practical and feasible within industry.

This second body of research addresses oven improvements from both an environmental and economic perspective, by reducing energy consumption and enhancing process performance simultaneously. By providing an industrial case study example, the proposed approach has been demonstrated at an industrial scale.
5. Third Body of Research: Developing Sustainable Industrial Ovens

Part A

Sustainability indicators and multi-criteria analysis for industrial ovens

This chapter presents Part A of the third body of research. It develops an approach that incorporates all aspects of sustainability into industrial oven development. This research body is split into two chapters; Part A develops an approach to justify sustainable decisions in oven development and applies it to a small-scale industrial problem, while Part B applies the approach to the investigation of the feasibility of biomass process heating.

This chapter provides the background of how the third body of research developed and the associated literature review can found in Chapter 2, Section 2.4. A new methodology of multi-criteria analysis using Fuzzy set theory and Monte Carlo simulation is presented. A set of specific sustainability indicators for the assessment of industrial ovens, along with justifications, is then provided with proposed indicator weightings. An industrial case study using the indicator set and methodology to assess the sustainability of three oven modification options is used to demonstrate the intended use of the research. The chapter should be read in conjunction with the journal paper found in Appendix F.

5.1 Background

This body of research developed through an attempt to identify the most sustainable way to increase adhesive cure conversion in a festoon oven at Factory B. The existing oven process did not supply a sufficient amount of energy to fully cure an adhesive layer, which resulted in reduced product performance. A number of process modification options were proposed to increase cure conversion. Traditionally, the manufacturing industry relies almost entirely on economic assessment when evaluating potential projects or investment. However, this traditional evaluation does not necessarily highlight the most suitable project and can often overlook sustainability considerations. An alternative approach for investment appraisal was needed that incorporated all sustainability dimensions.

Considering multiple sustainability dimensions, a suitable set of sustainability indicators for industrial ovens would be useful to help justify sustainable oven development in manufacturing environments. Sustainability indicators can be used to evaluate investment options against a variety of criteria, allowing for all aspects of sustainability to be incorporated into a decision-making process. It became evident that such a sustainability indicator set was not available in the existing literature, as shown in Section 2.4.1. Therefore this gap in sustainability indicator research was addressed by identifying a specific set of indicators for industrial ovens. This was done by reviewing existing literature and through consultation with industrial and academic experts.

In this chapter, sustainability indicator sets are analysed using multi-criteria analysis. Existing methods of multi-criteria analysis, which can be found in Section 2.4.2, were found to be unsuitable for technology assessment in the manufacturing industry. These established techniques did not incorporate uncertainty into the final study outcome, which presented decision makers with an
outcome that appeared definite, when in reality it is based on uncertainty. Therefore, a new methodology was developed that is suitable for manufacturing industrial scenarios.

As mentioned in Section 1.3.3, the aim of research activities associated with the third body of research is to establish approaches that incorporate all aspects of sustainability into industrial oven development. The objectives of this chapter are to:

- Identify suitable sustainability indicators specifically for industrial ovens.
- Develop a suitable methodology to analyse sustainability indicators for a manufacturing process environment.
- Use case study examples to demonstrate the indicator set and accompanying methodology.

This chapter addresses the first three objectives of the third body of research by presenting a sustainability indicator set for industrial ovens, and an accompanying methodology to inform investment decisions within a factory environment. A case study example is used to demonstrate the intended application. A discussion of research findings is then provided before a summary of the chapter is given.

5.2 Methodology

A set of sustainability indicators for industrial ovens is to be identified in Section 5.3. This section details a hybrid method of multiple criteria decision making using Fuzzy set theory and Monte Carlo simulation to analyse sustainability indicators. Figure 5.1 outlines all the important stages of the methodology, while the rest of this section details each step fully.

![Figure 5.1: Flowchart of approach used for assessment of criteria using fuzzy optimisation](image)

The methodology entails a multi-criteria decision analysis tool to identify a preferred option, \( A_m \) amongst \( m \) alternatives. The method evaluates alternative options through the use of indicators. Equation 5.1 displays the multi-criteria decision analysis matrix, where \( c_n \) is the sustainability indicator, \( x_{mn} \) is the indicator score, \( m \) is the number of alternative option, and \( n \) is the number of indicators. When using such an approach, the sustainability indicators and alternative options for system improvements should be defined by expert insights. The list should not be exhaustive; the
indicators should be the most important ones without overlap between them and should be those that make a difference in the overall sustainability performances between options and thus help in the selection of the overall best option (Sadhukhan et al., 2014). The sustainability indicators of industrial ovens are presented in Section 5.3.

Specific criteria  
\[ C_1 \quad C_2 \quad \ldots \quad C_n \]

Weighting
\[ w_1 \quad w_2 \quad \ldots \quad w_n \]

Alternatives
\[
x = \begin{pmatrix}
A_1 \\
A_2 \\
\vdots \\
A_m
\end{pmatrix}
\begin{pmatrix}
x_{11} & x_{12} & \ldots & x_{1n} \\
x_{21} & x_{22} & \ldots & x_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
x_{m1} & x_{m2} & \ldots & x_{mn}
\end{pmatrix}
\]

Eq. (5.1)

As previously stated, Fuzzy set theory is applied to multi-criteria decision problems to handle uncertainty of quantitative and qualitative criteria (Fu, 2008). It is likely that sustainability indicator sets will have both quantitative and qualitative information, and will inherently have a degree of uncertainty; thus highlighting why Fuzzy theory is appropriate for sustainability indicator analysis. The indicator score \( x_{mn} \) is presented as a triangular fuzzy number \((f_{1mn}, f_{2mn}, f_{3mn})\). A triangular fuzzy number describes the membership grade function that a value for an indicator will occur; \( f_1 \) is the lower limit membership grade equal to 0, \( f_2 \) is the most possible value membership grade equal to 1 (can be interpreted as the mean), and \( f_3 \) is the upper limit membership grade equal to 0.

For technology assessment, fuzzy numbers for each indicator are estimated based on product and process understanding. Baseline indicator scores are determined for the existing scenario and the impact that would occur if a modification option were installed can be estimated. For example, an oven’s existing system airflow can be measured, and the impact on this could be estimated if an option were installed that optimised the oven for energy saving. This can then be used to estimate \( f_2 \) for energy or emission based indicators. Uncertainty surrounding \( f_2 \) is used to estimate the range of potential values, thus providing \( f_1 \) and \( f_3 \) scores.

Fuzzy numbers for quantitative indicators can be identified in measurable units. The task is to then convert quantitative scores \( x_{mn} \) to normalised values between 0-1, so that indicators can be directly compared to each other. Indicators are either a benefit or a cost having positive or negative effects on the system performance, respectively; benefit indicators should be maximised, while cost indicators should be minimised. Equation 5.2 shows the calculation to normalise scores for benefit indicators, and Equation 5.3 for cost indicators. The normalised score \( \tilde{x}_{mn} \) is calculated using \( c_n^+ \) as the maximum score for \( C_n \), and \( c_n^- \) the minimum score for \( C_n \).

\[
\tilde{x}_{mn} = \left( \frac{f_{1mn}}{c_n^+}, \frac{f_{2mn}}{c_n^+}, \frac{f_{3mn}}{c_n^+} \right) \quad \text{Eq. (5.2)}
\]

\[
\tilde{x}_{mn} = \left( \frac{c_n^-}{f_{3mn}}, \frac{c_n^-}{f_{2mn}}, \frac{c_n^-}{f_{1mn}} \right) \quad \text{Eq. (5.3)}
\]

Qualitative assessment can be used for indicators where it is difficult to use numerical figures due to uncertainty or the nature of the indicator. Fuzzy set theory is advantageous as it can analyse quantitative and qualitative data simultaneously. Table 5.1 displays the linguistic variables and associated fuzzy numbers used in this study. Linguistic variables are used in standard fuzzy partition to enable for an indicator score to be given a linguistic term, which then corresponds to a fuzzy set and numerical value. The numerical value for each linguistic variable was chosen to provide the necessary range of desirability on a scale of 0-1, and also to provide sufficient resolution and
distinction between the potential indicator scores that are seen in the case study example in Section 5.4.

Table 5.1: Linguistic values associated with fuzzy numbers for qualitative indicators

<table>
<thead>
<tr>
<th>Linguistic values</th>
<th>$w_n$-weighted fuzzy number $(f^{1mn}, f^{2mn}, f^{3mn})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low (VL)</td>
<td>(0.00, 0.00, 0.05)</td>
</tr>
<tr>
<td>Low (L)</td>
<td>(0.05, 0.15, 0.3)</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>High (H)</td>
<td>(0.35, 0.5, 0.65)</td>
</tr>
<tr>
<td>Very high (VH)</td>
<td>(0.55, 0.7, 0.85)</td>
</tr>
<tr>
<td>Extremely high (EH)</td>
<td>(0.7, 0.85, 1)</td>
</tr>
</tbody>
</table>

Weighted fuzzy numbers ($w_n$) and the normalised scores ($\tilde{x}_{mn}$) are used to determine $\tilde{c}_{mn}$ using Equation 5.4. The weighting factors are necessary as the indicators will not all have equal importance when creating a sustainable system. Weightings should be determined objectively through consultation with experts working in relevant fields. For each alternative option, $\tilde{c}_{mn}$ values provide a triangular distribution of desirability of each sustainability indicator.

$$\tilde{c}_{mn} = w_n \cdot \tilde{x}_{mn} \quad \text{Eq. (5.4)}$$

The Monte Carlo simulation is now used as a tool to evaluate $\tilde{c}_{mn}$ values simultaneously and to determine which alternative option is favourable while understanding uncertainty in the final results. $\tilde{c}_{mn}$ values are fuzzy numbers and therefore represent a triangular distribution that can be used as the model input variables for Monte Carlo simulation. This triangular distribution is used primarily due to nature of raw data fed into the analysis from Fuzzy Set theory. A Fuzzy number is a triangular distribution of three data points: median and upper/lower limits. Alternative distributions, for instance a normal distribution, would require more than three data points to justify their use. Each alternative option now has $n$ number of distributions of desirability. The aim is to combine all these distributions into one meaningful level of desirability for each alternative option. Monte Carlo simulation is used to numerically solve the problem by aggregating information in a stochastic way.

Random numbers are generated using the distributions provided by $\tilde{c}_{mn}$; the lower, mode and upper inputs for the triangular distribution are provided by fuzzy numbers $(f^{1mn}, f^{2mn}, f^{3mn})$. The count of random numbers generated must be deemed sufficiently large; 10000 random numbers is reasonable (Esmalifalak et al., 2015).

The next task is to identify the transfer linking equation; used to combine all the indicators into one, enabling the overall desirability of each alternative options to be calculated. As the data is normalised and weighted, the indicators can be directly assessed against each other. Equation 5.5 displays the transfer linking equation, where $D(A_m)$ is the total desirability for alternative option $A_m$, and $\bar{r}_{mn}$ is a randomly generated number for a given indicator. The desirability is provided between 0 and 1.

$$D(A_m) = \frac{\bar{r}_{m1} + \bar{r}_{m2} + \bar{r}_{m3} + \ldots + \bar{r}_{mn}}{n} \quad \text{Eq. (5.5)}$$
Equation 5.5 is used to generate a data set of the total desirability for each alternative option. A normal distribution plot of the desirability can be created which determines the mean, variance and standard deviation; used to rank each alternative option. The higher the mean, the more desirable the option. The spread of data is used to indicate result certainty, which is a key advantage of using the proposed methodology. Furthermore, a cumulative distribution plot of each alternative option can be created to provide decision makers with analysis findings that can be aligned to a business’s risk strategy. This is a development on previous methodologies as it provides decision makers with information of the desirability uncertainty.

Figure 5.2 demonstrates why knowledge of desirability uncertainty is beneficial. Each triangle represents the triangular distribution of desirability for alternative options A₁, A₂ and A₃ with the peak showing the mean, and the edges showing the variance. A₂ has a greater mean desirability than A₁, however there is more uncertainty in A₂’s results. A business may decide that it prefers A₁ despite the decreased mean, because they have more confidence that the desirability will be within an acceptable range. Therefore Monte Carlo simulation presents the spread of data rather than just the mean, thus providing decision makers with all available information.

Figure 5.2: Graphical representation of desirability for alternative options A₁, A₂, A₃

A hybrid approach has been presented for the analysis of multiple criteria/indicators using Fuzzy set theory and Monte Carlo simulation. It requires basic statistical software and can be used across a wide range of industrial scenarios and other technologies. The following section identifies specific sustainability indicators for industrial ovens, and then the intended use of methodology and indicator set is demonstrated in Section 5.4.

5.3 Sustainability indicators for ovens

A generic schematic diagram of an oven system is shown in Figure 5.3. Using this understanding, sustainability indicators for industrial ovens have been identified. Table 5.2 shows the overview of the seven sustainability indicators chosen for industrial ovens. The table highlights the sustainability dimensions represented for each indicator, the indicator ID, units, type of indicator and a short description. To keep the assessment framework simple, it has been intended that each indicator affect a primary sustainability theme (i.e. environmental, economic and social), although it is worth noting that in reality some indicators will impact more than one sustainability dimension. For instance, toxicity affects humans who interact with the oven process, and will also have environmental impacts e.g. as in the case of toxic airborne particulates which interact with local environmental receptors. The remainder of this section then goes into further detail describing all seven indicators.
Table 5.2: Sustainability indicators for industrial ovens

<table>
<thead>
<tr>
<th>Theme</th>
<th>Name</th>
<th>ID</th>
<th>Units</th>
<th>Type</th>
<th>Description</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>System airflow</td>
<td>c1</td>
<td>kg/s</td>
<td>Cost</td>
<td>The mass flow rate through the system</td>
<td>Minimising system air flow reduces over processing and fuel consumption.</td>
</tr>
<tr>
<td></td>
<td>Production Efficiency</td>
<td>c2</td>
<td>%</td>
<td>Benefit</td>
<td>The efficiency of the system to produce product compared to operation time</td>
<td>High production efficiency minimises waste generation and energy consumption per tonne of output.</td>
</tr>
<tr>
<td>Economic</td>
<td>Operating costs</td>
<td>c3</td>
<td>£/hr</td>
<td>Cost</td>
<td>Cost of running the oven, including labour, energy, materials.</td>
<td>Minimising operating costs is beneficial for profit margins.</td>
</tr>
<tr>
<td></td>
<td>Quality</td>
<td>c4</td>
<td>-</td>
<td>Benefit</td>
<td>Quality improvement to product (high, medium, low, or no impact)</td>
<td>High quality products ensure high customer satisfaction.</td>
</tr>
<tr>
<td></td>
<td>Capital investment</td>
<td>c5</td>
<td>£ (000s)</td>
<td>Cost</td>
<td>Capital investment needed to get project off the ground</td>
<td>Lower capital expenditure increases project viability and is beneficial for a business’s cash flow.</td>
</tr>
<tr>
<td>Social</td>
<td>Toxicity</td>
<td>c6</td>
<td>ppm</td>
<td>Cost</td>
<td>Residual monomer in formulation and exhaust used to assess the impact on humans and environment</td>
<td>Low toxicity reduces potential harm on operators and environmental receptors.</td>
</tr>
<tr>
<td></td>
<td>Employment Opportunity</td>
<td>c7</td>
<td>-</td>
<td>Benefit</td>
<td>The employment opportunities generated from an oven, job numbers and skill level required</td>
<td>Increasing employment opportunity results in an engaged workforce and leads to job satisfaction.</td>
</tr>
</tbody>
</table>

These seven indicators are directly related to industrial ovens, and the indicator scores are practically obtainable in real life industrial scenarios. A limited number of indicators increases the practicality and ease of use in an industrial setting. Greenhouse gas emissions as a potential indicator was not chosen because the system airflow and production efficiency indicators either control, or are determining factors for, GHG emissions and would capture any changes in GHG emissions. Similarly, other cost items such as gross margin and overhead costs are not separate indicators as the operating cost indicator captures the majority of this information.

5.3.1 Detail for specific indicators

5.3.1.1 System airflow

The target is to minimise the system airflow which passes through the oven system to a safe level while ensuring oven performance; resulting in reduced energy demand and environmental impact. This indicator is directly related to the greenhouse gas emissions and is a suitable measure for the...
industrial setting of this study. Low energy consumption is desirable to minimise an oven's impact on the environment as well as being cost effective for the business. There will be a lower limit for system airflow, and this can be determined by oven function or safety constraints (i.e. drying force, humidity, lower explosion limit). The physical set up of an oven can impact this indicator and optimisation techniques can be used to minimise system airflow.

5.3.1.2 Production efficiency
Production efficiency is how efficient the system is in terms of production time compared to downtime. The downtime incorporates breakdowns, stoppages, heat up, cool down and can be affected by many aspects of the oven hardware, software, automation and interaction. A reliable and robust oven system can be constructed, and a well planned maintenance regime can ensure the oven equipment is working effectively. This ensures safety for workers, and has a large impact on the profitability of the process. Minimal unplanned downtime results in more manufacturing opportunity and positively impacts the production efficiency.

5.3.1.3 Operating costs
Operating costs are classified in two categories; fixed and variable operating costs. Fixed costs are independent of production rate/quantity and include maintenance, labour, taxation, insurance, overheads etc. Whereas variable rates are dependent on production and includes raw materials and utilities (Sahhukhan et al., 2014). This is an economic performance indicator and in many instances the operating costs are easily obtainable. The main aspects of oven modification which impact this indicator are the energy consumption, heating technology, materials for product formulation and human interaction.

5.3.1.4 Quality
Product quality is significantly affected by oven temperature uniformity and distribution. Product formulation can also impact the product quality. Quality is monitored within a manufacturing facility, however quality improvements can be overlooked when reviewing project options due to difficulty attributing quantitative improvement of a final product to a single unit oven process. In such cases, a linguistic description of quality improvement can be a suitable method of qualitative assessment. Table 5.1 displays the linguistic descriptions, and associated fuzzy numbers that can be used for this indicator. On top of the obvious waste issues resulting from poor quality, inconsistent products (that are still within quality tolerances) affect customer satisfaction and loyalty. This quality indicator captures both the economic and environmental dimensions of sustainability.

5.3.1.5 Capital investment
Although improvements should result in financial benefits to the business, there is often an initial capital investment required which has negative consequences to cash flow. The capital required for a modification should be estimated to a good degree of accuracy during an option approvals phase of a process. This indicator influences the economic performance of a business. It is clear that any business would want to have the highest economic margin and minimise costs. Thus it is important to understand the direct costs of expenditure for a modification option.

5.3.1.6 Toxicity
Toxic materials or exhaust emissions are common in many industrial heating processes and can be harmful to humans and the environment. At the very minimum toxicity must comply with regulations, but exceeding regulatory standards is beneficial. This indicator signifies the potential
health impact by the evaluation of the extent of residual monomers in the product. The product formulation has the highest effect on toxicity of the industrial oven process. In the authors’ industrial setting, the level of residual monomers is a suitable measure of this indicator. This indicator is primarily assessing the social aspect of industrial ovens.

5.3.1.7 Employment opportunity
The employment opportunity is an indicator of social performance and is viewed as a benefit. Employment opportunity can be increased by creating more jobs, or by increasing the skill level of existing jobs so that personnel have greater responsibility. Increasing the number of jobs can only be achieved if production demand increases, which can benefit a business, but also the individual. Increasing the skill level increases job satisfaction, responsibility and development. The head count required to operate an oven needs to be carefully calculated to ensure sufficient, but not excessive, manpower; this indicator ensures that workers are viewed as important stakeholders in such decisions. Linguistic descriptors are used to evaluate the potential change in employment opportunity, with the descriptions and associated fuzzy number found in Table 5.1.

5.3.2 Weighting of indicator
The importance of each indicator to sustainable decision making has been assessed by experts in the field of industrial oven management and sustainability. Fifteen individuals were asked to score each indicator between 0 and 1 for its importance when developing a sustainable oven (0 being least important, 1 being of most importance). This method of identifying indicator weightings is appropriate because it reflects the opinions of decision makers in industry and has sufficient input from experts across all three dimensions of sustainability. Fifteen opinions was deemed an appropriate number for the purpose of this study because of the balance of individual’s knowledge backgrounds. Figure 5.4 displays the results with the box plot showing the median, lower and upper quartiles for each indicator. Triangular fuzzy number weightings, shown in Table 5.3, are given to each indicator which are then used in the multiple criteria analysis; the lower quartile becomes \( f_1 \), the median becomes \( f_2 \) and the upper quartile becomes \( f_3 \).

Figure 5.4: Box plot of weighted scores for sustainability indicators

<table>
<thead>
<tr>
<th>Name of indicator</th>
<th>Indicator</th>
<th>Weighting using Fuzzy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Weighting of indicators using fuzzy numbers
Chapter 5: Third body of research Part A

5.4 Case study
To demonstrate applicability, the indicator set and methodology has been used to evaluate three different modification options to improve the sustainability of an industrial oven system at Factory B. The oven system is the same that was used in the second body of research’s case study, see Section 4.3 for greater detail. The oven’s purpose is to cure an adhesive resin and it was identified by the RE and product engineers that insufficient cure was being achieved in the current process. Therefore, three modification options were developed that could ensure sufficient cure. The aim is to identify which of the three options outlined in Table 5.4 is the most sustainable.

Table 5.4: Alternative descriptions

<table>
<thead>
<tr>
<th>Alternative ID (A_m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_1</td>
<td>Increase size of the oven</td>
</tr>
<tr>
<td></td>
<td>Increase the size of the oven to increase the</td>
</tr>
<tr>
<td></td>
<td>time the product is exposed to a thermal</td>
</tr>
<tr>
<td></td>
<td>regime. The current process is constrained</td>
</tr>
<tr>
<td></td>
<td>in terms of product throughput.</td>
</tr>
<tr>
<td>A_2</td>
<td>Increase temperature within the oven</td>
</tr>
<tr>
<td></td>
<td>Increasing the temperature will result in</td>
</tr>
<tr>
<td></td>
<td>more cure. This option will increase the</td>
</tr>
<tr>
<td></td>
<td>temperature within the oven by x°C.</td>
</tr>
<tr>
<td>A_3</td>
<td>Change the product formulation</td>
</tr>
<tr>
<td></td>
<td>Use an additive in the product formulation</td>
</tr>
<tr>
<td></td>
<td>in order to catalyse the curing reaction.</td>
</tr>
</tbody>
</table>

Using the sustainability indicators for ovens provided in Section 5.3, Table 5.5 displays the initial indicator scores for each alternative option. Furthermore, in Table 5.5 the values for c_n^+ (maximum score for c_n) and c_n^- (minimum score for c_n) are given. These are used in Equations 5.2 and 5.3 depending on whether the indicator is a cost or a benefit, therefore the cost criteria have ‘n/a’ in the c_n^- column, and the benefit criteria have ‘n/a’ in the c_n^+ column.

Table 5.5: Individual indicator scores

<table>
<thead>
<tr>
<th>Indicator ID</th>
<th>A_1 (x_1n)</th>
<th>A_2 (x_2n)</th>
<th>A_3 (x_3n)</th>
<th>c_n^+</th>
<th>c_n^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_1</td>
<td>(20, 21, 22)</td>
<td>(10, 11, 12)</td>
<td>(10, 11, 12)</td>
<td>n/a</td>
<td>10</td>
</tr>
<tr>
<td>c_2</td>
<td>(40, 50, 60)</td>
<td>(45, 55, 65)</td>
<td>(50, 55, 65)</td>
<td>65</td>
<td>n/a</td>
</tr>
<tr>
<td>c_3</td>
<td>(1050, 1100, 1150)</td>
<td>(800, 850, 900)</td>
<td>(850, 900, 950)</td>
<td>n/a</td>
<td>800</td>
</tr>
<tr>
<td>c_4</td>
<td>(0.7, 0.85, 1)</td>
<td>(0.35, 0.5, 0.65)</td>
<td>(0.35, 0.5, 0.65)</td>
<td>65</td>
<td>n/a</td>
</tr>
<tr>
<td>c_5</td>
<td>(900, 950, 1000)</td>
<td>(5, 5, 10)</td>
<td>(10, 15, 20)</td>
<td>n/a</td>
<td>5</td>
</tr>
<tr>
<td>c_6</td>
<td>(0.7, 0.8, 0.9)</td>
<td>(0.9, 1.0, 1.2)</td>
<td>(0.9, 1.1, 1.2)</td>
<td>n/a</td>
<td>0.7</td>
</tr>
<tr>
<td>c_7</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>0.45</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Table 5.6 shows the normalised quantitative and qualitative indicator scores ($\bar{x}_{mn}$) for each alternative option using Equation 5.2 and 5.3. These were determined using product and process understanding of the existing oven, as well as knowledge of how the alternative option would impact on each indicator. For instance, an oven of increased size would require an increased system flowrate ($c_1$) to maintain a sufficient number of air turns within the oven. A discrete value estimation of system airflow can be used as fuzzy number $f_2$, while a window of realistic values above and below $f_2$ can be estimated for the fuzzy numbers $f_1$ and $f_3$. The same principles can be applied to each indicator and modification option. Linguistic values were used to generate fuzzy numbers for indicators $c_4$ and $c_7$.

<table>
<thead>
<tr>
<th>Indicator ID</th>
<th>Weight using fuzzy numbers ($w_n$)</th>
<th>$A_1(x_{1n})$</th>
<th>$A_2(x_{2n})$</th>
<th>$A_3(x_{3n})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>(0.7, 0.7, 0.9)</td>
<td>(0.45, 0.48, 0.50)</td>
<td>(0.83, 0.91, 1.00)</td>
<td>(0.83, 0.91, 1.00)</td>
</tr>
<tr>
<td>$c_2$</td>
<td>(0.4, 0.5, 0.6)</td>
<td>(0.62, 0.77, 0.92)</td>
<td>(0.69, 0.85, 1.00)</td>
<td>(0.77, 0.85, 1.00)</td>
</tr>
<tr>
<td>$c_3$</td>
<td>(0.7, 0.8, 0.9)</td>
<td>(0.70, 0.73, 0.76)</td>
<td>(0.89, 0.94, 1.00)</td>
<td>(0.84, 0.89, 0.94)</td>
</tr>
<tr>
<td>$c_4$</td>
<td>(0.5, 0.7, 0.9)</td>
<td>(0.55, 0.70, 0.85)</td>
<td>(0.15, 0.30, 0.45)</td>
<td>(0.35, 0.50, 0.65)</td>
</tr>
<tr>
<td>$c_5$</td>
<td>(0.5, 0.6, 0.9)</td>
<td>(0.01, 0.01, 0.01)</td>
<td>(0.50, 1.00, 1.00)</td>
<td>(0.25, 0.33, 0.50)</td>
</tr>
<tr>
<td>$c_6$</td>
<td>(0.6, 0.8, 1)</td>
<td>(0.78, 0.88, 1.00)</td>
<td>(0.58, 0.70, 0.78)</td>
<td>(0.58, 0.64, 0.78)</td>
</tr>
<tr>
<td>$c_7$</td>
<td>(0.3, 0.5, 0.7)</td>
<td>(0.05, 0.15, 0.30)</td>
<td>(0.05, 0.15, 0.30)</td>
<td>(0.05, 0.15, 0.30)</td>
</tr>
</tbody>
</table>

The weightings for each indicator, $w_n$, is multiplied by $\bar{x}_{mn}$ using Equation 5.4 for the $\bar{c}_{mn}$ values, which are displayed in Table 5.7.

Table 5.7: Normalised and weighted $\bar{c}_{mn}$ fuzzy matrix

<table>
<thead>
<tr>
<th>Indicator ID</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>(0.32, 0.33, 0.45)</td>
<td>(0.58, 0.64, 0.90)</td>
<td>(0.58, 0.64, 0.90)</td>
</tr>
<tr>
<td>$c_2$</td>
<td>(0.25, 0.38, 0.55)</td>
<td>(0.28, 0.42, 0.60)</td>
<td>(0.31, 0.42, 0.60)</td>
</tr>
<tr>
<td>$c_3$</td>
<td>(0.49, 0.58, 0.69)</td>
<td>(0.62, 0.75, 0.90)</td>
<td>(0.59, 0.71, 0.85)</td>
</tr>
<tr>
<td>$c_4$</td>
<td>(0.28, 0.49, 0.77)</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.18, 0.35, 0.59)</td>
</tr>
<tr>
<td>$c_5$</td>
<td>(0.00, 0.00, 0.01)</td>
<td>(0.25, 0.60, 0.90)</td>
<td>(0.01, 0.02, 0.05)</td>
</tr>
<tr>
<td>$c_6$</td>
<td>(0.47, 0.70, 1.00)</td>
<td>(0.35, 0.56, 0.78)</td>
<td>(0.35, 0.51, 0.78)</td>
</tr>
<tr>
<td>$c_7$</td>
<td>(0.02, 0.08, 0.21)</td>
<td>(0.02, 0.08, 0.21)</td>
<td>(0.02, 0.08, 0.21)</td>
</tr>
</tbody>
</table>

Using the triangular distribution given by the fuzzy numbers ($\bar{c}_{mn}$) for each indicator and option, 10000 random numbers were generated using statistical software. The overall desirability of each alternative option was calculated by combining the information from all seven indicators, using the transfer linking Equation 5.5. Figure 5.5 shows the histogram plot of desirability for each alternative option. It shows that the mean desirability of A1 is 0.38 (left hand side plot), the desirability of A2 is 0.48 (right hand side plot), and the desirability of A3 is 0.42 (middle plot). Therefore, A2 (to increase oven temperature) is the most sustainable option as it has the highest desirability. The advantage of presenting findings in this way is that the spread of data can be visualised; thus enabling more informed decision-making. Figure 5.5 shows the largest spread of data for A2, suggesting greatest uncertainty in the mean value of its desirability compared to the other two options. The narrowest spread of A3 suggests that this carries the greatest certainty. But it has lower desirability than A2.

Thesis

Frederick Pask
Figure 5.5: Histogram showing desirability of A1, A2, and A3

A cumulative distribution plot can be generated with the data from the transfer linking Equation 5.5. Figure 5.6 shows the cumulative distribution of desirability for this case study. The advantage of presenting the data in this format is that the associated risks are more obvious. For instance, a business may decide that it requires a level of desirability of 0.43. For option A1, this will be achieved with a 1% certainty. For option A3, this will be achieved with a 15% certainty. While for option A2, this will be achieved with a 95% certainty. Presenting findings using cumulative distributions can help align decisions to a company’s risk acceptance levels.

Figure 5.6: Cumulative distribution of desirability
The analysis of sustainability indicators using Fuzzy set theory and Monte Carlo simulation has been communicated to decision makers within Factory B. Sufficient information has been provided so that an informed decision can be made on how best to develop a sustainable oven system. The systematic engineering improvements to this same oven that were highlighted in the second body of research, Section 4.3, will help establish a heating system that is tightly controllable. This enables for the oven temperature to be increased with greater confidence.

5.5 Discussion

There will inevitably be a degree of cross-over between indicators, however it is important to minimise replication in order to not skew findings. In the indicators presented, the operating cost includes fixed and variable costs. Fixed costs are those which do not change with sales or production, and it is important to try to separate these fixed costs from capital investment. Variable costs include the utility costs and will be impacted by the system airflow, which also impacts on energy consumption related indicators. These have been taken into consideration and it was decided that the seven indicators are separate enough not to affect overall finding.

In the case study, an example is given for determining the fuzzy score for system airflow (c₁). A triangular distribution, and associated triangular fuzzy number \((f_1, f_2, f_3)\), are estimated for each indicator score: \(f_1\) is the lower confidence boundary, \(f_2\) is the estimated mean system airflow and \(f_3\) is the upper confidence boundary. The research presented in this chapter evaluates potential modification options to an existing oven system, thus, real data cannot be obtained to determine indicator scores for modification options. Instead, fuzzy indicator scores are estimated presuming the modification option were installed. This is achieved with product and process understanding of the existing system, and an awareness of how the modification would affect each indicator. Product and process understanding can determine the indicator fuzzy number for an existing oven system with high confidence; this may involve data collection and analysis. From the baseline of existing oven performance, predicting scores for modified oven systems becomes possible. This approach is acceptable due to the small scale of application and because the methodology’s intended use, to evaluate investment decisions, does not justify significant resources spent accurately modelling indicator scores; instead, it is used to aid the investment decision making process by incorporating environmental and social factors into a project appraisal.

Indicator weighting can change depending on the desired purpose of the process being studied. A commodity business might have greater concern with initial capital or operating costs. However, a highly profitable industry would perhaps be less interested in costs and more interested in quality and throughput. The indicators and weightings presented in this chapter have been designed for one particular industrial application, and there could therefore be industrial scenarios when they are not suitable. It is recommended that before any potential use, an evaluation of the industrial process and its supporting business should be conducted to fully understand the suitability of the presented indicator set.

Decision-making when assessing sustainability from the perspectives of different disciplines is a difficult task. It is rare that one option can be definitively determined as more sustainable than another. There is often a significant degree of uncertainty, as well as cross over, with the sustainability performance of alternative options; therefore the method of multi-criteria analysis should reflect this. Being able to incorporate uncertainty using Fuzzy set theory has enhanced the
practical application of sustainability indicators, however many previous approaches have fallen short on presenting uncertainty in the final results. The methodology used in this chapter aids the decision making process further by providing all the information so that decisions can be aligned to business strategy.

Overall desirability of an option gives an indication of the sustainability. The model, in Equations 5.1-5.5, incorporates scores of individual sustainability indicators given by experts as independent variables. These raw scores could be varied to examine the sensitivity of each indicator on the overall desirability. If a particular indicator is found to significantly impact over desirability more than other indicators, then greater care needs to be given to understand the uncertainties related to key indicators. This can be achieved by greater depth of analysis, or by involving experts in the field to expand the breadth of knowledge.

5.6 Key findings

Below are the key research findings from the third body of research, Part A:

- A set of sustainability indicators for industrial ovens has been identified.
- A new methodology of multi-criteria analysis has been developed that combines Fuzzy set theory and Monte Carlo simulation.
- This new methodology incorporates uncertainty into the final outcome and is particularly useful for manufacturing decision-makers.
- The most sustainable method to increase cure conversion is to increase temperature within the oven.

5.7 Communication of findings

This body of research has been written into a paper that was submitted to the journal of Cleaner Production in November 2015. The paper is entitled: Sustainability indicators for industrial ovens and assessment using Fuzzy set theory and Monte Carlo simulation. The paper was accepted for publication in October 2016.

5.8 Summary of the third body of research: Part A

Sustainability indicators for technology assessment are essential to help decision makers identify suitable options. Having said this, the development of rigorous sustainability assessment for industrial ovens is in its infancy. In this study, a specific set of seven sustainability indicators has been developed for the assessment of an industrial oven; including system airflow, production efficiency, operating costs, quality, capital investment, toxicity and employment opportunity. Each indicator has been assigned a weighting through consultation with industrial oven and sustainability experts. The indicators have been chosen so that all aspects of sustainability are incorporated, and also with consideration of what information is readily available for industrial engineers. Such an indicator set for technology assessment of ovens has not previously been reported.

As well as identifying a specific set of sustainability indicators, this chapter presents a hybrid method of multiple criteria decision analysis which can be used to evaluate the sustainability of alternative technology improvement options. The methodology incorporates Fuzzy set theory and Monte Carlo simulation. Both techniques are established tools to help decision makers in multiple criteria analysis by incorporating uncertainty into the analysis. They are commonly used with sustainability indicators due to the inherent uncertainty which is common with many indicators, however the approach
presented in this chapter is more effective due to the fact that it incorporates uncertainty into the final desirability. This provides industrial decision-makers with greater information than many previous methodologies.

The sustainability indicators and multiple criteria analysis have been demonstrated in an industrial environment by evaluating three alternative options for oven improvement at Factory B. It was identified that the level of adhesive cure being achieved in the oven was not sufficient. Consequently, three alternative options to increase cure conversion were developed. The predicted performance of each alternative option was scored against the seven sustainability indicators, before analysis was performed to determine their overall desirability. Using a normal distribution histogram plot of desirability and a cumulative distribution plot, the most sustainable option to provide improved treatment of an adhesive resin was identified, which is increasing the oven temperature.
6. **Third Body of Research: Developing Sustainable Industrial Ovens**

**Part B**

Industrial feasibility study of biomass process heating using multi-criteria and economic analysis

This chapter presents Part B of the third body of research. It applies the set of sustainability indicators and multi-criteria analysis from Part A, along with techno-economic analysis, to assess the industrial feasibility of biomass technology as an alternative fuel for the process heating. The study background is presented before outlining the methodology used to understand industrial feasibility. Reviewing existing literature (Section 2.4.3) identified gap in literature communicating industrial perception and acceptability of biomass heating in manufacturing settings. This chapter therefore evaluates the sustainability and economic desirability of biomass process heating in two case studies for retrofit and new build process scenarios. This evaluation provides insights into the sustainability advantages of biomass heating technology and the barriers that must be overcome. This industrial feasibility study stands independently of the third body of research because the findings could stand alone as a separate contribution to knowledge.

6.1 **Background**

The research applies the set of sustainability indicators established in Chapter 5 to another industrial case. This part of the study developed in response to an industrial challenge at Factory B. Management at the factory were exploring the possibility of retrofitting their existing direct-fired natural gas heating process to an indirect-fired system, i.e. one central burner with an energy transfer fluid to distribute heat around the system. Indirect-fired process heating presents significant safety benefits for operators over a direct-fired system, as it eliminates the potential for oven workers to be exposed to harmful combustion fumes. It was clear that when investigating options for an indirect-fired system, biomass technology should be considered as an alternative fuel to natural gas. Biomass fuel supply is relatively reliable and is used to powering a convection heating process. Biomass offered Factory B with a realistic renewable alternative whereby their products could remain unchanged, albeit heated with a different fuel source and energy transfer method.

Natural-gas is the conventional fuel used in many industrial heating processes due to its convenience in terms of availability, distribution and maintenance. Furthermore, natural gas is considered low-risk and reliable. In contrast, biomass is a relatively uncommon fuel in the process industry, and manufacturers have little experience working with the technology. The key advantage of biomass over fossil-fuels is the reduced environmental impact. Therefore, biomass could have the potential to offer the manufacturing industry with a feasible way to sustainably power its heating processes.

This chapter provides a comprehensive industrial perspective on sustainability and policy analyses for the uptake of biomass heating technologies in the manufacturing industry within the UK and EU. Two case studies are used to investigate industrial feasibility in retrofit and new build scenarios. Retrofitting replaces a pre-existing manufacturing process with biomass technology. The first retrofit case study is based on the real-life industrial scenario that arose at Factory B. The second case study investigates the feasibility of installing biomass technology in a newly build factory. This is a
hypothesised case study and attempts to understand whether a manufacturing business would install biomass technology in a newly built factory.

Modification options are assessed using an industrially relevant set of sustainability indicators and a multi-criteria analysis tool to determine the sustainability desirability. A techno-economic analysis of biomass heating technology is also performed, using feedback from manufacturing managers, to gauge the likelihood of adopting biomass-based technology in the manufacturing industry. Based on the results of the feasibility study, the effectiveness of policy drivers in supporting biomass resource use in the manufacturing industry is discussed.

The aim of the third body of research, shown in Section 1.3.3, is to establish approaches that incorporate all aspects of sustainability into industrial oven development. This chapter addresses the final two objectives of the research body, which are to:

- Use case study examples to demonstrate the indicator set and accompanying methodology.
- Evaluate the sustainability benefits of renewable process heating for the manufacturing industry.

This chapter is structured by presenting the methodology used to evaluate the industrial feasibility of biomass heating. The two case studies for retrofit and new build process are presented, which identify the sustainable and economic desirability rank of four options. A discussion of research findings is then provided before a summary of the chapter is given.

6.2 Methodology

Two industrial case studies evaluate the feasibility of biomass process heating in the manufacturing industry, including a) retrofitting existing gas process with a biomass burner, and b) installing a biomass burner in a new build factory. For both case studies, biomass technology is analysed using sustainability indicators and multi-criteria analysis. Furthermore, a techno-economic analysis is performed to help justify manufacturer’s decisions. Figure 6.1 displays the methodology used to carry out this research.
6.2.1 Sustainability indicators for biomass technology assessment

Options are to be analysed against a set of sustainability indicators. Indicators should be applied using a ‘fit for purpose’ approach rather than making a generic set of indicators fit for all applications (Dewulf and Van Langenhove, 2005). An obvious indicator for 'why biomass?' is the GHG emission reduction. Existing literature in Section 2.4.3 showed that GHG emissions are a significant part of all previous studies that assess the sustainability implications of biomass. Furthermore, the GHG consequences of switching to biomass technology was an important driver for the client, which in this case is Factory B.

The sustainability indicator set developed in Chapter 5 did not explicitly incorporate GHG emissions. Instead, the GHG related environmental impact was covered by the system airflow indicator, which is directly related to oven emissions if the fuel-type and heating technology remained unchanged. However, an indicator that directly measures GHG emissions is more appropriate for the industrial case study in this chapter, which evaluates process modification from direct-fired to indirect-fired processes, as well as changing fuel-type. The absolute values of kg CO₂ equivalent per MJ of energy provision for each technology over the total life-cycle can be used to calculate the GHG emissions. The energy consumption for a heating system over a year can be calculated and the associated GHG emissions can therefore be determined.

The sustainability indicator set for this chapter reflects the perspectives of manufacturers and covers important sustainability dimensions. Measurement and estimation of chosen indicators is straightforward and assists the practical application of the approach. Table 6.1 outlines the sustainability indicator set used in this study.
Table 6.1: Sustainability indicator set for indirect biomass heating

<table>
<thead>
<tr>
<th>ID</th>
<th>Indicator name</th>
<th>Indicator description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Greenhouse gas (GHG) emissions or global warming potential</td>
<td>The life-cycle GHG emissions that result from the oven due to fuel consumption, in kg CO₂ equivalent per MJ of energy provision.</td>
</tr>
<tr>
<td>C2</td>
<td>Operational time</td>
<td>The percentage time the manufacturing plant operates in average in a year.</td>
</tr>
<tr>
<td>C3</td>
<td>Capital investment</td>
<td>Capital investment needed to get project off the ground, including both direct and indirect capital costs, detailed in Sadhukhan et al. (2014).</td>
</tr>
<tr>
<td>C4</td>
<td>Operational cost</td>
<td>The cost of running the oven, including labour, energy and materials. It can be classified into fixed and variable operating costs, detailed in Sadhukhan et al. (2014).</td>
</tr>
<tr>
<td>C5</td>
<td>Quality</td>
<td>Product quality improvement (high, medium, low, or no impact). Quality of product must be met, and if possible enhanced. Linguistic and qualitative descriptors are used for the impact on quality.</td>
</tr>
<tr>
<td>C6</td>
<td>Safety</td>
<td>The impact on employee safety is an important social indicator. Linguistic and qualitative descriptors are used to describe the impact on quality.</td>
</tr>
<tr>
<td>C7</td>
<td>Employment opportunity</td>
<td>The employment opportunities generated from a process, job numbers and skill level required. Both linguistic and qualitative descriptors are used for this criterion.</td>
</tr>
</tbody>
</table>

6.2.2 Multi-criteria analysis

In Chapter 5, Section 5.2 presented a method of multi-criteria analysis using Fuzzy set theory and Monte Carlo simulation to analyse modification options for industrial ovens in the manufacturing industry. This section gives an overview of the methodology to aid the reader’s understanding in this chapter.

Process understanding is used to predict initial fuzzy indicator scores \((f_{1mn}, f_{2mn}, f_{3mn})\). \(n\) is the indicator number, \(m\) is the alternative option, \(f_2\) is the mean predicted score, \(f_1\) and \(f_3\) are the lower and upper quartile scores. Linguistic descriptors are used for qualitative indicators, such as impact on safety. Table 6.2 shows the descriptor of impacts and associated fuzzy numbers for qualitative linguistic indicators.

Table 6.2: Linguistic values associated fuzzy numbers for qualitative indicators

<table>
<thead>
<tr>
<th>Linguistic values</th>
<th>(w_n)-weighted fuzzy number ((f_{1mn}, f_{2mn}, f_{3mn}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low (VL)</td>
<td>(0.00, 0.00, 0.05)</td>
</tr>
<tr>
<td>Low (L)</td>
<td>(0.05, 0.15, 0.3)</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>High (H)</td>
<td>(0.35, 0.5, 0.65)</td>
</tr>
<tr>
<td>Very high (VH)</td>
<td>(0.55, 0.7, 0.85)</td>
</tr>
<tr>
<td>Extremely high (EH)</td>
<td>((0.7, 0.85, 1))</td>
</tr>
</tbody>
</table>
Scores are normalised between 0-1 so that indicators can be directly compared to each other, with 0 being the least desirable and 1 the most desirable. Indicators are either a benefit or a cost depending on whether they have a positive or negative effect on system performance. Shown below are calculations to normalise scores for benefit indicators (Equation 6.1) and for cost indicators (Equation 6.2).

\[
\tilde{x}_{mn} = \left( \frac{f_{1mn}}{c_n^+}, \frac{f_{2mn}}{c_n^\circ}, \frac{f_{3mn}}{c_n^-} \right) \quad \text{Eq. (6.1)}
\]

\[
\bar{x}_{mn} = \left( \frac{c_n^-}{f_{3mn}}, \frac{c_n^\circ}{f_{2mn}}, \frac{c_n^+}{f_{1mn}} \right) \quad \text{Eq. (6.2)}
\]

Where \( \tilde{x}_{mn} \) is the normalised fuzzy score, \( c_n^+ \) is the maximum score for indicator \( c_n \), and \( c_n^- \) the minimum score for indicator \( c_n \). Indicator weightings are necessary as indicators do not have equal importance. The weighting factors have been determined through consultation with 20 industrial and academic experts in manufacturing processing and sustainability. Experts rated indicators on their importance on a scale from 0 to 1. Triangular fuzzy number weightings \( (w_n) \) are given to each indicator, which are then used in the multiple criteria analysis. Figure 5.4, in Chapter 5, shows a box plot showing the weighting median, lower and upper quartiles for each indicator.

Weighted fuzzy numbers \( (w_n) \) and normalised scores \( (\tilde{x}_{mn}) \) are used to determine \( \bar{c}_{mn} \) using Equation 6.3. For each alternative option, \( \bar{c}_{mn} \) values provide a triangular distribution of desirability of each sustainability indicator.

\[
\bar{c}_{mn} = w_n \cdot \tilde{x}_{mn} \quad \text{Eq. (6.3)}
\]

Fuzzy set theory is limited in providing decision makers with a suitable level of information that can be aligned with risk strategies. Therefore, Monte Carlo simulation is used to numerically solve the desirability of each indicator by aggregating information in a stochastic way from probability distributions (Sadeghi et al., 2010). Monte Carlo simulation evaluates \( \bar{c}_{mn} \) values simultaneously and combines all distributions into one meaningful level of desirability for each alternative option, with a corresponding certainty level. 10,000 random numbers are generated for each indicator using the distribution \( \bar{c}_{mn} \). The lower, mode and upper inputs for the triangular distribution are provided by fuzzy numbers (Esmalifalak et al., 2015). The transfer linking equation (Equation 6.4), enables overall desirability of each alternative option to be calculated. As the data is normalised and weighted, the indicators can be directly assessed against each other. The desirability is provided between 0 and 1.

\[
D(A_m) = \bar{r}_{m1} + \bar{r}_{m2} + \bar{r}_{m3} + \ldots + \bar{r}_{mn} \quad \text{Eq. (6.4)}
\]

Where \( D(A_m) \) is the total desirability of alternative option \( A_m \), and \( \bar{r}_{mn} \) is a randomly generated number for a given indicator. A normal distribution plot of the desirability is created to determine the mean, variance and standard deviation. This can be used to rank each alternative option.

6.2.3 Economic analysis

Manufacturing companies use basic economic tools for prioritizing investments. Replicating the economic analysis that manufacturers use can identify barriers to biomass resource implementation and evaluate the policy effectiveness. The analysis uses discounted cash flow (DCF) analysis. The DCF analysis accounts for the net cash flow, the difference between the price of the product (heat), i.e., RHI and the annual cost of capital and cost of labour, fuel and maintenance. Companies prioritise projects with short payback periods to minimise risk relating to uncertainty of factory, company or
market performances. DCF analysis is an effective technique to appraise capital projects that use future cash flow projections, before using a discount rate to arrive at an estimate of the net present value (NPV) (Sadhukhan, et al. 2014). The NPV is calculated for both the manufacturing company and the government. This clarifies the feasibility of a biomass installation to both the key stakeholders. A positive NPV does not necessarily result in project implementation because many companies also require a sufficiently short payback period. For example, many businesses stipulate capital expenditure projects that must have a payback period of 3 years or lower.

6.3 Case study A: Retrofit scenario

This case study is based on a real industrial scenario presented at Factory B. 3M considered retrofitting their existing 2MW direct-fired gas oven system with a number of modification options, two of which included biomass technology.

6.3.1 Modification options

Table 6.3 describes the four modification options to change the way the heat energy is supplied to the existing industrial oven system at Factory B.

<table>
<thead>
<tr>
<th>Table 6.3: Modification options overview</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option A1:</strong> Business as usual (BAU), leave existing direct-fired natural gas</td>
</tr>
<tr>
<td>This option does not change the process and provides a baseline. Direct fired heating has high energy conversion efficiency but can create potentially hazardous working environments due to harmful products of combustion.</td>
</tr>
<tr>
<td><strong>Option A2:</strong> Indirect-fired natural gas</td>
</tr>
<tr>
<td>This option changes the heating process by installing an indirect-fired system fuelled by natural gas. Indirect heating increases safety by separating process air and combustion air, resulting in a lower system airflow due to absence of moisture from combustion. The natural gas burner has an energy output of 2.5MW.</td>
</tr>
<tr>
<td><strong>Option A3:</strong> Indirect-fired biomass</td>
</tr>
<tr>
<td>This option changes the process to an indirect biomass-fuelled heating system. Wood pellet biomass fuel is used. The energy demand of this option is 2.5MW. Biomass consumption generates a revenue from RHI.</td>
</tr>
<tr>
<td><strong>Option A4:</strong> Indirect-fired dual-fuel (biomass and natural gas)</td>
</tr>
<tr>
<td>This option involves an indirect, dual-fuelled heating system powered by biomass and natural gas. Dual-fuelled systems reduce risk associated with biomass fuel supply. The 2.5MW burners are designed to operate at full demand powered by biomass. However, there is added capability for natural gas to be used if needed.</td>
</tr>
</tbody>
</table>

Figure 6.2 displays a schematic of direct-fired and indirect-fired oven systems. The direct-fired system has three separate burners, whereas the indirect-fired system has a central burner, which can be powered by natural gas or biomass, and energy is transferred to a heat exchanger at each bay using an energy transfer fluid. Figure 6.3 displays a photograph of the direct-fired gas burner at Factory B, which represents the BAU option A1.
6.3.2 Sustainability indicator scores

For the indicators c1 and c4, scores are estimated from kg CO₂ equivalent emission per MJ output energy provision from natural gas and biomass from (BiomassEnergyCentre, 2015) and from (BiomassEnergyCentre, 2013) for economic parameters respectively. The score for indicator c3 is obtained from vendor quotation. For the other indicators, average scores are acquired from primary process measurements and experts’ knowledge. Quantitative and qualitative scores are given as triangular fuzzy numbers, with (minimum, mean, maximum), as shown in Table 6.4.
Table 6.4: Sustainability indicator fuzzy scores for retrofit case study

<table>
<thead>
<tr>
<th>Option</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU, direct gas</td>
<td>(2000, 2090, 2100)</td>
<td>(2450, 2590, 2700)</td>
<td>(800, 1040, 1200)</td>
<td>(1000, 1350, 1550)</td>
</tr>
<tr>
<td>c1 (kg CO₂ equivalent/MJ)</td>
<td>(83, 87, 92)</td>
<td>(89, 93, 95)</td>
<td>(89, 93, 95)</td>
<td>(89, 93, 95)</td>
</tr>
<tr>
<td>c2 (%)</td>
<td>(0, 0.05, 0.3)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>c3 (million £)</td>
<td>(1890, 1920, 1950)</td>
<td>(2040, 2073, 2110)</td>
<td>(1680, 1725, 1750)</td>
<td>(1760, 1810, 1860)</td>
</tr>
<tr>
<td>c4 (×1000 £/year)</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.35, 0.5, 0.65)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>c5</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
</tr>
<tr>
<td>c6</td>
<td>(0.05, 0.15, 0.3)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>c7</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
<td>(0.00, 0.000, 0.05)</td>
</tr>
</tbody>
</table>

6.3.3 Multi-criteria analysis

Table 6.5 shows the normalised and weighted fuzzy number scores of all the indicators and modification options, from Equation 6.3.

Table 6.5: Normalised and weighted scores for each option

<table>
<thead>
<tr>
<th>Option</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU, direct gas</td>
<td>(0.27, 0.27, 0.36)</td>
<td>(0.21, 0.22, 0.29)</td>
<td>(0.47, 0.54, 0.90)</td>
<td>(0.36, 0.41, 0.72)</td>
</tr>
<tr>
<td>c1</td>
<td>(0.35, 0.46, 0.60)</td>
<td>(0.37, 0.49, 0.60)</td>
<td>(0.37, 0.49, 0.60)</td>
<td>(0.37, 0.49, 0.60)</td>
</tr>
<tr>
<td>c2</td>
<td>(0.50, 0.60, 0.90)</td>
<td>(0.03, 0.05, 0.08)</td>
<td>(0.02, 0.02, 0.03)</td>
<td>(0.02, 0.02, 0.04)</td>
</tr>
<tr>
<td>c3</td>
<td>(0.58, 0.67, 0.77)</td>
<td>(0.53, 0.62, 0.71)</td>
<td>(0.67, 0.78, 0.90)</td>
<td>(0.63, 0.74, 0.86)</td>
</tr>
<tr>
<td>c4</td>
<td>(0.03, 0.11, 0.27)</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.08, 0.21, 0.41)</td>
</tr>
<tr>
<td>c5</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.21, 0.40, 0.65)</td>
<td>(0.09, 0.24, 0.45)</td>
<td>(0.09, 0.24, 0.45)</td>
</tr>
<tr>
<td>c6</td>
<td>(0.00, 0.00, 0.04)</td>
<td>(0.00, 0.00, 0.04)</td>
<td>(0.05, 0.15, 0.32)</td>
<td>(0.05, 0.15, 0.32)</td>
</tr>
<tr>
<td>c7</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
</tr>
</tbody>
</table>

Data from Table 6.5 can be used in Monte Carlo simulation as a triangular distribution of desirability, which then generates a histogram plot of desirability, as shown in Figure 6.4. The histogram shows that installing an indirect biomass burner has the highest desirability and hence, is the most sustainable option. Predictably, the uncertainty associated with changing to biomass is greater than the BAU option; a larger spread of data reflects greater uncertainty.

It is acknowledged in this industrial case study, the decision-making process does not yet make use of the spread of the distributions in the results. This is because the uncertainty associated with each option is similar, and would not impact a business’s decision. However, during a more detailed analysis with greater understanding of different risks, there could be opportunity to utilise the spread of data more effectively.

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Chapter 6: Third body of research Part B

Figure 6.4: Histogram plot of desirability for options

6.3.4 Economic analysis
A basic economic analysis is performed on each option. The DCF analysis is performed using a discount rate of 8% over a 20 year period, which is also a typical weighted average cost of capital (WACC) for a FTSE 100 company. The Net Present Value (NPV) is calculated from the net cash flows, discounted with respect to year, as shown in Equation 6.5.

\[ NPV = \sum_{\text{plant life in years}} \frac{\text{RHI revenue} - \text{annual operational cost} - \text{annual capital cost}}{(1+\text{discount rate})^{\text{year}}} \]  

Eq. (6.5)

Table 6.6 displays the key data for each option used in the economic analysis. However, an example calculation is given for the annual revenues from RHI for option A3, with mean operational time of 93% and RHI tariff of 2.05p/kWh (OFGEM, 2016):

Revenue from RHI = 0.0205 \( \frac{£}{kWh} \times 3000kW \times 24h \times 4d \times 48 weeks \times 0.93 = £263,554 \)

The net operational cost for option A3 (£1.725m, Table 6.4), including the revenue from RHI, is estimated as follows:

Net annual operational cost = £1,660,000 (labour) + £45,000 (maintenance) + £285,000 (biomass fuel costs) − £263,000 (RHI) = £1,725,000

For option A3 (biomass heating technology), thus, substituting the values, the following equation is obtained:

\[ NPV = \sum_{\text{year}=1}^{20} \frac{0.263 - 1.725 - 3.1 \times 0.08}{(1+0.08)^{\text{year}}} = \sum_{\text{year}=1}^{20} \frac{-1.71}{(1+0.08)^{\text{year}}} \]
Table 6.6: Key data of alternative options in economic analysis

<table>
<thead>
<tr>
<th>ID</th>
<th>Capital cost (£m)</th>
<th>Annual energy demand (MWth)</th>
<th>RHI assumed (p/kWh)</th>
<th>Annual costs incl. production and operating, excluding RHI (£m)</th>
<th>Production efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.00</td>
<td>3</td>
<td>0</td>
<td>1.92</td>
<td>87</td>
</tr>
<tr>
<td>A2</td>
<td>1.26</td>
<td>3</td>
<td>0</td>
<td>2.07</td>
<td>93</td>
</tr>
<tr>
<td>A3</td>
<td>3.10</td>
<td>3</td>
<td>2.05</td>
<td>1.99</td>
<td>93</td>
</tr>
<tr>
<td>A4</td>
<td>2.90</td>
<td>3</td>
<td>2.05</td>
<td>1.99</td>
<td>93</td>
</tr>
</tbody>
</table>

Figure 6.5 shows the cash flow of the 4 scenarios, in cumulative present value (discounted terms). After 10 years Option A3 shows a net cost lower than that for A1 BAU, and thus the (discounted) break even time of the biomass investment is 10 years. Over a 20-year time horizon, the most favourable option economically is A3, which has a cumulative cost of -£17.6m, while for the BAU option (A1) it is -£18.9m.

Table 6.7 shows a summary of the sustainable desirability and economic rank of options for case study A. The findings from the economic analysis differ slightly from the analysis based on sustainability indicators. However, it is clear that option A3, to install a biomass burner, is the most beneficial over a 20-year period. The break-even point between A1 and A3 occurs in year 10, which can be interpreted as the operation gain vs. excess capital investment for biomass technology.
## Table 6.7: Rank of sustainable and economic desirability of modification options

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Sustainable desirability rank</th>
<th>Economic rank</th>
<th>NPV after 20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Direct-fired natural gas</td>
<td>4</td>
<td>3</td>
<td>-£18.9m</td>
</tr>
<tr>
<td>A2</td>
<td>Indirect-fired natural gas</td>
<td>2</td>
<td>4</td>
<td>-£20.6m</td>
</tr>
<tr>
<td>A3</td>
<td>Indirect-fired biomass</td>
<td>1</td>
<td>1</td>
<td>-£17.6m</td>
</tr>
<tr>
<td>A4</td>
<td>Indirect-fired dual-fuel</td>
<td>3</td>
<td>2</td>
<td>-£18.9m</td>
</tr>
</tbody>
</table>

### 6.4 Case study B: New-build process scenario

Case study B explores the hypothesis that biomass is more feasible in new-build process scenarios. This is based on a hypothetical industrial scenario whereby a company considers installing a 3 bay oven system with a 2MW energy demand in a new-build factory. The options include conventional heating technologies and biomass resource use in heating technologies.

#### 6.4.1 Options

Table 6.8 gives a description of how the four options vary in the way that heat energy is supplied to this industrial oven system.

<table>
<thead>
<tr>
<th>Option details for a new-build oven system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option B1: Direct-fired natural gas</strong></td>
</tr>
<tr>
<td>The process is powered by three direct fired gas burners. It involves reliable equipment and the airflow through each bay meets the oven’s requirement in the retrofit case study.</td>
</tr>
<tr>
<td><strong>Option B2: Indirect-fired natural gas</strong></td>
</tr>
<tr>
<td>A 2.5 MW indirect-fired burner fuelled by natural gas heats the oven system. A thermal fluid system transfers energy from the burner to each bay. This option enhances worker safety by separating operators from the combustion fumes, and also reduces energy consumption by minimising the system airflow.</td>
</tr>
<tr>
<td><strong>Option B3: Indirect-fired biomass</strong></td>
</tr>
<tr>
<td>A 2.5MW indirect-fired biomass-fuelled burner heats the oven system. Wood pellet biomass fuel is used. Biomass consumption generates a revenue from RHIs. This option increases safety of employees, reduces running costs and minimises the producer’s environmental impact.</td>
</tr>
<tr>
<td><strong>Option B4: Indirect-fired dual-fuel (biomass + natural gas)</strong></td>
</tr>
<tr>
<td>This option involves an indirect dual-fuelled heating system powered by biomass and natural gas. Dual-fuelled systems reduce risk associated with biomass fuel supply. The 2.5MW burners are designed to operate at full demand powered by biomass. However, there is added capability for natural gas to be used if needed.</td>
</tr>
</tbody>
</table>

### 6.4.2 Sustainability indicator scores

Indicator scores are estimated using knowledge gained in case study A, vendor quotations and an understanding of how each option affects each indicator. The fuzzy number indicator scores for each option are given in Table 6.9.
Table 6.9: Sustainability indicator fuzzy scores for new-build case study

<table>
<thead>
<tr>
<th>Option</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct gas</td>
<td>Indirect gas</td>
<td>Indirect biomass</td>
<td>Indirect dual-fuel</td>
</tr>
<tr>
<td>c1 (kg CO₂ equivalent/MJ)</td>
<td>(2000, 2090, 2100)</td>
<td>(2450, 2590, 2700)</td>
<td>(800, 1040, 1200)</td>
<td>(1000, 1350, 1550)</td>
</tr>
<tr>
<td>c2 (%)</td>
<td>(83,87,92)</td>
<td>(89,93,95)</td>
<td>(89,93,95)</td>
<td>(89,93,95)</td>
</tr>
<tr>
<td>c3 (million £)</td>
<td>(0.6,0.8, 1.0)</td>
<td>(1.1, 1.26, 1.5)</td>
<td>(2.8, 3.1, 3.3)</td>
<td>(2.5, 2.9, 3.3)</td>
</tr>
<tr>
<td>c5</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>c6</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
<td>(0.15, 0.3, 0.45)</td>
</tr>
<tr>
<td>c7</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.00, 0.00, 0.05)</td>
</tr>
</tbody>
</table>

6.4.3 Multi-criteria analysis

Table 6.10 displays the normalised and weighted fuzzy numbers derived from Table 6.9 using Equation 6.3.

Table 6.10: Fuzzy number for multi-criteria analysis of new-build thermal processes

<table>
<thead>
<tr>
<th>Option</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct gas</td>
<td>Indirect gas</td>
<td>Indirect biomass</td>
<td>Indirect dual-fuel</td>
</tr>
<tr>
<td>c1</td>
<td>(0.27, 0.27, 0.36)</td>
<td>(0.21, 0.22, 0.29)</td>
<td>(0.47, 0.54, 0.90)</td>
<td>(0.36, 0.41, 0.72)</td>
</tr>
<tr>
<td>c2</td>
<td>(0.35, 0.46, 0.58)</td>
<td>(0.37, 0.49, 0.60)</td>
<td>(0.37, 0.49, 0.60)</td>
<td>(0.37, 0.49, 0.60)</td>
</tr>
<tr>
<td>c3</td>
<td>(0.30, 0.45, 0.90)</td>
<td>(0.20, 0.29, 0.49)</td>
<td>(0.09, 0.12, 0.19)</td>
<td>(0.09, 0.12, 0.22)</td>
</tr>
<tr>
<td>c4</td>
<td>(0.58, 0.67, 0.77)</td>
<td>(0.53, 0.62, 0.71)</td>
<td>(0.67, 0.78, 0.90)</td>
<td>(0.63, 0.74, 0.86)</td>
</tr>
<tr>
<td>c5</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.08, 0.21, 0.41)</td>
</tr>
<tr>
<td>c6</td>
<td>(0.00, 0.00, 0.05)</td>
<td>(0.21, 0.40, 0.65)</td>
<td>(0.09, 0.24, 0.45)</td>
<td>(0.09, 0.24, 0.45)</td>
</tr>
<tr>
<td>c7</td>
<td>(0.00, 0.00, 0.04)</td>
<td>(0.00, 0.00, 0.04)</td>
<td>(0.05, 0.15, 0.32)</td>
<td>(0.05, 0.15, 0.32)</td>
</tr>
</tbody>
</table>

Table 6.10 is used for the triangular distribution of desirability in Monte Carlo simulation. The outcome is a histogram plot of desirability, as shown in the histogram plot Figure 6.6. For the same reason as when interpreting the histogram of desirability for case study A, Figure 6.4, the spread of data is not used when interpreting Figure 6.6. Indirect biomass burner (option A3) is the most sustainable option. Although it has the highest desirability, this option also has the largest uncertainty. The next most desirable option is B4, installation of a biomass and gas dual-fuelled burner.
6.4.4 Economic analysis

DCF analysis using the calculation shown in Equation 6.5 evaluates the four options against each other. Table 6.11 displays the key data used in the analysis for new build case study economic analysis. Figure 6.7 shows the NPV to operate the manufacturing process for the four options. It shows that over 20 years, indirect biomass technology (B3) is the cheapest option with indirect dual-fuelled and conventional gas-fired burner (B1) closely behind, and finally that an indirect gas-fired system as the most expensive option.

Table 6.11: Key data of alternative options in economic analysis

<table>
<thead>
<tr>
<th>ID</th>
<th>Capital cost (£m)</th>
<th>Annual energy demand (MWth)</th>
<th>RHI assumed (p/kWh)</th>
<th>Annual costs incl. production and operating, excluding RHI (£m)</th>
<th>Production efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.80</td>
<td>3</td>
<td>0</td>
<td>1.92</td>
<td>87</td>
</tr>
<tr>
<td>B2</td>
<td>1.26</td>
<td>3</td>
<td>0</td>
<td>2.07</td>
<td>93</td>
</tr>
<tr>
<td>B3</td>
<td>3.10</td>
<td>3</td>
<td>2.05</td>
<td>1.99</td>
<td>93</td>
</tr>
<tr>
<td>B4</td>
<td>2.90</td>
<td>3</td>
<td>2.05</td>
<td>1.99</td>
<td>93</td>
</tr>
</tbody>
</table>
Figure 6.7: NPV to the manufacturer for four options in new-build case study

Table 6.12 shows a summary of the sustainability and economic desirability of options B1-B4 for case study B. The analysis for new-build scenarios shows that biomass is the most desirable option, which is the same conclusion as in retrofit scenarios. The break-even point between B1 and B3 occurs in year 8. This is shorter than the 10 year break-even point in case study A. This suggests that biomass heating is more feasible in new-build scenarios than in retrofit scenarios.

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Sustainable desirability rank</th>
<th>Economic rank</th>
<th>NPV after 20 years (£ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Direct-fired natural gas</td>
<td>4</td>
<td>3</td>
<td>-£19.0m</td>
</tr>
<tr>
<td>B2</td>
<td>Indirect-fired natural gas</td>
<td>3</td>
<td>4</td>
<td>-£21.0m</td>
</tr>
<tr>
<td>B3</td>
<td>Indirect-fired biomass</td>
<td>1</td>
<td>1</td>
<td>-£17.6m</td>
</tr>
<tr>
<td>B4</td>
<td>Indirect-fired dual-fuel</td>
<td>2</td>
<td>2</td>
<td>-£18.9m</td>
</tr>
</tbody>
</table>

6.5 Discussion

6.5.1 Communication with business

Despite the study finding that biomass indirect heating is sustainable and economically attractive, decision makers at Factory B concluded that the benefits of biomass did not justify a £3.1 million capital investment. Furthermore, the break-even of 10 years for such a project is in excess of the company’s general 2-year payback requirement.

The main barrier preventing an existing fossil-fuelled process to be replaced with biomass technology is the short-term economic viability. Business decisions are currently based on generating a profit and/or complying with regulations. Manufacturers only invest in large capital projects if these are thought to be critical in moving the business forward financially, or to comply with regulations: in 2016, a biomass installation does neither of these for many manufacturers. In the retrofit example, a capital expenditure of £3.1 million is required to retrofit the existing process.
with biomass technology. A RHI threefold greater than the present is needed so that the payback period for biomass process heating is acceptable in the manufacturing industry.

Although the RHI reduces the operational cost of biomass heating, this study has found that manufacturers are more concerned with payback period on capital expenditure when evaluating project viability. Retrofitting an existing process with biomass technology is difficult because the capital cost associated with changing technology is evaluated against the BAU option, which has no capital expenditure.

For a newly-built facility, biomass technology also offers the most sustainable option compared with natural gas-fuelled or dual-fuelled processes. As case study B is hypothetical, the expected reaction of industry is speculative. However, it is thought that a manufacturer is more likely to install biomass technology for a newly built factory than for a retrofit scenario because all options, gas or biomass, have capital investment costs. This removes the main barrier to biomass heating technology.

6.5.2 Alternative incentive policy

This section presents an alternative policy scheme to incentivise biomass technology that aims to overcome the barriers presented in Section 6.1. The alternative scheme increases viability of biomass in retrofit scenarios by negating the capital cost away from businesses. A low interest loan from the government is provided to cover the capital cost of the biomass installation and a RHI tariff reduces operating costs. The RHI tariff of 1p/kWh is chosen as this is sufficient to reduce operation costs compared to BAU.

Table 6.13 provides an economic evaluation of an alternative scheme to the current RHI seen in case study A. The DCF analysis determines the NPV to both the company and the government over a 20-year period. Three options are evaluated: BAU, the existing RHI scheme and an alternative incentive scheme. For the company, the existing scheme generates a NPV of -£17.6m over 20 years, whereas the alternative scheme has an NPV of -£18.2m. However, the alternative scheme still has a £0.6m saving over BAU. The alternative scheme increases biomass viability because the company no longer has the capital expenditure, which is the key barrier to implementation.

For the government, the alternative incentive scheme has a NPV of -£2.2m compared to -£2.5m for the existing scheme. This is a £0.3m saving to the government over a 20-year period. The interest rate on the capital loan, which is supplied by the treasury, is influenced by the loan default risk. This default risk considers the company’s history and operation, as well as the average government bond yield for a given period (12 months or more) prior to when the loan is issued. In this study, a 2.5% interest rate is chosen as the manufacturing company is deemed low risk and the average UK government bond yield over the previous twelve months is 2.33%.

In conclusion, the proposed alternative scheme results in a NPV benefit to both the government and the company over a 20-year period. As well as the cost saving, the viability of installing biomass technology in retrofit scenarios increases because the company does not have to pay the capital expenditure in one lump sum.
Table 6.13: Comparison of incentive schemes to encourage biomass process heating

<table>
<thead>
<tr>
<th>Description of scheme</th>
<th>BAU</th>
<th>Current RHI scheme</th>
<th>Alternative incentive scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital investment by company</td>
<td>£0</td>
<td>£3.1 million</td>
<td>£0</td>
</tr>
<tr>
<td>Breakdown of annual operating costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labour costs</td>
<td>£1,660,000</td>
<td>£1,660,000</td>
<td>£1,660,000</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>£0</td>
<td>£45,000</td>
<td>£45,000</td>
</tr>
<tr>
<td>Fuel costs</td>
<td>£260,000 (gas at 2.7p/kWh)</td>
<td>£285,000 (biomass at 2.3p/kWh)</td>
<td>£285,000 (biomass at 2.3p/kWh)</td>
</tr>
<tr>
<td>RHI revenue</td>
<td>£0</td>
<td>£264,000 (RHI at 2.05p/kWh)</td>
<td>£129,000 (RHI is 1p/kWh)</td>
</tr>
<tr>
<td>Total annual operating costs</td>
<td>£1,920,000</td>
<td>£1,726,000</td>
<td>£1,862,000</td>
</tr>
<tr>
<td>NPV over 20 years</td>
<td>-£18.9 million</td>
<td>-£17.6 million</td>
<td>-£18.2 million</td>
</tr>
</tbody>
</table>

6.5.3 Carbon trading and taxation for biomass

Since 2005, emissions of GHGs have been subjected to regulations under a market-based mechanism known as the EU Emission Trading Scheme (ETS). The EU ETS focuses on minimising emissions of CO₂ from large energy consuming industry such as oil refineries, power plants, metal manufacturers and airlines etc. (EU, 2013). Carbon pricing attaches an economic value to CO₂ emissions and encourages businesses to adopt low-carbon practices; the cost of carbon is roughly a minimum of £21/tCO₂ in 2016, rising to £70/tCO₂ in 2030 (HM_Treasury, 2013). Energy consumers are given a carbon allowance and are able to trade unused carbon credits or buy additional credits if emissions exceed their allowance. The EU ETS reduces the cap of the carbon allowances by 1.74% each year, and by 2.2% after 2021 (DECC, 2016).

Much of the light manufacturing industry is exempt from the EU ETS because its energy consumption is comparatively low, and accounting for its emissions is difficult. However, biomass technology can become viable if the EU ETS is applied to these energy consumers. To understand the effect of EU ETS on NPV, Equation 6.6 is applied, with substitution of RHI revenue by total carbon taxation. It is assumed that the current emission level is the initial carbon allowance and that gas consumption remains unchanged over 20 years. As the emission allowance reduces by 1.74% each year until 2021 and 2.2% thereafter and cost of carbon increases, the NPV of oven operation is impacted by an increasing tax expense. The NPV over 20 years to operate the gas consuming oven system under the EU ETS scheme is -£19.1m, compared to -£18.9m for BAU exempt from the
scheme. Thus, the light manufacturing industry can have a greater motivation to invest in renewable technology.

\[
NPV = \sum_{plant\ life\ in\ years}^{\text{annual operational cost} - \text{annual capital cost} - \text{carbon tax}} \frac{1}{(1+\text{discount\ rate})^\text{year}} \quad \text{Eq. (6.6)}
\]

An alternative to incorporating EU ETS to the light manufacturing industry is carbon taxation on existing fossil fuels. Although both ETS and taxation can work well in reducing emissions, ETS can lead to volatile prices and speculative trading, which makes it hard for firms to evaluate the costs and benefits of adopting new and cleaner technologies. Alternatively, taxation can allow for better planning knowing what tax companies will have to pay. The tax scheme could be set up so that it incentivises newer low-carbon technologies, thus leading to reduced emissions.

Businesses are not sufficiently motivated to use renewable fuels in manufacturing heating processes with the current level of RHI incentives. The positives of installing biomass do not outweigh the negatives in terms of resource expenditure and investment. Increasing the level of RHI could result in a positive change within industry, or alternatively, introducing a carbon taxation scheme to all industrial processing would send a clear message from the Government to industry that reducing carbon emissions is important.

### 6.6 Key findings

Below are the key research findings from the third body of research, Part B:

- Sustainability indicators can be used to assess the industrial feasibility of biomass process heating.
- In retrofit industrial scenarios, indirect biomass-fuelled heating is the most sustainable option, as it reduces net operational cost and GHG emissions and performs favourably in DCF analysis.
- Biomass process heating would be a sustainable option for Factory B. However, decision makers at the factory consider biomass unviable due to the high capital cost.
- For new-build scenarios, biomass is again the most sustainable option. However, it is thought to be more viable than in retrofit scenarios as the short-term economic evaluation is more favourable.
- Existing RHIs in the UK do not sufficiently incentivise biomass process heating in existing manufacturing environments.
- Carbon taxation according to the EU ETS scheme can be an effective tool to incentivise biomass heating for the manufacturing industry.

### 6.7 Communication of findings

This body of research has been written into a paper that was submitted to the journal of Biomass and Bioenergy in June 2016. The paper is entitled: Industrial feasibility study of biomass process heating using multi-criteria analysis and economic analysis. The first review of this submission has not yet been received.
6.8 Summary of the third body of research: Part B

This chapter presents a feasibility study on biomass heating technology from the perspective of industrial practitioners to UK biomass strategy developers and policy makers. The study uses sustainability indicators and accompanying methodology of multi-criteria analysis that was developed in Part A of the third body of research, Chapter 5. The list of indicators is not exhaustive, but captures triple bottom line criteria for an industrial setting. The results of the analysis in an industrial setting do not need to be conclusive to be effective in making decisions between numerous options. To help understand the industrial perspective to biomass investment, a DCF analysis of different options is also conducted.

Two case studies, for retrofit and new-build process scenarios, are used to illustrate industrial biomass feasibility. The first case study is based on the manufacturing scenario at Factory B, and considers retrofitting their 2MW existing gas-fired heating process with biomass technology. Indirect biomass-fuelled heating has been found to be the most sustainable option, as it reduces net operational cost and GHG emissions. Biomass also performs favourably in DCF analysis. However, due to the high capital cost, the decision makers at Factory B consider biomass unviable in retrofit scenarios. Businesses only invest in large capital projects if they present a significant financial return or are required in order to comply with regulation; biomass in retrofit scenarios meets neither of these requirements. The second case study, which is hypothetical, investigates the feasibility of biomass technology for newly-built manufacturing processes. Here, biomass is the most sustainable option and is thought to be more viable than in retrofit scenarios as the short-term economic evaluation is more favourable.

The current UK RHI scheme does not successfully incentivise biomass in retrofit scenarios. Retrofitting is difficult because the capital cost associated with changing technology is evaluated against the BAU option, which has no capital expenditure. Therefore, a new technology must offer considerable benefits to make it economically viable. New technologies, such as biomass, are more viable in a new-build process because project evaluation incorporates capital expenditure for both biomass technology and a conventional heating technology. An alternative incentivisation scheme is proposed that mitigates high capital expenditure away from manufacturers by offering a government loan, while also lowering operational costs with a RHI tariff. The scheme can save the company £0.6m compared to BAU option and save the government £0.3m over a 20-year period compared to the existing RHI scheme. Such an incentivisation scheme can increase biomass viability for businesses. It is also shown that the carbon taxation according to the EU ETS scheme can be an effective tool to incentivise biomass heating for the manufacturing industry.
7. **Conclusion**

This chapter integrates all three research bodies and provides an overview of this EngD thesis. The main research findings, which are specific to the manufacturing environment from where the study was conducted, are presented. Next, generalised implications of the research are presented to systematically improve performance in any industrial heating process. A discussion on how this EngD is broadly applicable to the wider manufacturing industry is then given. The research limitations and recommendations for further studies are provided before a final overall conclusion.

7.1 **Research overview**

This EngD research project set out to explore concepts to deliver systematic engineering improvements within industrial ovens. The scope of study was short-to-medium term practical improvements that could be implemented within the four years of the project. In Chapter 1, the overall research aim was established to derive appropriate and feasible approaches to improve the environmental and economic performance of industrial ovens in the manufacturing industry. The three main study objectives were to:

- Identify oven improvement opportunities in 3M factories.
- Develop methods that will reduce energy, improve product quality and increase safety of industrial oven systems.
- Implement projects at multiple factories to have a positive impact on those manufacturing processes.

Three oven systems were investigated over the four years of the EngD project. Different systems presented unique problems that required a distinctive approach. In light of this, three research bodies were developed for three bespoke solutions with the same overarching aims. The bodies of research work towards the purpose of systematically improving the performance of industrial ovens.

In Chapter 2, the literature review revealed the research field of industrial ovens is underdeveloped. The potential positive impacts that this study could deliver were substantial given the significant impact that ovens have on the environment, the quality of product being manufactured, the factory financial expenditure and its employees. Although there has previously been research conducted that looked to reduce energy consumption and increase sustainability within the process industry, there was a lack of research focusing specifically on industrial ovens. Furthermore, there were specific knowledge gaps on how product understanding could lead to energy saving in ovens, on appropriate sustainability indicators for ovens and on a suitable multi-criteria decision making analysis for technology assessment in the manufacturing industry. The benefits to both industry and academia of being able to generate data from industrial case studies were also identified, as well as being able to identify the barriers preventing implementation.

Chapter 3 presented the first body of research on energy saving in industrial ovens through process optimisation. Initially, the EngD project focused primarily on energy consumption within heating processes at Factory A. For Factory A, the most feasible option was to squeeze, or optimise, the process. A curing oven offered the greatest opportunity for energy saving, and work was undertaken to optimise process settings. A novel optimisation methodology based on a Six Sigma approach was developed, which led to a 30% reduction in system airflow, delivering an annual energy cost saving of £58,000. From this work, a journal paper entitled 'Systematic approach to industrial oven
optimisation for energy saving’ has been published in the Journal of Applied Thermal Engineering. Furthermore, the research was presented at the International Conference CHISA PRES 2014, Prague, Czech Republic.

Chapter 4 gave details the second body of research on process enhancement within industrial ovens considering both energy consumption and product quality. The research focus moved to Factory B, which presented different barriers and research challenges. Instead of focusing entirely on energy saving, the improvement process also had to improve product quality. An iterative approach highlighting the importance of product understanding was used to deliver a combined annual energy cost saving of £63,000 from two optimisation projects. Moreover, product understanding of abrasive product was developed to understand adhesive curing kinetics, helping the site develop their capability to manufacture high quality products. Both the iterative approach and methodology of cure characterisation are novel and beneficial to industry and academia. From this work an original journal paper, entitled ‘Industrial oven improvement for energy reduction and enhanced process performance’, was published in the Journal of Clean Technologies and Environmental policy. Furthermore, the research was presented at the International Conference Sustainable Design and Manufacturing (SDM) 2016, Crete, Greece.

Chapter 5 presented Part A of the third body of research to develop sustainable industrial ovens. In order to justify sustainable investment within 3M, a set of sustainability indicators and accompanying multi-criteria analysis was developed for industrial ovens. Financial payback is the most critical factor when manufacturers evaluate capital investment projects. Sustainability indicators offer an alternative approach and a specific set of indicators for industrial oven applications were developed in this study. The multi-criteria analysis method developed incorporates Fuzzy set theory and Monte Carlo simulation. This methodology offers an advantage over existing methods by incorporating uncertainty in the final outcome, which can be aligned to business risk strategy. An industrial case study looking to increase cure conversion in a pre-existing oven at Factory B was used to demonstrate the intended use of the sustainability indicator set and methodology. The study found that increasing oven temperature was the most sustainable option. From this work an original journal paper, entitled ‘Sustainability indicators for industrial ovens and assessment using Fuzzy set theory and Monte Carlo simulation’, was published in the Journal of Cleaner Production.

Chapter 6 presented Part B of the third body of research to develop sustainable industrial ovens. Here, sustainability indicators, multi-criteria analysis and techno-economic analysis were used to assess the industrial feasibility of biomass process heating in the manufacturing industry. It was found that retrofitting gas heating with biomass technology is not viable due to economic barriers. An alternative incentive scheme instead of the Government’s current Renewable Heat Incentive (RHI) scheme was proposed, which aims to enhance biomass viability in retrofit scenarios and reduce the cost to the Government over the life of the asset. The same method of analysis was applied to a newly built process scenario. It was also found that biomass technology is more viable in new-build than in retrofit scenarios, as the economic assessment is more favourable. Additionally, it was found that the EU Emission Trading Scheme (ETS) is an effective tool to encourage the uptake of the biomass heating technology in the manufacturing industry.

Table 7.1 provides an overview of the academic and industrial contributions made during the four years of this EngD project. This project has shown 3M UK that energy reduction within their manufacturing processes is possible. 3M UK, with the help of the RE, are currently in the early stages
of formulating a dedicated role within the organisation that would be responsible for its energy strategy. Along with the financial saving at two 3M factories, this demonstrates the positive industrial legacy of this EngD project.

### Table 7.1: Overview of academic and industrial contributions

<table>
<thead>
<tr>
<th>Academic outputs</th>
<th>Industrial outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Three journal papers published:</td>
<td>✓ Three industrial ovens have been improved at two factories:</td>
</tr>
<tr>
<td>• Methodology for energy saving</td>
<td>• Gas costs reduced by £121,000 per year</td>
</tr>
<tr>
<td>• Iterative approach to oven improvement</td>
<td>• Saving 4,536,000 kWh per year or 836 tCO₂e per year</td>
</tr>
<tr>
<td>• Sustainability indicators for ovens</td>
<td>• Improved oven performance for better product quality</td>
</tr>
<tr>
<td>✓ One journal papers under review:</td>
<td>✓ Developed innovative approach to understand polymer curing.</td>
</tr>
<tr>
<td>• Industrial feasibility of biomass process heating</td>
<td>✓ Helped formulate a dedicated energy role in 3M UK.</td>
</tr>
<tr>
<td>✓ Two international conferences:</td>
<td></td>
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<tr>
<td>• PRES 2014</td>
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<td>• SDM 2016</td>
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### 7.2 Main findings

The thesis has achieved its aim to establish practices to reduce the environmental and economic impact of industrial ovens by satisfying the three original research objectives, which are shown below:

- Identify oven improvement opportunities in 3M factories.
- Develop methods that will reduce energy, improve product quality and increase safety of industrial oven systems.
- Implement oven improvement projects in at multiple factories.
- Investigate the opportunity to use renewable fuel sources for process heating.

This section summarises the study’s main findings that have helped to meet these research objectives. Table 7.2 shows an overview of the main thesis findings, with the following sub-sections going into further detail.

### Table 7.2: Overview of main findings

<table>
<thead>
<tr>
<th>Section</th>
<th>Finding</th>
</tr>
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<tbody>
<tr>
<td>7.2.1</td>
<td>Minimising oven system airflow can result in 30% energy saving.</td>
</tr>
<tr>
<td>7.2.2</td>
<td>DMTA cure understanding should be linked to actual product quality on the manufacturing line.</td>
</tr>
<tr>
<td>7.2.3</td>
<td>Installing insulation to lower the effect of structural thermal mass has a positive impact on process downtime and temperature variation.</td>
</tr>
<tr>
<td>7.2.4</td>
<td>Existing multi-criteria decision analysis approaches were not suitable for technology assessment in a factory environment.</td>
</tr>
<tr>
<td>7.2.5</td>
<td>Government RHIs do not encourage manufacturers to install renewable heating technology in existing processes.</td>
</tr>
</tbody>
</table>
7.2.1 Minimising oven system airflow can result in 30% energy saving

Over-processing is common within ovens in the manufacturing industry and is often a result of excessive system airflow. Excessive airflow reduces risks to operator health and safety by maintaining sufficient oven pressure negativity, which ensures harmful fumes do not leak from the oven and can dilute harmful fumes to a safe level. Excessive airflow also reduces risk to product quality by guaranteeing a sufficiently high drying force is maintained. However, unjustified excessive system airflow and over-processing can be minimised by establishing a controllable and repeatable process, and then by investigating options to optimise process parameters. It is possible to reduce system airflow through an oven by up to 30%. This was demonstrated at two factories, delivering a combined annual cost saving of £121,000. The typical greenhouse gas emissions from a direct gas-fired industrial range is from 0.2-0.4 tCO₂e per tonne of product throughput, depending on operating conditions and system efficiency. Considering a 30% reduction in airflow is possible, a 30% reduction in oven energy consumption is also possible. Therefore, the potential positive environmental impact of systematic oven improvements is considerable.

An innovative methodology based on Six Sigma principles has been developed to reduce energy consumption within ovens. The methodology demonstrates a practical approach to reducing system airflow within pre-existing industrial ovens. Industrial ovens had previously been overlooked when attempting to reduce energy consumption at 3M factories. This was due to greater focus given to projects that require less resource for analysis and implementation, and also because of the lack of knowledge in 3M factories on the best methods to improve heating processes.

7.2.2 DMTA cure understanding should be linked to actual product quality on the manufacturing line.

Dynamic Mechanical Thermal Analysis (DMTA) is commonly used to develop polymer cure understanding. This laboratory-based technique analyses physical property changes to an adhesive when subjected to a thermal regime. However, DMTA findings do not easily relate to an actual manufacturing line. For instance, it was not known whether the tan D peak (a key output from DMTA analysis) must be achieved in order for a product to perform as desired.

This thesis presents a novel methodology linking adhesive physical property and product quality that works for phenolic-based resin systems. The method uses DMTA to generate understanding on the physical property of cure and a free-phenol test to relate physical properties to the actual manufacturing process. A CIE-Lch colour test is used to quantify the free-phenol test results. An industrial case study was used to demonstrate the link between DMTA tan D peak data and product performance. It was found that temperature variation, which is common in many curing ovens, could result in a significantly different final level of cure conversion, and therefore impact on product quality.

7.2.3 Installing insulation to lower the effect of structural thermal mass has a positive impact on process downtime and temperature variation.

Existing festoon ovens are typically constructed with thermal blockwork. Thermal blockwork has a significant impact on oven air temperature due to the energy retained within the structure acting as a temperature damper. The impact of structural thermal mass results in long start-up and cool-down periods, causing significant process downtime. It also increases the time taken for an oven to change temperature, which is problematic when products with different temperature profiles are run.
sequentially. Insulating the inside surfaces of an oven can benefit oven operation and productivity, and can also help to deliver a consistent thermal regime to the product. For a large festoon oven, installing insulation to the inside surfaces of the walls and floor has the potential to reduce process downtime by 88%.

7.2.4 Existing multi-criteria analysis methods are not suitable for technology assessment in a factory environment.

Although there are many existing methods of multi-criteria analysis for different industrial scenarios, this study found that none were suitable for technology investment assessment in a manufacturing factory environment. Existing methods did not incorporate risk sufficiently throughout the analysis, or highlight uncertainty in the final outcome. This is problematic as it provides decision-makers with an outcome that has a perceived high degree of certainty, when in reality, the option could be very risky and have potential negative consequences with a factory environment. Decision makers must be able to align decisions to their business strategy and existing methods did not allow for this to happen.

This study developed a method of multi-criteria analysis that incorporates risk into the final outcome; rather than a single desirability level being provided, this new methodology provides a desirability range. This is more suitable for the manufacturing factory environment as it ensures that technology investment can be aligned with business risk strategy.

7.2.5 Government RHIs do not encourage manufacturers to install renewable heating technology in existing processes.

Renewable heat incentives (RHIs) are used by the UK government to encourage the up-take of renewable heating in both commercial and domestic environments. This thesis has found that RHIs do not successfully encourage manufacturers to install biomass process heating in retrofit scenarios. The research has found that although biomass offered the most sustainable option, companies are not willing to accept the large capital expenditure required for retrofitting existing processes. In new-build scenarios, the RHIs are a much more suitable incentive tool because the capital cost of biomass is analysed directly against the conventional technology capital cost.

Alternative incentive schemes have the potential to increase viability of renewable heating technology in the manufacturing industry. Schemes that mitigates high capital expenditure away from manufacturers by offering a government loan, also offer a reduced RHI to lower operational costs can increase industrial viability. Furthermore, carbon taxation according to the EU ETS scheme can be an effective tool to incentivise renewable heating for the manufacturing industry.

7.3 Generalised implications

This section presents generalised implications from this EngD research. These implications are derived from the main findings and experiences gained during four years of industrial-based research. They are not specific to the manufacturing scenarios where the research was conducted, but instead offer more generic research implications that can be used to reduce energy consumption and improve process performance in any industrial oven system. Table 7.3 shows an overview of the generalised implications, with the following sub-sections providing further detail.
Table 7.3: Generalised implications overview

<table>
<thead>
<tr>
<th>Section</th>
<th>Generalised implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3.1</td>
<td>Significant energy saving is possible within many industrial ovens.</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Improvements in heating processes should consider both energy saving and product quality enhancement.</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Conventional approaches to appraise capital investments are insufficient for the manufacturing industry to face future sustainability challenges.</td>
</tr>
<tr>
<td>7.3.4</td>
<td>Biomass process heating is not the best way for the manufacturing industry to sustainably improve existing oven systems.</td>
</tr>
</tbody>
</table>

7.3.1 Significant energy saving is possible within many industrial ovens

Over-processing is prevalent in many pre-existing ovens due to risk aversion and because process parameters were established at a time when energy consumption was not considered a priority. There are two options to reduce energy consumption in ovens: a) Squeeze the process through optimising parameters, or b) Innovate the process by making significant changes to the way that heat is supplied to an oven.

Processes can be squeezed by optimising parameters to deliver important energy savings; process parameter optimisation can deliver energy saving in the region of 30% depending on the industrial scenario. Although a considerable amount of resource is needed to identify, scope, analyse and implement optimisation projects, the actual modifications are relatively simple and are well within the abilities of manufacturing process engineers.

Innovating a process can deliver further energy saving. Innovation can involve upgrading existing equipment and hardware, but can also encompass fundamentally changing heating technology. There is considerable opportunity to intelligently improve process control in both squeezing and innovative improvements. Higher intelligence to process control has the ability to save energy, as well as enhance process capability.

When new heating processes are commissioned, it is important to ensure that the correct control equipment is installed, such as appropriate sensors, variable speed drives on fans (VSDs) and dampers. This reduces life-cycle costs associated with upgrades and enables continual process optimisation to create a thermal regime that the manufacturer desires.

By examining industrial case studies, this EngD project has found that innovation of existing processes is more difficult than squeezing. Factories find it difficult to raise the capital required to change existing equipment once it is installed, which was demonstrated in Chapter 6 and the finding that biomass technology is not economically feasible in retrofit scenarios. Therefore, squeezing should precede innovation as it offers a more feasible improvement approach and can still deliver sizable energy saving. Furthermore, squeezing can change the process requirements for process innovation. For instance, process flows should be optimised before installing heat exchangers for energy recovery, which could otherwise be wrongly designed. However, squeezing is limited in potential energy saving and at some point, manufacturers must look to innovation to continue to reduce their energy consumption in ovens.
7.3.2 Improvements in heating processes should consider both energy saving and product quality enhancement

Traditionally, heating process improvements consider either energy reduction or process enhancement. However, a strategic way to reduce energy in ovens is to simultaneously enhance the process capability, as this aligns more closely with the key business interests. Factory management will generally prioritise creating high quality products over energy reducing activities. Therefore, ignoring product quality can significantly hinder energy reduction in the manufacturing industry, because it will struggle to get significant support by key decision-makers.

Product and process understanding should be developed to achieve energy saving and product quality improvements simultaneously. It can not only maximise benefits, but also increase the viability of energy projects in real manufacturing environments. Greater knowledge of a process and its products enables for projects to be implemented with reduced risk. Understanding can most likely be improved in the areas of product variation, product development, quality control, process safety and heat interaction with the product.

7.3.3 Conventional approaches to appraise capital investments are insufficient for the manufacturing industry to face future sustainability challenges

The use of sustainability indicators for technology assessment is not common in current published literature, and it is scarcely used in the manufacturing industry. Sustainability indicators offer the manufacturing industry an alternative method to appraise investment opportunities. The majority of existing sustainability indicator applications are for large-scale problems, such as evaluating the use of wind power for contributing to the UK’s electrical power generation. However, this thesis demonstrates the use of sustainability indicators at a more localised scale, and how their use can add value to project evaluation within a factory environment.

Incorporating sustainability indicators alongside conventional economic appraisal, such discounted cash flow (DCF) analysis, is a practical approach that can ensure sustainability is represented during investment appraisals. It is unlikely that manufacturing will use sustainability and methods of multi-criteria analysis when appraising capital investment projects in the near future. However, there is an opportunity to increase industrial awareness of sustainability by using alternative investment assessment.

7.3.4 Biomass process heating will not make a significant impact on sustainably improving existing oven systems

It is unlikely that biomass process heating will replace conventional heating techniques in pre-existing manufacturing processes. Although biomass fuel is more sustainable, the feasibility is low in retrofit industrial processes the capital expenditure to retrofit industrial processes is too great due to the costs of biomass burners, thermal transfer circuit, civic ancillaries etc. However, the case can be different for new build factories. If biomass is incorporated from the start then it can offer considerable advantages over conventional fuel systems.

Biomass as a renewable heating fuel for industrial applications is in its infancy in the UK. Government schemes, such as the RHI, attempt to encourage the uptake of renewables so that there is a self-reliant renewable energy industry. However, from the industrial experiences gained it seems unlikely that businesses in the UK will invest in biomass technology. The UK manufacturing
industry sector has not experienced significant growth for some time, and as a result, only a few new process lines are being built. Cheap labour forces businesses to move investment elsewhere, and if biomass is to be implemented in new build factories it is more likely to occur in factories outside of the UK. Engineers would generally prefer to install conventional process heating, such as gas burners, as the technology is well understood and deemed to be more reliable. Large multinational companies have the ability to disseminate knowledge of the potential benefits of biomass technology and apply it throughout its manufacturing operations. In this way, biomass process heating could have a more positive future.

7.4 Broad applicability

Heating process improvements should be incorporated into the operational (factory) sustainability section of a manufacturing company’s sustainability strategy, which should also include product development and supply chain sustainability. Operational sustainability is important for all manufacturers, not only because it minimises environmental impacts and decreases waste at a factory level, but it can also present a valuable addition to the company’s sustainability story. Significant advances in operational sustainability are difficult because of the inertia that must be overcome in order to change the way factories operate. Factories do not purposefully resist change, but they do not generally have resource spare, in terms of finance or time, that can be focussed on developing operational sustainability.

This study highlighted significant improvement opportunities in the ovens within both of the factories investigated. Of the eight factories in the UK, the two factories investigated were chosen due to the presence of significant heating processes. 3M have approximately 180 manufacturing operations worldwide, and a reasonable assumption would be that a quarter of 3M factories have energy intensive heating processes that could be improved. If industrial ovens within 45 3M factories were improved, then this would have an important impact on the sustainability performance of the corporation. In order to realise this research’s potential impact, communication throughout the business is necessary. Knowledge has been disseminated throughout 3M via technology forum presentations, while journal papers and conference presentations have communicated research to the wider manufacturing industry.

At a macro-level, manufacturers must consider how to best use resources to maximise the sustainability benefit. The emphasis on oven improvement is dependent on a variety of factors including: the number of existing heating processes, how the existing systems perform compared to best available technology and sustainability performance of the rest of the business. Nevertheless, at a micro-level within a factory environment oven improvements should always be considered. Engineers working with industrial ovens will undoubtedly find improvement opportunities in existing industrial ovens, regardless of technology or the age of the process.

Large manufacturers risk damaging their brand if they do not have a competitive sustainability strategy, which has a negative impact on profits and share value. Currently, many companies are reasonably successful in selling their sustainability story and publicising their strategy, but are less effective in delivering real and significant change within their factory operations. In years to come, this will not be enough. Companies will have to demonstrate that they are proactive in improving their operational sustainability and potentially will have to meet targets set by national or
international regulators. It is at this point that greater resource will be provided to improve operational sustainability.

The work conducted within this EngD demonstrates an effective approach that manufacturers can take to develop operational sustainability. By presenting practical research that is broadly applicable to many manufacturing scenarios, this thesis demonstrates that process heating improvement should be incorporated into sustainability strategies. This will help the industry develop and move society towards a sustainable future.

7.5 Critical knowledge contribution in practical methodologies

The first research body contributed to knowledge by demonstrating that oven optimisation is possible within industry, and that it can deliver a financial and environmental benefit. This work resulted in an academic journal publication. The approach to energy optimisation has been presented in a direct and straightforward way. The research applied fundamental engineering principles to an industrial setting and the methodology is practical and systematic. However, a critical perspective may be that the majority of understanding in this thesis is developed from simulation efforts, rather than from the developing theoretical models. Having said this, simulation can be seen as advantageous because of the practical nature of the EngD. As discussed in literature review, such methodologies such as CFD, are plentiful, and there has been a clear gap in a methodology for oven retrofit optimisation that can be applied in industrial settings. Hence, the objective of implementation of a practical methodology for existing oven energy performance optimisation has been met.

The second body of research proposed an approach to oven improvement to improve both energy consumption and product quality. It needed a bespoke solution to an oven application to demonstrate the application potential. A combination of cure understanding, modelling of oven temperature and airflow optimisation has been developed that is relevant to industrial curing festoon oven scenarios.

In the third body of research, appropriate sustainability indicators were chosen by consulting academic and industrial experts. A larger number of indicators and deterministic approaches constitute the other side of the argument. However, the approach used in this third research body is appropriate for the industrial application because it is important for the indicators to reflect the opinions of decision makers in industry and the list of indicators should not be exhaustive, but should be adequate for feeding back experts’ judgment into the decision making framework.

In the third body of research Part B, the developed methodology led to a serious discussion and debate on installing biomass technology into a newly-built oven process. Unlike the retrofit case study, the assessment for a newly-built biomass process did not present a business case to industry. The analysis concluded that biomass would be more viable for new build manufacturing facilities than retrofit scenarios because the capital expenditure of retrofitting a process is the main factor preventing project viability for industry. The economic tradeoffs are not clear to industry under the set of policy directives. Therefore, for new build factories, the difference in capital expenditure of biomass technology and natural gas technology is significantly reduced by the proposition of an alternative funding mechanism.
The environmental and economic impacts of an oven process are obvious because of fossil fuel consumption that is necessary to generate heat; however, the social dimension of oven operation is less clear. Social impacts have been represented in the sustainability indicator set developed in Chapter 5. Worker safety and job creations have been considered and deemed important in sustainability agenda. This would enable a more rounded sustainability perspective for industries.

7.6 Future recommendations

The research findings are used to recommend further research avenues. Industrial oven systems represent an underdeveloped research field and this thesis has made important contributions to build this research field for practical implementations. It is expected that as manufacturers begin to improve operational sustainability in factories, energy consumption and process performance of industrial ovens will be subjected to greater scrutiny. Industrial ovens offer the greatest improvement opportunity for manufacturing industry. To generate momentum for oven improvements and to reduce the perceived risk of sustainable modifications, there is a need for more industrial EngD research within factory environments.

Industrial case studies demonstrate that sustainability improvements in ovens are possible and can be successfully implemented. There is a need for case study examples in other areas of manufacturing that are not addressed in this thesis. This thesis looks primarily to improve gas fired ovens operating below 250°C in the light manufacturing industry. It is expected that as manufacturers begin to improve operational sustainability in factories, energy consumption and process performance of industrial ovens will be subjected to greater scrutiny. Industrial ovens offer the greatest improvement opportunity for manufacturing industry. To generate momentum for oven improvements and to reduce the perceived risk of sustainable modifications, there is a need for more industrial EngD research within factory environments.

Studies in this thesis are focused primarily on curing processes. The purpose of curing ovens is to ensure sufficient cure is maintained, based on the temperature and residence time within the oven. Drying ovens have different process requirements with the added complexity that a drying force at the product interface must be maintained, determined by time, temperature, turbulence and moisture content. This would make reducing system airflow for energy saving more challenging as the moisture content in the airstream would increase, and thus reduce drying capability. It would be interesting for future studies to apply the process parameter optimisation to a drying oven.

This research has found that the role of the temperature distribution on the curing of the product is of crucial importance to manufacturers. Techniques such as CFD can be used (and have been demonstrated extensively) to create detailed temperature maps within ovens. Incorporating such techniques into a systematic oven improvement strategy would be a natural extension to the work carried out in this thesis.

This thesis has focused primarily on the environmental and economic impacts of oven operation. Process automation could fall within the scope of such a study. It could evaluate the social impacts of personnel being made redundant by machinery verses the higher skill level needed to operate such equipment. Using industrial based case studies could highlight an area of manufacturing development that is not properly understood by many manufacturers.
Chapter 7: Conclusion

7.7 Overall conclusion

This doctorate research project has been conducted in collaboration with 3M and the University of Surrey. The field of study has investigated how industrial ovens can be enhanced to improve their environmental and economic performance. This thesis questioned how could manufacturers improve the environmental and economic performance of industrial ovens. The EngD project has been successful in achieving its original aim by developing three bodies of research that all look to either implement or appraise projects for energy reduction and enhanced process capability.

The three bodies of research developed from the different industrial challenges that were presented. The first body of research focussed on energy optimisation and developed a methodology for oven optimisation through reducing system airflow. The second body of work developed a holistic approach to oven improvement that highlighted the importance of product as well as process understanding. The third body of work developed a set of sustainability indicators for industrial ovens and a method of multi-criteria decision-making analysis aimed at improving the assessment of technology in industry, by focussing on all three sustainability dimensions. An in-depth feasibility study of biomass process heating developed from the third research body,

The EngD project has delivered three improvement projects at two 3M factories that have the potential to deliver a combined energy cost saving of £121,000 per year and enhance process performance. This reduces gas energy consumption by 4,536,000 kWh and cuts carbon emissions by 836 tCO₂e per year. Three academic journal papers have been published during the EngD project, and one more is in the reviewing process. Along with two international conference presentations, efforts have been made to communicate research in order to maximise research impact.

Improving industrial ovens should be a part of a company’s sustainability strategy, and will be increasingly important in the future as manufacturers are pressured to develop the sustainability of their operations. Therefore, this research can play a role in helping the manufacturing industry become more sustainable.
Appendix A: Journal Paper in Applied Thermal Engineering

Systematic approach to industrial oven optimisation for energy saving

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HIGHLIGHTS

- A systematic approach to oven optimisation for energy saving is presented.
- Flexible approach for unique oven scenarios while still providing a clear pathway.
- Understanding of process & product with engineering & physical constraints is key.
- Optimisation of a cure oven demonstrates an energy saving of 1,658,000 kWh.
- Determining optimum oven pressure is fundamental for reducing system air flow.

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ABSTRACT

Industrial ovens consume a sizable proportion of energy within the manufacturing sector. Although there has been considerable research into energy reduction of industrial processes throughout literature, there is not yet a generalised tool to reduce energy within industrial ovens. The systematic approach presented aims to guide an engineer through five stages of oven optimisation. These involve defining the scope of the optimisation project, measuring and analysing process variables in order to develop fundamental understanding of the system so that an optimisation plan can be established and then implemented. The paper gives an application example of the methodology to a curing oven within a masking tape manufacturing facility. This approach showed an estimated annual saving of 1,658,000 kWh (28% reduction of the oven’s energy consumption and a 4.7% reduction of the whole plant’s energy consumption) with very little capital expenditure. As the methodology can be tailored to accommodate individual optimisation options for each oven scenario, while still providing a clear pathway it has potential applications within the wider manufacturing industry.

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1. Introduction

Process heating applications are one of the key energy consuming activities in the manufacturing industry. In the US, it is estimated that 17% of all industrial energy is used for process heating [1]. The components of heating application include devices that generate or supply heat, devices that transfer heat from sources to products, heat containing devices and heat recovery devices. This paper will focus on heat containing devices, and in particular industrial ovens. If it is assumed that the product must remain unchanged, then energy reduction can be achieved by either process optimisation or through implementing energy efficient heating technology. Changing technology can be advantageous [2] but often requires significant capital investment. Whereas process optimisation can deliver energy saving without the need for excessive capital expenditure, and can be performed on almost any heating application.

There has been a lot of interest in energy reduction of industrial processes, and there are a handful of methodologies that reflect this [3–5]. Process integration is the umbrella term used to describe a family of methodologies to reduce resource consumption and includes pinch analysis of heat, mass, water, hydrogen and oxygen [6]. Process synthesis is widely accepted as the strategy for process development and design. Process design and redesign to minimise energy consumption should be approached in a logical sequence of
redesigning the product, followed by optimising the process, exploring heat recovery options and by finally considering alternative site heat and power systems [7]. The research presented in this paper falls within the category of process optimisation.

Thermal optimisation of manufacturing processes has not received a great deal of attention throughout literature; hence the discipline has significant room for development. At a unit process level, optimisation of process parameter settings and controls can typically achieve energy reduction by a factor of 1.1 [2]. Techniques such as computational fluid dynamics (CFD) have been used alongside experimental analysis to determine optimum operating conditions as well as uniform temperature profiling, which can deliver up to 10--15% energy saving [8--10]. Although approaches such as this can be beneficial, they might not be feasible for retrofit design in many facilities due to lack of available resource. What is clear however, is that complete analysis of a process is vital for appropriate selection of process parameters to be considered in optimisation [11].

As discussed in Ref. [12], there is generally a lack of overarching optimisation methods that could be replicated across a wide range of heating applications, with studies tending to lack industrial oven operability analysis and clear optimisation techniques that can be applied in practice. Procedures have more recently been established for various individual oven scenarios; whether it is an optimisation algorithm for a paint cure oven [13], a multi-objective approach for CFD design [10], or an energy modelling approach that maximises production [14]. Although these optimisation tools can be replicated in related scenarios their field is narrow which limits their application potential. A conceptual optimisation framework has been constructed for more universal optimisation that utilises experimentation, models and an understanding of the required energy to obtain an optimal design [15]. Existing literature tends not to address the link between product and process understanding with the physical engineering principles of an industrial oven. This should be fundamental for optimisation of commercial ovens in order to reduce risk to safety and product performance, and the research presented will aim to address this.

This paper provides a methodology for engineers to thermally optimise industrial ovens for energy saving. The systematic approach develops a detailed understanding of a particular system, before formulating an optimisation plan that alters key process variables to maximise energy saving within process limitations and constraints. This research looks to address oven optimisation from a more general level than previously published work, which could offer useful guidance to a wide range of oven scenarios.

The structure of this paper involves presenting an overview of the methodology, followed by a more detailed description of how to work through each stage. An application example on a cure oven is presented to demonstrate the intended use; experimentally verified optimisation hopes to provide evidence for the methodology's industrial and commercial application. Finally, the paper concludes with remarks on how this work can be replicated further afield.

2. Methodology

2.1. Overview

The methodology displayed in Fig. 1 comprises five stages: Define, Measure, Analyse, Improve and Control. The methodology adapts 6 Sigma’s general DMAIC method for problem solving specifically for oven optimisation. As this is a well known approach within industry [16], it is in a language that many engineers will be familiar with and can thus be applied with greater ease. The sequence starts at the top left of the figure and moves through the stages to the bottom right. Although the methodology follows a
2.2. Description of stages

2.2.1. Define

Background knowledge of the oven system forms the foundation for oven optimisation. The purpose of the oven must be understood, as well as knowledge of the physical arrangement. Process or product constraints must be identified early on. System boundaries have to be drawn so the project scope can be defined. A problem statement gives clarity to the ultimate purpose of the optimisation project, and will most likely involve comments referring to safe reduction in energy consumption while retaining product quality.

2.2.2. Measure

It is necessary to identify all process streams within the system boundaries. Once all process streams and components are identified, a mass balance can be developed. Streams into the system may include wet product, air or other drying agents, and the streams leaving the system may include exhaust gases, water vapour and dry product. The mass balance can be calculated theoretically or empirically.

The energy streams must be identified. The energy into the system will be from the heating supply system, and the energy leaving the system will be in the exhaust gases, radiation from the body of the oven, and in the product. The theoretical energy required for the process is calculated. Actual consumption is determined through measurement or metering. Discrepancies between ideal and actual energy use will give an indication of saving potential.

The final task in this section is to identify all the process variables. ‘X’ input factors are variables which can be directly controlled (e.g. damper position). Intermediate ‘Y’ variables are directly affected by altering ‘X’ (e.g. humidity within the oven). Finally, ‘T’ variables are the outputs of the process (e.g. product performance). Evaluation of all variables can be conducted to identify which variables require further investigation.

2.2.3. Analyse

This stage improves process and product understanding. The ‘Y’ outputs considered should fall within energy and quality related categories, and the engineer must have a good understanding of both dimensions. Initially, the quality baseline for the product must be established, and any critical safety constraints must also be considered.

The stage then looks to understand the impact each ‘X’ has on the output ‘Y’s. In many instances, this knowledge can only be ascertained through experimentation. Conventional experiment can be conducted, or design of experiments (DOEs) can be constructed in order to test multiple inputs at once. ‘X’s are analysed for sensitivity on energy saving with the aim to identify input variables that influence ‘Y’s, which ultimately influence critical ‘Y’s. Input variables are labelled as X1, X2, X3, or X4 depending on whether they either influence energy (E) or quality (Q) related outputs, or both (EQ).

Sensitivity and controllability of the equipment must also be assessed to able to determine which variables can be altered to successfully obtain energy saving. The outcome from this stage is to identify which, and to what extent, variables can be altered while still ensuring the oven performs its primary purpose.

2.2.4. Improve

This stage develops options which can deliver energy savings. Identifying an array of ways in which process parameters can be changed is useful to determine the most appropriate modification plan. A process hazard analysis evaluates the safety implication of making modifications. A business case must be made to show financial benefits of the project by calculating capital expenditure and payback periods. Only then can a final modification plan be developed. The final task in this stage is to complete a trial period to prove the product quality is not diminished.

2.2.5. Control

The final stage looks to permanently implement the plan from Stage 4. Implementation includes a validation period, where the optimised process is monitored to verify there are no product quality and safety concerns. Once the optimisation is proven then it can be implemented in full. The final task is to confirm the projects energy saving and to replicate across additional ovens as necessary.

3. An application example: cure oven optimisation

3.1. Define

The methodology has been applied to an oven used to cure adhesive on a masking tape web. Fig 2 shows process flows and the system boundaries. Thermal oil, heated with natural gas, provides energy to the oven. A small amount of solvent residue left over from previous unit operations is also driven off within the oven. The system is controlled by lower explosive limit (LEL) analysers, which shut the system down if 35% LEL is reached. The problem is stated as to determine a way to optimise the cure oven for energy saving improvements while ensuring the oven’s primary purpose does not diminish.
Appendix A

Table 1
Parameter value for energy analysis.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter value for theoretical energy required</th>
<th>Parameter value for actual energy consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m )</td>
<td>0.087 kg/s</td>
<td>0.073 kg/s</td>
</tr>
<tr>
<td>( c_p )</td>
<td>3,000 J/kg K</td>
<td>3,000 J/kg K</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>(100 °C - 20 °C)</td>
<td>(100 °C - 20 °C)</td>
</tr>
</tbody>
</table>

3.2. Measure

3.2.1. Mass balance

The process stream into and out of the oven system, as well as the mass flow rate of each stream, are displayed in Fig. 2. The flow rates shown were determined empirically and theoretically. The mass into the system equals the mass out of the system.

3.2.2. Energy analysis

The theoretical minimum energy is determined by the minimum safe air flow through the system. The shutdown LEL of 35% determines minimum dilution air flow required. For the average solvent flow, the air into the system must be above 3553 kg/h to ensure % LEL remains at a safe level. Eq. (1) and the parameters in Table 1 are used to calculate the heat energy required for a given temperature change. The theoretical minimum energy to heat this air flow has been calculated at 169 kW.

3.2.3. Process variables

The input variables can be changed in order to impact upon the intermediate variables and ultimately on process outputs (Y). Table 2 presents the input variables, the intermediate variables, and the output variables. A cause and effect analysis was conducted for X variables to indicate which variables must be investigated further.

Table 2
Process variables.

<table>
<thead>
<tr>
<th>X variables</th>
<th>I variables</th>
<th>Y variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply air</td>
<td>Web slot flow</td>
<td>Gas consumption in burner</td>
</tr>
<tr>
<td>Exhaust fan</td>
<td>Oven insulation</td>
<td>Adhesive core</td>
</tr>
<tr>
<td>Air dumper</td>
<td>Fresh air inlet flow</td>
<td>Moisture content of marking tape</td>
</tr>
<tr>
<td>Recirculation</td>
<td>Recirculation flow</td>
<td>Tyre doors of adhesive</td>
</tr>
<tr>
<td>Damper</td>
<td>Oven exhaust flow</td>
<td>Solvent over in adhesive</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>Thermal oxidizer flow</td>
<td>Masking tape adhesion</td>
</tr>
<tr>
<td>Conditions</td>
<td>Oven pressure</td>
<td></td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Oven location</td>
<td>Oven temperature</td>
<td></td>
</tr>
<tr>
<td>Thermal oil</td>
<td>within oven</td>
<td></td>
</tr>
<tr>
<td>temperature</td>
<td>Residence time</td>
<td></td>
</tr>
<tr>
<td>LEL analyser reading</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The matrix highlighted that fan speeds and damper positions had the greatest impact on both energy and quality outputs.

3.3. Analyze

Product quality is determined by cure conditions, i.e., temperature and residence time. Any risk to product quality must be avoided, changes to the line speed and the oven temperature were not considered. LEL and the oven negativities were the key process constraints that had to be considered throughout this stage. Fig. 3 displays the important X variables considered, with damper values labelled with ‘T’ and fans with ‘F’. The main fresh air supply to the oven is via D2, F4 draws the system exhaust to a thermal oxidizer, and F3 provides flow to an air floatation roller. As variable speed drives were not installed on the fans, the damper was used to replicate this effect and three experiments were conducted in order to determine the impact of X variables.

3.3.1. Experiment 1

A Design of Experiment (DOE) was constructed and run without product, but with heat and air flow systems on. Table 3 shows which variables were considered. Experiment 1 concluded that flow into the oven through the web entrance and exit slots was greater than expected, and that changes to D3 did not significantly impact recirculation flow. The recirculation flow to the air floatation roller was restricted due to a permanent blockage. And D2 was effective at controlling the fresh supply air, and had the greatest effect on oven pressure; as can be seen in the main effects plot of Fig. 4.

3.3.2. Experiment 2

Table 4 shows variables considered for experiment 2. This experiment concluded that D3 was not effective at re-circulating flow; even when set to D0, 2000 kJ/h of flow was still reached at F4. Therefore future process modification should not rely on damper D3 for process control. The optimum oven pressure was found to be ~0.3 mbar, as determined to ensure flow does not exit the web slots.

3.3.3. Experiment 3

Experiment 3 was conducted with product to understand how the LEL responds to reducing air flow through the system. Table 3 shows the variables that were considered. The experiment concluded that D2 did reduce flow into the system, but not significantly until closed to 20%. D6 controlled the exhaust flow effectively. Therefore altering D2 and D6 can balance system so that optimum pressure and minimum flow through the system (9547 kJ/h) is obtained. To achieve this; D2 is closed fully at 0%, and D6 is closed to 46%. This 28% reduction in flow results an average % LEL increase of 4.8%.

Table 4 shows an overview of the X and Y variables considered in the three experiments and whether they affect quality or energy related outputs. Through analysis, the intermediate variables were altered for process optimisation including reduce the supply air inlet flow and the oven exhaust flow. The X input factors which would impact on these I variables include D2, D6, F1 and F2.

3.4. Improve

The analysis stage (Section 3.3) identified the most appropriate X variables that can be changed to reduce air flow. Two options were put forward. Option A involved blanking off D2 permanently, setting D6 to 46° and turning off F1 permanently. Option B upgraded D2 to be closed when in production but open
during emergency shutdown and for maintenance. A variable speed drive would be installed to F2 which would operate at a reduced fan speed during production but fully during emergency shutdown. F1 would be off during production, but switched on for emergency shutdown to flush system with fresh air. D6 would be unchanged. A Process Hazard Assessment concluded that option B was favourable due to the added safety dimension from the ability to flush air though the system during an emergency shutdown.

<table>
<thead>
<tr>
<th>Variables considered in experiment 1, 2 &amp; 3.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X's considered</td>
</tr>
<tr>
<td>D1, D2, D3 and D6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intermediate</th>
<th>measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal oxidizer flow, recirculation flow, oven pressure, supply air flow, web slot flows</td>
<td></td>
</tr>
</tbody>
</table>

Experiment 3 determined that the air flow through the system could be reduced by 28%. Fig. 5 shows the percentage of total volume for each product as well as the % Eli that would be reached if the oven were optimised. Additionally, the cumulative energy saving is displayed and it can be seen that the optimisation would result in a 1.6038,000 kWh per year saving in natural gas, which would be a 20% reduction in oven energy consumption when taking into account of system efficiency. This would also reduce the entire plant's energy consumption by 4.7%. Trials were conducted to verify that the optimisation did not diminish product quality; with results from laboratory testing proving quality is not diminished.

3.5. Control

Implementation is required with a two month validation period to verify the modification. Following this, documents such as start-up/shutdown procedures or PIDs must be updated. Evaluation of actual vs. calculated savings is to be conducted before the project is closed. It is planned that the methodology will be replicated to optimise two further ovens within this manufacturing facility.

Fig. 3. Oven schematic showing key damper and fan X variables.

Fig. 4. Main effects plot for oven pressure (mbar) vs damper position (%).

Thesis

Frederick Pask
Appendix A

Table 1

<table>
<thead>
<tr>
<th>Grouping of variables considered in experiments 1, 2, 3.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output: Y variables</td>
</tr>
<tr>
<td>Intermediate: I variables</td>
</tr>
<tr>
<td>Input: X variables</td>
</tr>
</tbody>
</table>

Fig. 5. Cumulative energy saving by product taken into account of product volumes, also shown is the 5 UEL that would be reached post modification.

4. Recommendations

Recommended steps for reducing the total air flow through the system:

- Determine the limiting variable for reducing the total inlet flow (T, LEL, relative humidity, etc.).
- Define a baseline of the limiting variable for all products. Identify the most sensitive product.
- Calculate acceptable inlet air flow rate and validate with on-line experiments measuring the limiting variable levels.
- Determine optimum oven pressure. Experimental design to understanding slot flows and balancing inlet and exhaust flows. Conduct with and without product running.

Although the case study presented looks to reduce overall air flow there are alternative methods that this research's systematic approach could be applied to:

- Increase heat transfer coefficient of the oven, so faster drying rates can be attained (higher product output).
- Optimise the temperature and residence time based on drying or cure simulation.
- Balance internal air flows to ensure there are no dead spots within the oven.
- Ensure uniform oven temperature profile.
- Maintain heat exchangers to ensure heat transfer remains effective.
- Insulate to minimise energy losses to the surrounding environment.

5. Conclusion

Energy reduction within the manufacturing sector has a role to play in reducing global energy consumption. The research presented addresses the energy consumption of industrial ovens, which use a considerable proportion of energy associated within manufacturing. The systematic methodology guides an engineer from the basic understanding of an oven to optimisation for energy saving. The stages include design, measure, analyse, improve, and control. Combining process & product understanding with consideration of physical and engineering constraints is a powerful tool which can deliver significant energy savings.

This methodology has been applied to a curing oven for masking tape production at a 3M facility in the UK. The optimisation plan consisted of reducing air flow through the system by altering process parameters, resulting in a predicted annual gas saving of 1,508,800 kWh. The methodology is now being applied to additional ovens across 3M facilities in the UK. This systematic approach can be tailored to accommodate individual optimisation options, while still providing a clear pathway. As such, there is potential for such a methodology to reduce energy consumption within other 3M facilities and the wider manufacturing industry.

Acknowledgements

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References

Practical Approach for Engineers to Optimise Industrial Ovens for Energy Saving

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Energy saving within the manufacturing sector has a role to play in reducing global energy consumption and greenhouse gas emissions. Despite heating applications being common throughout industry, there is currently no framework that provides practical guidance for energy optimisation in ovens. This paper presents a systematic approach to guide an engineer through five stages of optimisation. It begins with defining the problem and system boundaries, before developing a thorough understanding of the oven system through mass balance and energy analysis as well as identifying all process variables. Analysis of key process variables is conducted to develop process & product understanding and to identify key variables. Improvement of the system and then controlling for full implementation leads to successful conclusion of the project. Application of this methodology has been conducted on curing oven for masking tape manufacture. The optimisation results in a potential 4.7% annual reduction of the plants energy consumption and offsetting 305 tCO2 from minimal capital expenditure. As the methodology can be tailored to accommodate individual optimisation options for each oven scenario, while still providing a clear pathway, it has potential to reduce energy within the wider manufacturing industry.

1. Introduction

Process heating applications are one of the key energy consuming activities in the manufacturing industry. In the US, it is estimated that 17% of all industrial energy is used for process heating (EERE, 2013). This paper will focus on industrial ovens, which fall within the heat containing device category of heating applications. Energy saving within industrial ovens can be achieved through effective maintenance procedures (Darabnia and Demichelis, 2013), or by applying heat integration to reduce energy demand within heating units (Tovszhynsky et al., 2011). Alternatively, process optimisation can lead to significant energy saving without the need for excessive capital expenditure, and can be performed on almost any heating application. Thermal optimisation of manufacturing processes has not received a great deal of attention throughout literature; hence the discipline has significant room for development. At a unit process level, optimisation of process parameter settings and controls can typically achieve energy reduction by a factor of 1.1 (Duflo et al., 2012). Techniques such as computational fluid dynamics can be beneficial to determine optimum process parameter settings (Khatir et al., 2013), however they can remain unfeasible for retrofit design in many facilities due to lack of available resource. Furthermore, complete analysis of a process is vital for appropriate selection of process parameters (Apostolos et al., 2013).

In 2005, there was no overarching optimisation method that could be replicated across a wide range of heating applications within different manufacturing operations, with studies tending to lack industrial oven operability analysis and clear optimisation techniques that can be applied in practice (Cheng and Jaluria, 2005). Although procedures have since been established for various industrial oven scenarios; whether it is an optimisation algorithm for a paint cure oven (Ashrafzadeh et al., 2012), a multi-objective approach for CFD design (Khatir et al., 2013), or an energy modelling approach that maximises production (Perez and

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Carvalho, 2007), this research area is still underdeveloped with the optimisation tools developed only applicable in narrow fields. Furthermore, existing literature tends not to address the link between product and process understanding with the physical engineering principles of an industrial oven. This should be fundamental for optimisation of commercial ovens in order to reduce risk to safety and product performance, and the research presented will aim to address this.

This paper provides a methodology for engineers to thermally optimise industrial ovens for energy saving. The systematic approach is built on developing a detailed understanding of a particular system, and to then formulate an optimisation plan that alters key process variables to maximise energy saving within process limitations and constraints. This research looks to address oven optimisation from a higher level than previously published work, which can give clarity and guidance to more oven scenarios. An application example is presented to demonstrate the intended use and industrial applicability.

2. Description of the 5 stages

Figure 1 shows the outline to the approach for energy reduction which is adapted on 6 Sigma’s DMAIC method to problem solving. It is a well known approach within industry (de Mast and Lokkerbol, 2012) and is in a language that many engineers will be familiar with.

![Figure 1: Systematic approach to optimise ovens for energy saving](image)

2.1 Define
- Understand oven purpose
- Identify system boundaries
- Develop problem statement

Background knowledge of the oven system is important, it is imperative that the oven’s purpose and physical arrangement are understood. Process and product constraints must be identified early on. System boundaries are to be drawn so the project scope can be defined. A problem statement gives clarity to the ultimate purpose of the optimisation project, and will most likely involve comments referring to safe reduction in energy consumption while retaining product quality.

2.2 Measure
- Process stream identification and quantification.
- Mass balance on the system.
- Energy analysis.
- Process variables identified and evaluated.

It is necessary to identify all process streams within the system boundaries, after which a mass balance of the system can be developed. Theoretical or empirical calculations should be conducted for process streams into the system (including air, wet product and solvents etc.), and the streams out of the system (including exhaust gases, water vapour and dry product). An energy analysis of the system is then performed. The theoretical energy required for the process is calculated and then compared to the actual energy consumed. Discrepancies between ideal and actual energy use will give an indication of saving potential. Process variables are identified as ‘X’ input factors (variables which can be directly controlled e.g. damper position), Intermediate ‘Y’ variables (directly affected by altering X’s e.g. humidity within the oven), and ‘Y’ variables (process outputs e.g. product performance or energy consumption). Evaluation of all variables, through techniques such as cause and effect analysis, can be conducted to identify which variables require further investigation.

2.3 Analyse
- Quality baselines set.
- Empirical understanding to develop understanding of X factors and how they affect energy and/or quality outputs, and then label accordingly.
- Process sensitivity analysis.
- Determine process parameters which can be changed that reduce energy whilst retaining quality.
This section improves process and product understanding. The Y’s considered should fall within two categories; energy and quality related outputs. For the optimisation to be successful, the engineer has to have a good understanding of both dimensions. Initially, the quality baseline for the product must be established, and in certain instances, critical safety constraints must also be considered.

The stage then looks to understand the impact each X has on the output Y’s. In many instances, this knowledge can only be ascertained through empirical studies. The aim is to identify the X’s that influence Y’s, which ultimately influence critical Y’s. Input variable are label as X_1, X_2, or X_3 depending on whether they either influence energy (E) or quality (Q) related outputs, or both (EQ). Sensitivity and controllability of the equipment must also be assessed for successfully maximise energy savings.

2.4 Improve

- Identify modification options to alter process parameters.
- Safety and risk evaluation.
- Financial assessment: costs, savings and payback periods.
- Finalise modification plan.
- Trail period.

A number of modification scenarios should be generated before identifying the most suitable option. A process hazard analysis must be completed to evaluate the safety implications of making modifications. A business case will then be developed to present the financial benefits of the project by calculating capital expenditure, savings and payback periods. After a modification plan is developed, the final task in this stage is to complete a trial period prove the product quality is not diminished.

2.5 Control

- Full implementation.
- Validation period and project evaluation.

The final stage looks to permanently implement the plan from Stage 4. This includes a validation period, where the optimised process is monitored to verify there are no product quality and safety concerns. Once the optimisation has been proven to be successful then it can be implemented in full. The final task is to confirm the projects energy saving and to replicate across additional ovens as necessary.

3. An application example: Cure oven optimisation

3.1 Define

The methodology has been applied to a thermal oil curing oven used to cure adhesive on a masking tape web shows the oven flows along with the system boundaries. The oven is controlled by lower explosive level (LEL) analysers which shut the system down if 35 % LEL is reached. The aim of this project is to determine a way in which to optimise the cure oven for energy saving improvements while ensuring the oven’s primary purpose does not diminish.

3.2 Measure

The process streams into and out of the oven system, as well as the mass flow rate of each stream, is displayed in Figure 2. The flows rates shown were determined through empirical and theoretical calculations. The mass into the system equals the mass out of the system.

The theoretical minimum energy is determined by the minimum safe air flow through the system. An emergency shutdown LEL of 35 % determines minimum dilution air which is required. For the average solvent flow into the oven, the air into the system cannot fall below 3,500 kg/h to keep % LEL at a safe level. Knowing this, the energy minimum required has been calculated as 166 kW using the simple thermodynamic equations. The actual energy consumed within the oven is calculated using the exhaust flow, which requires 909 kW of energy to heat from ambient to set point temperature. Therefore, the theoretical maximum energy saving potential is 740 kW.

All process variables were collected and evaluated. Examples of the X inputs that were considered are fan speeds, damper positions, valve positions and atmospheric conditions. Intermediate variables considered included process air flows, oven pressure, temperature and residence time etc. Output Y variables included things such as natural gas consumption, effective cure of the masking tape product. A cause and effect analysis was conducted for X variables which highlighted that fan speeds and damper positions had the greatest impact on both energy and quality outputs.
Appendix B

Figure 2: Oven system flows

3.3 Analyse
Product quality is determined by temperature and residence time within the oven to ensure that the product is sufficiently cured. Therefore, any risk to product quality had to be avoided. Changes to the line speed and the oven temperature were not considered. The % LEL within the oven and the oven negativity were the key process constraints that had to be considered throughout this stage.

Figure 3 displays the important X variables which were considered. On the diagram, D denotes a damper (both automatically and manually controlled), and F denotes fans. Altering fan speeds was not an option during the experiments as variable speed drives (VSDs) were not installed. Therefore, dampers were used to replicate the effect of altering fan speeds. Three experiments were conducted in order to determine the impact of X factors, with Table 1 showing which variables were considered for each experiment.

Experiment 1 highlighted that changes to D5 did not have a significant impact on recirculation flow and that recirculation flow to the air flotation roller was restricted. In this experiment it was shown that D5 was most effective at controlling the exhaust flow from the oven; as can be seen in the main effects plot of Figure 4. Experiment 2 concluded that the optimal oven pressure is -0.24 mbar, as can be seen on Figure 5; optimum pressure is defined when there is the minimal safe quantity of air is drawn into the oven via the slots, 500 kg/h in this example. Experiment 3 was conducted to understand how the LEL responds to reducing air flow through the system. D1 and D4 successfully reduced flow through the system to its optimal value of 9,300 kg/h. To achieve this; D1 is closed fully at 0 %, and D4 is closed to 46%.

Through detailed analysis, the intermediate variables to be altered for process optimisation, while limiting risk to product quality, include reducing the supply air inlet flow and the oven exhaust flow. The X input factors which would impact on these 1 variables include D1, D4 and F1.

Figure 3: Oven system schematic

Table 1: Variables considered in experiment 1, 2 & 3
### Appendix B

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X’s factors</td>
<td>Exhaust flow, recirculation flow, oven pressure, supply air flow</td>
<td>Exhaust flow, recirculation flow, oven pressure, web entrance and exit slot flow</td>
</tr>
<tr>
<td>I variables</td>
<td>D1, D2, D3 and D5</td>
<td>D5</td>
</tr>
</tbody>
</table>

#### Figure 4: Main effects plot for main exhaust flow (m³/h)

![Main Effects Plot for Main Exhaust flow (m³/h)](image)

#### Figure 5: Fitted line plot of oven pressure (mbar) vs. total slot flow (kg/hr)

![Fitted Line Plot](image)

### 3.4 Improve

A number of modification options were considered, and it was decided that three X variables (D1, D4 and F1) will be changed to reduce air flow through the system. The modification plan outlines that D1 will be upgraded and set at 0% (closed) during production mode, and at 100% (open) during emergency shutdown mode. D4 will be upgraded to and set to 45° during production and set to 0° (open) during emergency shutdown. F1 will be off during production mode, but switched on for emergency shutdown. A Process Hazard Assessment was conducted to ensure the modification will not cause any unintended safety implication. Reducing the flow through the system will raise the average % LEL of all products by 4.8%. Cumulative annual energy saving across all products is 1,658,000 kWh which represents a 4.7% reduction on the plants total energy, and is equivalent to offsetting 365 tCO₂. The financial cost of the modification is small and a payback period of 4 months is predicted. Trials were conducted on high
volume, high solvent product to verify that the optimisation did not diminish product quality. Furthermore a laboratory testing proved the modification could be implemented without affecting product quality.

3.5 Control
Implementation is required with a two month validation period to verify the modification. Following this, documents such as start-up/shutdown procedures or PIBs must be updated. Evaluation of actual vs. calculated savings is to be conducted before the project is closed.

4. Recommendations
To reduce total air flow through the system it is recommended that the engineer should determine the limiting variable for reducing the total inlet flow early on. Collecting data to define a baseline of the limiting variable for all products is useful, as is identifying the most sensitive product. Calculation of minimum acceptable inlet air flow rate acceptable and validation this with on-line experiments is necessary. Determine optimum oven pressure is also vital. Although the case study presented looks to reduce overall air flow there are alternative methods that this research’s systematic approach could be applied to, such as; to increase heat transfer coefficient of the oven so faster drying rates can be attained, to optimise the temperature and residence time based on drying or cure simulation, or to balance internal air flows.

5. Conclusion
Energy reduction within the manufacturing sector has a role to play in reducing global energy consumption now and in the future. The research presented addresses the energy consumption of industrial ovens, which use a considerable proportion of energy associated with manufacturing. The systematic methodology guides an engineer from the basic understanding of an oven to optimisation for energy saving. The stages include define, measure, analyse, improve and control. Combining process & product understanding with consideration of physical and engineering constraints is a powerful tool which can deliver significant energy savings. This approach has been applied to a curing oven for masking tape production at a 3M facility in the UK. The optimisation plan consisted of reducing air flow through the system by altering process parameters, resulting in a predicted annual reduction of 305 tCO₂ being emitted. The methodology is now being applied to additional ovens across 3M facilities in the UK. This systematic approach can be tailored to accommodate individual optimisation options, while still providing a clear pathway. As such, there is potential for such a methodology to reduce energy within other 3M facilities and the wider manufacturing industry.

References
Appendix C: Pinch Analysis for Factory A

C1 Introduction
Pinch analysis is an established technique to reduce energy consumption across heating processes Kemp (2007). The technique is applied to the heating process at the Factory A. The stages of pinch analysis include:

- Identifying and quantifying process streams
- Generate shifted composite curves and grand composite curves
- Calculate of energy targets and pinch points using a $\Delta T_{\text{min}}$ of 20°C
- Calculate minimum energy requirement compared to actual energy use
- Develop process redesign strategy
- Investigate possibilities for process change and design Heat Exchanger Network (HEN)

Kemp (2007) suggested a three way approach to process redesign that include: product redesign, process optimisation, heat recovery and site heat and power systems. Product redesign looks to develop a product that requires less energy to produce. Process optimisation ensures that the process runs as effectively as possible without any significant capital investment; optimisation can impact process streams properties. Heat recovery involves minimising utility demand by installing heat exchanger networks, while site heat and power systems involves re-evaluating how energy is supplied and generated on site.

If the process at Factory A were to be improved, then the analysis shows that the ovens would present the greatest opportunity for energy reduction as this is where the majority of the energy transfer occurs. Kemp (2005) suggests ways to reduce energy consumption in ovens include:

1. Reduce inherent energy required for the product, e.g. removing water content
2. Improve efficiency by reducing heat loss, total airflows or batch times
3. Heat recover within dryer between hot and cold streams
4. Heat exchange between the oven and surrounding processes
5. Use low grade, low cost heat sources to supply thermal energy
6. Coming heat and power
7. Use of heat pumps to recover waste heat to provide dryer heating

These steps should be carried out in the logical order. Methods 1 and 2 directly reduce dryer heat duty, methods 3 and 4 increase heat recovery and 5, 6 and 7 are focused to reduce the cost of utilities. Work to improve oven efficiency is to be conducted, but this report is to investigate the opportunity for heat recovery in Factory A’s processes.

C2 Pinch analysis for one oven unit
To demonstrate how pinch analysis can be beneficial, it is useful to apply the methodology across one unit as this leads to greater process understanding. However, this does not necessarily point to the best opportunities for heat integration across the whole factory. The oven which is to be analysed has three process streams; the exhaust, the web exit, and the inlet air to the oven, as shown in Figure C1. CP is the constant heat capacity.
Appendix C

Figure C1: Single oven unit process stream data

Shifted (Figure C2) and grand (Figure C3) composite curves have been created for the singles unit to better understand the thermodynamic requirements of the system for the winter scenario. Figures C2 and C3 show that the process pinch temperature across the oven is 30°C. The cooling duty is 80kW, and the heating duty is 412kW, therefore, the heat recovery potential is 338 kW. Latent heat could be recovered from the exhaust air in a condensing exchanger and this could be used to pre-heat air into the oven. It is suggested that up to a third of the latent heat available can be recovered, depending on the operating temperatures involved (Moraitis and Akritidis, 1997). The $\Delta T_{\text{min}}$ for this type of heat exchange between gaseous streams may be closer to 40°C. The type of heat exchanger could be a simple U-tube shell and tube heat exchanger which would make any alterations relatively simple compared to a non-condensing heat recovery unit (which would require a counter current exchanger).

Figure C2: SCC for single drying oven
Figure C3: GCC for single drying oven

Schemes to recover heat from exhaust gases have previously been conducted within 3M but findings have been disappointing, due to the wet and dusty nature of the exhaust leading to fouling and corrosion of the heat exchanger. This can lead to high maintenance costs which increase payback periods for projects. Alternative methods are to recycle the warm exhaust air after the humidity of the stream is reduced from the condensation of water. However, this would reduce the exhaust stream to below 40°C meaning which inhibits any potential large gain from recycling the air (Kemp, 2005). Applying pinch analysis to a single unit has demonstrated that single oven units have optimisation opportunities. Furthermore, heat exchangers to transfer energy to inlet air are theoretically favourable, but would have issues with contamination build up within the exchanger.

C3 Pinch analysis across the whole site

22 process streams were identified for the entire Factory A, with 14 hot streams and 8 cold streams. Thermodynamically, a factory operates differently in the summer and winter seasons. During the winter months extra heating utility is required for space heating, meaning that 22 streams are identified for winter compared to the 20 streams analysed for summer. Therefore the initial stages pinch analysis is performed for both summer and winter scenarios. Stream data is collected from metered readings, measurements using hand held equipment, power and flow ratings of equipment and product design specifications.

C3.1 Shifted composite curve (SCC)

Hot and cold streams can be plotted on to a temperature/enthalpy diagrams using the process stream data. This technique allows us to handle multiple streams at once. The shifted composite curves (SCC) have a $\Delta T_{\text{min}}=0$ and highlight the pinch point. Additionally SCC display the cooling and heating duty, as well as the amount of heat recovery potential between the hot and cold streams. Figure C4 and C5 display the SCC for the winter and summer scenarios respectively.
The process pinch point during both winter and summer scenarios is 116°C. The pinch point shows where the process is most constrained, as well as separating the process into two distinct thermodynamic regions. Later, when designing a heat exchanger network (HEN), there are three rules which must be met to achieve the minimum energy target:

- Don’t transfer heat across the pinch
- Don’t use cold utilities above the pinch
- Don’t use hot utilities below the pinch

C3.2 Grand composite curve (GCC)

Grand composite curves (GCC), as seen in Figure C6 and C7, are formed from the Pr-T calculations and represents the difference in heat available (net heat flow) between the hot and cold streams at any given temperature interval. The problem table method (Pr-T) is a method of obtaining energy targets and identifies the heat transfer potential between all the temperature intervals throughout the process. GCC separates the processes into separate regions and is useful for visualising the pinch.
C3.3 Minimum Energy Requirements (MER)

Using the SCC and GCC, the minimum energy requirements (MER) can be determined. The sum of all loads from hot process streams is 1940kW, while the load of cold process streams is 2104kW. The heat load can be viewed as the enthalpy change of the process streams which results from the streams’ temperature change. The minimum utility requirements are determined using the GCC, and are shown in Table C1.

<table>
<thead>
<tr>
<th>Table C1: Minimum utility requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>During winter</strong></td>
</tr>
<tr>
<td>Minimum hot utility demand</td>
</tr>
<tr>
<td>Minimum cold utility demand</td>
</tr>
</tbody>
</table>

Maximum heat recovery can also be found using the SCC, and represents the upper limit of heat recovery which we are working towards. For the winter months, the theoretical amount of energy...
recoverable from a HEN is determined by subtracting the minimum cooling duty (602 kW) from the maximum heat load of the hot streams (2350kW), giving a possible heat recovery of 1748 kW. Similarly for the summer months, the theoretical maximum heat recovery potential is found to be 1251 kW.

C3.4 Utility Consumption
Table C2 displays the total hot and cold utilities used at Factory A, determined using metered data. Hot utilities power the ovens, thermal oil heaters, the thermal oxidiser, and a steam boiler for heating (only in winter). Cold utilities include refrigeration system in the solvent recovery unit and the chillers.

<table>
<thead>
<tr>
<th>Season</th>
<th>Min utility demand (kW)</th>
<th>Actual utility use (kW)</th>
<th>Difference (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Hot utility</td>
<td>447</td>
<td>3,293</td>
</tr>
<tr>
<td></td>
<td>Cold utility</td>
<td>602</td>
<td>83</td>
</tr>
<tr>
<td>Summer</td>
<td>Hot utility</td>
<td>447</td>
<td>2,928</td>
</tr>
<tr>
<td></td>
<td>Cold utility</td>
<td>1099</td>
<td>83</td>
</tr>
</tbody>
</table>

In theory, actual hot utility consumption minus the hot minimum should equal the cold actual minus the cold minimum \((Q_{h,\text{actual}} - Q_{h,\text{min}}) = (Q_{c,\text{actual}} - Q_{c,\text{min}})\). However, \(Q_{c,\text{actual}}\) and \(Q_{c,\text{min}}\) are not directly comparable due to the fact that many of the hot process streams at Factory A are released to the environment and do not require artificial cooling such as refrigeration or cooling water, thus causing for the positive difference between the minimum cold utility demands and the actual utility shown in Table C2. It can be seen that theoretically the process only requires less than 20% of the hot utility supplied currently. This inefficiency may come from excessive production downtime, or from poor oven performance due to ineffective insulation, fan circulation, heat loss through transportation, gas burner inefficiency, or un-optimised settings.

C3.5 Heat Exchanger Network (HEN)
Developing a site wide a heat exchanger network (HEN) enables for maximum site energy reduction. Heat exchanger networks (HEN) matches process streams together to best utilise waste heating and cooling potential, allowing for the maximum energy recovery. Up until this point the summer and winter scenarios have been considered separately. However, the factory will have to use the same HEN all year round and therefore only one design can be taken forward. If the winter scenario is used to design a HEN, then during the summer months the warm air needed for space heating would have to be replaced with additional cooling duty. Considering this, and that space heating is not as energy intensive as other heating processes, the summer scenario will be used to create the HEN.

The HEN will not consider all hot and cold process streams with an enthalpy change of less than 100kW; thus 7 of the 20 streams will be omitted. This simplifies the HEN and more practical as more emphasis is placed on the streams which would give greater cost and energy savings. An additional pinch analysis of the remaining 13 streams was conducted and found that the process pinch point remains at 116°C. Therefore, streams can be matched to create a HEN. There are a number of rules which must be followed in HEN design in order to achieve MER:
• Thermal energy cannot be transferred across the pinch point
• There must be no cooling utility used above the pinch, and no heating utility used below the pinch
• Above the pinch, $C_{P_{\text{hot}}} \leq C_{P_{\text{cold}}}$
• Below the pinch, $C_{P_{\text{hot}}} \geq C_{P_{\text{cold}}}$
• When considering the number, $N$, of hot and cold streams
  o Above the pinch, $N_{\text{hot}} \leq N_{\text{cold}}$
  o Below the pinch, $N_{\text{hot}} \geq N_{\text{cold}}$

An initial HEN was designed as an exercise to determine the theoretical maximum heat recovery, not taking into account the physical location of the process streams. This theoretical exercise was then taken further to create a more practical design that has the potential to be implemented at Factory A. Figure C8 displays the relaxed design that incorporates a zoning, whereby stream matches in close physical proximity are given priority. Zoning helps to reduce heat losses and capital costs. A drawback from this approach is that extra splitting streams may have to be incorporated into the design to adhere to the aforementioned rules. The key results from the final relaxed HEN are:

• Heat recovery of 1100 kW
• Hot utility demand falls from 2928 kW to 1828 kW
• New theoretical hot utility required in total 958 kW
• New theoretical cold utility required 952 kW
• Design involves installation of 7 heat exchangers
Figure C8: Relaxed HEN for summer
Appendix C

C3.6 Heat exchanger financial assessment

Design evolution looks to form a business case for the HEN design. Initial cost calculations provide an indication of which heat exchangers are worth perusing. UA analysis, using Equation C1, is used alongside the C value method as the crude tool to evaluate heat exchanger costs; UA value are multiplied by a C-value of sterling pounds per unit surface area: £/(W/K).

\[ UA = \frac{Q}{\Delta T_{\text{LMTD}}} \quad \text{Eq. C1} \]

Where \( U \) is the overall heat transfer coefficient (kW/m\(^2\).K), \( A \) is the area (m\(^2\)), \( Q \) is the heat transferred in the exchanger (kW), and \( \Delta T_{\text{LMTD}} \) is the log mean temperature difference (K). The C-value for each exchanger is found through logarithmic interpolation from standard sized exchanger data (ESDU, 1992). It is assumed that all exchangers in the HEN would be shell and tube exchangers.

Total project costs (including installation, equipment, ancillaries and transportation) can be calculated using the Hand method, which involves multiplying the purchase cost of the equipment by a ‘module’ factor. Equation C2 shows the Hand method of calculating capital costs. For a shell and tube heat exchanger the module factor is 3.2. An instrument factor (\( F_i \)) is also applied; \( F_i = 1.2 \) is reasonable for well automated plants (Hand, 1958) (Brown, 2000).

\[ \text{capital cost} = \sum (\text{equipment purchase cost} \times \text{hand or module factor}) \times F_i \quad \text{Eq.C2} \]

Table C3 shows the capital project cost of all 7 matches (as seen in Figure C8) using Equation C1 and Equation C2.

<table>
<thead>
<tr>
<th>Match</th>
<th>Energy Saving (kW)</th>
<th>Hot stream</th>
<th>Cold stream</th>
<th>UA value (W/K)</th>
<th>C value £/(W/K)</th>
<th>Equipment Cost 2012 (£)</th>
<th>Capital Project Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>Exhst back</td>
<td>Air into sat</td>
<td>1171</td>
<td>5.17</td>
<td>£ 9,758.60</td>
<td>£ 37,473.04</td>
</tr>
<tr>
<td>2</td>
<td>184</td>
<td>Exhst LAB</td>
<td>Air into LAB</td>
<td>12298</td>
<td>1.21</td>
<td>£ 23,992.12</td>
<td>£ 92,129.72</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>Exhst back</td>
<td>Air into back</td>
<td>1544</td>
<td>4.36</td>
<td>£ 10,847.24</td>
<td>£ 41,653.40</td>
</tr>
<tr>
<td>4</td>
<td>127</td>
<td>Sol. Loop 1</td>
<td>Sol. Loop 2</td>
<td>6282</td>
<td>1.94</td>
<td>£ 19,685.00</td>
<td>£ 75,590.41</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>Exhst prime</td>
<td>Air into prime</td>
<td>4202</td>
<td>2.35</td>
<td>£ 15,909.85</td>
<td>£ 61,093.81</td>
</tr>
<tr>
<td>6</td>
<td>293</td>
<td>Exhst sat</td>
<td>Air into sat</td>
<td>14296</td>
<td>1.45</td>
<td>£ 33,359.63</td>
<td>£ 128,100.99</td>
</tr>
<tr>
<td>7</td>
<td>143</td>
<td>TO exhaust</td>
<td>Air into cure</td>
<td>7882</td>
<td>1.59</td>
<td>£ 20,237.83</td>
<td>£ 77,713.25</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>£ 133,790.27</td>
<td>£ 513,754.62</td>
</tr>
</tbody>
</table>

The total current hot utility consumption is 2,928 kW, which cost the plant £513,754. The proposed HEN has the potential to reduce this figure by 1,100 kW to 1,828 kW, which is a reduction of 38%. Therefore an annual utility cost reduction of £230,000. This would give a payback period of 2.2 years.

C3.7 Individual heat exchanger payback

As well as assessing all heat exchangers as one network, it is useful to determine which matches would provide the greatest benefit, as it is can be unrealistic for a factory to install all HEN matches simultaneously. Table C4 shows the financial analysis of each heat exchanger. The top heat
exchanger based on payback period is to recover heat from the thermal Oxidiser exhaust stream, and put it into to the cold air input to the cure oven.

Table C4: Ranking of match payback period

<table>
<thead>
<tr>
<th>Match</th>
<th>Hot stream</th>
<th>Cold stream</th>
<th>Annual Energy Saving (kWh)</th>
<th>Annual cost saving due to gas reduction</th>
<th>Payback (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>TO exhaust</td>
<td>Air into cure</td>
<td>1,959,552</td>
<td>£ 68,584.32</td>
<td>1.13</td>
</tr>
<tr>
<td>6</td>
<td>Exhst sat</td>
<td>Air into sat</td>
<td>2,362,752</td>
<td>£ 82,696.32</td>
<td>1.55</td>
</tr>
<tr>
<td>4</td>
<td>Sol. Loop 1</td>
<td>Sol. Loop 2</td>
<td>1,378,944</td>
<td>£ 48,263.04</td>
<td>1.57</td>
</tr>
<tr>
<td>2</td>
<td>Exhst LAB</td>
<td>Air into LAB</td>
<td>1,669,248</td>
<td>£ 58,423.68</td>
<td>1.58</td>
</tr>
<tr>
<td>5</td>
<td>Exhst prime</td>
<td>Air into prime</td>
<td>822,528</td>
<td>£ 28,788.48</td>
<td>2.12</td>
</tr>
<tr>
<td>3</td>
<td>Exhst back</td>
<td>Air into back</td>
<td>483,840</td>
<td>£ 16,934.40</td>
<td>2.46</td>
</tr>
<tr>
<td>1</td>
<td>Exhst back</td>
<td>Air into sat</td>
<td>193,536</td>
<td>£ 6,773.76</td>
<td>5.53</td>
</tr>
</tbody>
</table>

C3.3 Feasibility

After completing pinch analysis and evaluating the financial viability of various heat exchangers, the practicalities of installation must be considered. These might be process constraints which do not allow for streams to be cooled below a certain temperature, or the distance or physical obstacles which prevent duct work connecting the two streams. Table C5 summarises the key issues concerning the feasibility of implementing each heat exchanger in descending payback period rank.

Table C5: Heat exchanger feasibility issues

<table>
<thead>
<tr>
<th>Match</th>
<th>Issues concerning feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>Ducting complications</td>
</tr>
<tr>
<td></td>
<td>TO is outside, cure oven is inside of main building</td>
</tr>
<tr>
<td></td>
<td>Danger of reducing the TO exhaust temp too low that it would breach environmental regulations</td>
</tr>
<tr>
<td>6</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>Condensation of exhaust stream and thus fouling of heat exchanger</td>
</tr>
<tr>
<td>4</td>
<td>Solvent recovery circuit sensitivity; Solvent temperature cannot be allowed to fall below dew point of harmful components before it enters the correct section of the system</td>
</tr>
<tr>
<td></td>
<td>Heat exchanger fouling</td>
</tr>
<tr>
<td>2</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>LAB oven not run on all products, so reduced annual savings</td>
</tr>
<tr>
<td></td>
<td>Condensation of exhaust stream and thus fouling of heat exchanger</td>
</tr>
<tr>
<td>5</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>Condensation of exhaust stream and thus fouling of heat exchanger</td>
</tr>
<tr>
<td>3</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>Condensation of exhaust stream and thus fouling of heat exchanger</td>
</tr>
<tr>
<td>1</td>
<td>Effectively re-directing preheated air into oven</td>
</tr>
<tr>
<td></td>
<td>Condensation of exhaust stream and thus fouling of heat exchanger</td>
</tr>
</tbody>
</table>
Table C5 highlights the impracticalities of directing the pre-heated air back into the ovens. With the exception of the inert oven, all the ovens draw air from their surroundings into the oven to be heated. The air is drawn in through the two slots at either end of the ovens where to product enters and exits (approximately 2.0m x 0.15m), and it is here that a unit should be installed to direct the pre-heated air into the oven. It is difficult to reduce the size of the product slots to prevent leaking of ambient temperature air into the oven. The solution for this would be that you provide a positive pressure into the unit, which will provide excess pre-heated air to the web entrance/exit. These feasibility issues highlight that investigating process optimisation might provide better energy savings and should be conducted before heat exchangers are installed.

C4 Pinch analysis conclusion

Pinch analysis has been conducted for Factory A’s manufacturing process. Composite curves have been generated and identify 116°C as the pinch point temperature. The minimum energy requirement for the process has been determined and the maximum reduction in utility consumption calculated. Theoretically, the process only requires less than 20% of the hot utility that was being supplied, suggesting that there is significant opportunity to reduce energy consumption.

Process synthesis gives direction on how a process should be designed or redesigned. It provides a systematic approach that progresses from product design, to process optimisation, to heat recovery before looking at site heat and power systems. Analysis of Factory A manufacturing site indicates there is potential for process optimisation in many of the industrial ovens, which needs to be investigated further. However, the aim of this report was to investigate the feasibility, benefits and costs of a heat exchanger network. Therefore, a heat exchanger network was designed for the existing system to indicate feasibility of such an installation.

The designed heat exchanger network would have a heat recovery potential of 1100 kW and would involve 7 heat exchangers. A financial assessment of the network determined that the total estimated cost would be £513,000 with a payback period of 2.2 years. When looking at each heat exchanger individually, the feasibility was reduced due to the difficulties in effectively re-directing preheated air into oven and the potential condensation of exhaust stream and fouling of heat exchanger plates. It was concluded that before heat exchanger projects developed further, the process should be optimised. Process optimisation may offer a more feasible way to deliver important energy savings to the plant.
Industrial oven improvement for energy reduction and enhanced process performance

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Abstract Industrial ovens consume a considerable amount of energy and have a significant impact on product quality; therefore, improving ovens should be an important objective for manufacturers. This paper presents a novel and practical approach to oven improvement that emphasises both energy reduction and enhanced process performance. The three-phased approach incorporates product understanding, process improvement and process parameter optimisation. Cure understanding is developed using Dynamic Mechanical Analysis (DMA) and CIE-Lch colour tests, which together highlight the impact of temperature variation on cure conversion and resulting product quality. Process improvement encompasses thermodynamic modelling of the oven air to evaluate the impact of insolation on temperature uniformity and system responsiveness. Finally, process parameters, such as temperature, pressure negativity and air flow, are optimised to reduce energy consumption. The methodology has been effectively demonstrated for a 1 MW festoon oven, resulting in an 87.5 % reduction in cooling time, saving 20.2 h of annual downtime and a reduction in gas consumption by 20–30 %.

Keywords Industrial oven · Manufacturing · Energy saving · Process performance · Cure · Optimisation

Abbreviations
DMAIC Design, measure, analyse, improve, control
CFD Computational fluid dynamics
DMA Dynamic mechanical analysis
DOE Design of Experiments
x, y, z Physical locations on web
h Hour
y Year
Q Heat flux (kW)
ρ Density (kg m⁻³)
C_p Specific heat capacity (kJ kg⁻¹ K⁻¹)
T Temperature (K)
t Time (s)
k Thermal conductivity (W m⁻¹ K⁻¹)
γ Layer thickness (m)
ṁ Mass flow rate (kg s⁻¹)
M Mass of oven air (kg)
i Refers to an oven structural component (wall, ceiling or floor)
A Heat transfer area (m²)

Introduction

Industrial ovens are commonly used in the manufacturing industry for curing, drying or baking. An oven’s performance, compared to the best available practice, can decrease over time due to structural/mechanical degradation, technology advancements or changing process requirements. There is potential for functionality improvement, in terms of energy and process performance, in many existing industrial ovens. Heating applications consume almost 1/5 of all industrial energy (OEERE
Appendix D

2001), and this study has calculated that typical greenhouse gas emission from a direct gas fired industrial oven is 0.2-0.4 tCO₂e per tonne of product throughput for a 1 MW oven. Site-wide energy saving within heating processes is relatively common throughout the existing literature. Mish et al. (2014) present a decision making framework for heat integration in production lines to identify heat recovery opportunities. Dor et al. (2013) discuss a methodology that links energy-saving potential to the improvements for production processes, while Dufflo et al. (2012) give an overview of start of the art energy efficiency methods in manufacturing operations. Although potentially beneficial, site-wide process improvement via retrofitting is often unfeasible due to limitations in existing technologies, space availability, layout restrictions, heat losses, disruption to production, financial viability, etc. Reducing energy consumption of oven units offers a focused and feasible approach to energy saving.

The aim of improving industrial oven should be to increase product quality, production efficiency and worker safety, as well as to reduce energy consumption and waste. Process variation of operating conditions has a significant impact on product quality, performance, cost, safety and operational efficiency. The cost reduction associated with lean manufacturing is important for businesses in increasingly competitive markets (Srinivasan 2011). However, manufacturers are more concerned with the quality of their products over the energy consumption, and this prioritisation affects how energy reduction is pursued within industry. Therefore, linking energy and product quality deserves attention in the research. Puthare and Roskilly (2016) present quality and energy performance analysis in the food manufacturing industry; however, there is little evidence of emphasis on both dimensions for heating processes in the light manufacturing industry. Understanding of process variation has many benefits and is critical for manufacturers to be competitive. It can be used to develop better products, avoid excess precision in certain aspects of a process, minimise defects, allow for a faster transition from one product to another, deliver cost reduction and reduce scrap (Thornton 2004).

Lu et al. (2012) offer a dual objective framework for optimisation of energy saving and product quality for injection moulding processes. The study has been completed at a laboratory scale to deliver a 10 % energy reduction; however, the conclusion reached is that higher quality can result in higher energy consumption and that there must be a trade-off to satisfy the application needs. Khairi et al. (2013) demonstrate the thermal management of bread baking ovens using CFD (Computational Fluid Dynamics) modelling to minimise energy consumption and improve oven functionality. Khairi et al. (2015) also report laboratory-scale investigations to develop product understanding and combine this with industrial-scale investigations to thoroughly understand oven performance. Their research highlights the important link between product quality and energy reduction in industrial ovens. Bhanot et al. (2016) also present a framework for industry to analyse the economic and environmental performance of a turning process to maximise benefit to the manufacturer, while Mukherjee et al. (2015) utilised the sustainability footprint method to evaluate methanol production processes, thus incorporating economic, environmental and social performance into the analysis.

Organisations tend to use methods such as Six Sigma and Total Quality Management to improve oven performance (Thornton 2004). These tools can highlight improvement areas and can establish modification plans, which include upgrading equipment or installing additional hardware (Fapin 2011). Pask et al. (2014) show the application of a modified version of Six Sigma’s DMAIC (Design, Measure, Analyse, Improve, Control) methodology to reduce energy within industrial ovens, resulting in a decrease in gas consumption in an oven by 29 %. This study, however, is on energy consumption and does not focus on product quality.

Product understanding can be used to help identify constraints in an existing process and can highlight areas of potential process improvement. Polymer composites are used in many manufacturing applications, and techniques such as dynamic mechanical analysis (DMA) are used to develop understanding of polymer curing processes (Saba et al. 2016). DMA is a versatile technique that can provide information on the physical changes of a resin which is subjected to a thermal regime. At the same time, it is important to link lab-based DMA findings to product quality on the actual manufacturing line. This study focuses on oven improvement that involves energy reduction and process performance enhancement. A three-phased improvement approach is presented that includes product understanding, process improvement and process parameter optimisation. An industrial application demonstrates how the approach can be interpreted and applied to a manufacturing scenario.

Methodology

The iterative approach for improving industrial ovens is shown in Fig. 1. The method starts with product understanding before moving to process improvement and then finally looking at process optimisation. Incorporating product quality considerations throughout the improvement process helps to develop process capability, which results in economic benefits for a manufacturer in terms of energy saving and process performance. Ideally, activities should
Industrial oven improvement for energy reduction and enhanced process performance

Fig. 1 Iterative approach for oven improvement

be completed sequentially so that changes are made at the correct time during the improvement process. For instance, product understanding can highlight an aspect of oven performance which is underperforming and needs to be improved. Alternatively, optimisation should be completed once manufacturers are confident in the process hardware; optimising process settings before the hardware is changed is not efficient. That being said, in practice, the approach is likely to be an iterative process. This is because of the understanding gained from one phase can highlight areas, overlooked earlier. Developing knowledge of both the process and product can be done in parallel, and oven improvement should be a continuous process. This section details the methodology and the techniques used in the industrial oven case study.

Figure 2 presents a flowchart which interprets three-phased approach (Fig. 1) for industrial oven application. The flowchart starts by evaluating an existing oven system before using this insight to direct product understanding.

Fig. 2 Process-specific flowchart

The understanding of how process temperature variation affects product quality is used to direct the process improvements that are required. The next step is then to reduce oven pressure negativity and reduce system air flow through process optimisation.

Product understanding

The aim of this phase is to understand what affects product quality, which can be the determining factor for many modification projects. It establishes what is required from the process to deliver a product which performs to specification. This work, generally performed at a laboratory scale using experimental approaches, acts as an enabler for future projects by understanding risks associated with projects or by quantifying potential quality improvements. Establishing this knowledge at the beginning of the improvement approach is beneficial because it enables the right decisions for process improvement and optimisation to be made quickly.

For the industrial application presented in this paper, a number of different techniques are used to develop product understanding. Temperature logging of a product through the oven identifies the actual thermal regime the product is subjected to and highlights the areas of process temperature variation. DMA is used to understand the physical dynamic properties of an adhesive over a thermal process. The CIE-Lch colour test and accompanying free phenol analytical technique are used to give an indication of what the DMA data mean in terms of product quality. Further information on product understanding for the industrial application can be found in “Process improvement”.

Process improvement

Process improvement addresses the following three aspects of the oven system: system controllability, process variation and energy consumption. This activity looks to develop operability and maximise an oven’s capability under its current process settings. Analysis of the system, through a combination of experimental and computational techniques, evaluates how close to its original specification the current process performs. This can then be developed to establish a way to exceed and enhance the oven’s original capability. Improvements in this section are likely to be the physical changes to the oven system, which can be in the form of upgrading equipment or installing additional hardware. Product understanding can be used to help identify constraints in an existing process and can therefore highlight potential process improvement.

For the industrial application presented in this paper, process improvement takes the form of installing insulation on the inside of the oven walls to reduce the impact of
structural thermal mass on temperature responsiveness. Modelling heat transfer through the existing oven structure can determine the potential advantages in terms of energy saving and reduced process variation. Process improvement can involve installing additional sensors to assist with process control and understanding, which can then generate understanding of product quality, resulting in an iterative approach.

Process parameter optimisation

Process parameter optimisation is the final step in the oven improvement approach. The optimisation procedure questions whether the existing process settings can be altered in order to give benefits to process variability, product quality as well as energy consumption. Optimisation involves detailed analysis of process variables through empirical or theoretical approaches. Energy reduction is a key target in this stage, with the optimisation of process variables often being cost-effective. This is the final stage because optimisation of a process should ideally be completed once the manufacturer is satisfied with the physical setup of the system.

Pask et al. (2014) outline an optimisation methodology for industrial ovens which is applied in the industrial case study. The systematic approach follows Six Sigma principles and applies them to an oven scenario. The approach involves five stages as follows: Define, Measure, Analyse, Improve and Control. The optimisation objective is to establish process settings that minimise energy consumption and improve product quality. All process variables affecting energy consumption and product quality are identified and analysed, such as fans or dampers. Performance data energy consumption and product quality are analysed for different variables to identify optimal settings that best achieve the objective. The oven is then improved to its optimised state and closely monitored.

Case study: Improvement to an oven for adhesive resin curing

In order to demonstrate the intended use, the approach is applied to an industrial-sized festoon oven that cures a layer of adhesive resin to a backing. Energy is supplied to the oven with direct fired gas burners with fumes exhausted to atmosphere. The 1 MW oven performs its task reliably; however, it is identified as an area of process improvement and energy saving. Greater understanding of the product is required to minimise variability in quality, as well as reducing risks associated with process modifications. The rest of the section details how the approach has been applied to this oven.

Product understanding

A key gap in product understanding is the knowledge of how temperature variation affects adhesive resin curing. Temperature profiling within the industrial oven should be conducted to understand existing process variation. In the given example, this is investigated by additional measurement through four probes attached to the webbed product at periodic vertical intervals. Figure 3 shows the vertical web temperature deviation for one product above and below its set point, with Probe 1 being the highest point on the web, and Probe 4 being the lowest (numerical values have been removed due to confidentiality). It highlights that temperature variation is particularly problematic at the beginning and end of the process.

Cure characterisation is also required to understand the impact of temperature variation on product quality. The cure of a resin is represented on a scale of 0–1, and is a qualitative measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive (Smček and Kanik 2007). Understanding the cross-linking of polymers can help identify the most appropriate cure strategies (Dickie et al. 1997). In this particular case, the level of cure achieved in the process has not been known and the level of cure to be targeted has also been unclear.

To examine how final temperature affects adhesive cure properties, the adhesive resin has been analysed offline using a combination of two laboratory-scale analytical techniques, Dynamic Mechanical Analysis (DMA) and free phenol/CIE-Lab colour test. DMA provides information on how the physical property of the resin varies after being subjected to different temperature regimes, while the free phenol test is used to relate physical cure properties to the actual manufacturing process. The CIE-Lab colour test can be used to quantify the free phenol test results. Three temperatures have been used to replicate common temperature variation within the oven; x, y and z °C (actual temperatures omitted due to confidentiality), where x °C is the average temperature at the bottom of the oven, y °C at the middle and z °C at the top of the oven. Samples of adhesive-coated film are prepared for both the DMA and free phenol/CIE-Lab colour test. Standard isothermal DMA procedures are followed on samples at each temperature over 180 min. The DMA applies a sinusoidal force measuring the in-phase component (storage modulus) and the out-of-phase component (loss modulus). The storage modulus is an indication of the material’s elastic behaviour, and the tan delta (tan D) is ratio of loss to stored energy i.e. ‘dampening’. These are commonly used for cure understanding as the hardening of a material changes the elasticity and dampening effects.
Simultaneously, adhesive-coated samples are heated at matching temperatures in a separate laboratory oven. A free phenol test is conducted on these samples every 10 min. The free phenol experiment involves submerging the coated sample in a 2% mixture of sodium phosphate. If the sample is under-cured, the solution removes the free phenol from the adhesive and a sodium hypochlorite indicator can be used as a visual indication of cure. In order to quantify the level of the phenol in solution, and thus imply the cure conversion, a CIE-Lch color test is performed on the resulting solution. The CIE-Lch test measures three axis values: L axis is the lightness, a axis is the saturation and b is the hue.

Figure 4 plots the hue data from the CIE-Lch color test. Hue is measured in degrees, ranging from 0° (red) through 90° (yellow), 180° (green), 270° (blue) and back to 0°. The sample start at yellow/orange before changing to green and then to blue when a higher level of cure is established. Note that, at each temperature, there is a strong correlation between the trend of the hue value and that of the tan D value. More specifically, it appears that the tan D peak does not occur until a hue value has settled out above 250°. Therefore, the hue value has been used as a quick method to establish when the tan D peak has been achieved during online testing.

By investigating three different final temperatures, the study has shown the importance of achieving a uniform temperature profile within the industrial oven. The DMA analysis shows that the tan D peak, and implied complete cure conversion, falls from 73 min at 8 °C to 40 min when the oven is set at 15 °C. As the temperatures x, y and z °C represent a feasible variation in the oven, this study has demonstrated that the process temperature variation can significantly affect how cured a product is when exiting the oven, and thus can have a significant impact on quality.

Product understanding has demonstrated an aspect of the process that negatively affects product quality. This can be used to target specific aspects of the process which need to be improved to reduce energy saving and enhance process performance. The combination of the DMA analysis and the free phenol/CIE-Lch color test has not been presented in the literature before, with traditional cure understanding only using DMA data. The combined method presented in this paper is effective at linking lab-based DMA findings to product quality on the actual manufacturing line, a long-standing issue in industrial settings attempting to characterise adhesive cure.

Process improvement

Product understanding highlights the importance of delivering a uniform temperature profile. As well as cross-web variation, another constraint of the system is its inability to quickly change to a new temperature profile. As products with different temperature set points are run continuously after one another, the system’s inability to change temperature can result in different temperature profiles for products at the start and middle of a run.

The influence of structural thermal mass reduces the oven’s ability to change temperature. This results in long start-up periods and unnecessary downtime during breakdowns. The existing wall structure consists of thermal blockwork, insulated cavity and an external skin. A modification to install an insulation layer to the inside of the
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Fig. 4 Results from colour test: $R$ value of each sample and the tan $\delta$ values shown below the plot

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oven wall is proposed to reduce the impact of structural thermal mass. Along with reducing oven pressure negativity to minimise cold air ingress, insulation would help to develop a tightly controlled repeatable process.

To assess the effect of adding an insulation layer on the heat fluxes across the dimension of the solid oven structure during the heating and the cooling process, a heat transfer model is adopted as shown in Eq. (1). The boundary conditions assume a constant internal oven temperature during the heating process and a constant external ambient air (for walls and the ceiling) or ground (for floor) temperature for both the heating and the cooling process. The initial condition adopted for a heating simulation is an oven wall temperature that is just above ambient air temperature. The heat transfer equation is solved for simulating the heating process first. Once a steady-state temperature is reached, the structure’s temperature profile is taken as the initial condition to model the cooling process. For cooling, burners are turned off and the fans replace warm air with ambient air. As a preliminary analysis, the oven air temperature is first assumed to be constant at the ambient temperature throughout the cooling process, which in a second step is replaced by a more realistic treatment as presented later in this section.

$$\\rho C_p \frac{dT}{dt} = k \frac{d^2T}{dx^2}, \quad (1)$$

where $\rho$ is the density ($\text{kg m}^{-3}$), $C_p$ is the specific heat capacity ($\text{kJ kg}^{-1} \text{K}^{-1}$), $T$ is the temperature ($\text{K}$), $t$ is the time (s), $k$ is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) and $y$ is the layer thickness (m). Figure 5 presents the model output showing the heating and cooling temperature profiles for an industrial festoon oven wall with and without an insulation facing (numerical values have been removed for the reasons of confidentiality). Figure 5a, b shows the cross-sectional wall temperature for the existing structure for heating and cooling regimes, whereas Fig. 5c, d shows the same for a wall structure with a layer of insulation on the inside surface. A comparison of Fig. 5a-c demonstrates that the time taken for the structure to reach steady state reduces when insulation is installed: from 10 to 20 h, there is still a considerable change in temperature profile for the existing wall structure, while the insulated system does not have a significant temperature change after 10 h. Energy used to heat the wall structure results in higher supply temperatures to maintain the set point exhaust temperature. Higher supply temperature results in greater temperature variation within the oven and thus negatively affects the product quality variation. A comparison of Fig. 5b-d shows that the time taken for the wall structure to cool is reduced for the insulated system.

Encouraged by the positive effect of insulation suggested by the above preliminary analysis, a more realistic model is adopted to determine the cooling profile of a hot oven in a blow-down operation, when the burner is off and the exhaust and supply fans are fully on. The model included a heat balance equation for the inner-oven space, as shown in Eq. (2).

$$C_p M \frac{dT_e}{dt} = C_p m (T_0 - T_e) + Q, \quad (2)$$

where $T_e$ is the oven air temperature ($\text{K}$), $T_0$ is the inlet (i.e. ambient) air temperature ($\text{K}$), $M$ is the mass of air in the oven (kg), $m$ is the mass flow rate of the air that flows through the
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Fig. 5 Heating through the wall structure, a heating of existing brickwork, b cooling of existing brickwork, c heating of insulation faced brickwork, d cooling of insulation faced brickwork.

The oven (kg s⁻¹), $C_p$ is the heat capacity of air (kJ kg⁻¹ K⁻¹) and $Q$ is the total heat flux into the oven from its solid structure (kW). $Q$ can be evaluated by Eq. (3) as

$$Q = \sum_i h_i A_i (T_{oi} - T_a)$$  

where $h_i$ is the heat transfer coefficient (W m⁻² K⁻¹), $A_i$ is the heat transfer area (m²) and $T_{oi}$ is the temperature at the inner surface (K) of the oven’s structure component $i$ such as the wall, ceiling or floor. Together with the heat transfer equation introduced earlier, Eq. (1), which now includes Robin boundary conditions to connect the heat fluxes at the interface between the oven structure and external (ambient) or inner-oven environment, the blow-down cooling process is simulated, with results shown in Fig. 6.

Note that, long cooling periods have a negative effect on production efficiency as operators can only enter the oven after breakages once the temperature is below a safe limit. Figure 6a shows the cooling profile for the existing structure, while Fig. 6b displays the cooling profile for an oven with 50 mm of insulation on the oven walls and floor, both label the process temperature and the safe temperature for oven entry. As can be seen from Fig. 6a, b, the time taken to reach the safe temperature is 2 h for the case without insulation, whereas the insulation reduces it to approximately 15 min. This represents an 87.5% reduction which can save an estimated 202 bly downtime.

This analysis shows that the oven structure has a significant impact on oven temperature as heat retained within the structural thermal mass results in long cooling periods. Insulating the walls and floor benefits the operation and productivity of the oven system and also helps to deliver a consistent thermal regime to the product ensuring uniform cure and enhanced product quality. Process improvement enhances the process performance which has a positive economic impact as productivity and results in superior quality product to be manufactured.

Process parameter optimisation

Process parameter optimisation is the final stage of the improvement approach. Pask et al. (2014) present a Six
Sigma DMAIC (design, measure, analyse, improve, control)-based methodology for parameter optimisation that is adapted for this application. When applying the DMAIC methodology to this oven, the aim identified is to establish optimal process parameters to reduce energy consumption by minimising system airflow and to improve temperature uniformity by minimising cold air ingress through the oven slots. Figure 7 displays the process variables within the oven system affecting energy consumption and temperature uniformity including a direct fired gas burner/heater box, three fans (F), five dampers (D) and the ducting/recirculation system. The dashed line passing through the oven represents the web path.

Fans and dampers offer the most reliable and practical way to reduce energy consumption and improve temperature uniformity in this oven system. Experimental analysis of the process highlights that the three fans (supply, recirculation and exhaust fans) have the largest impact on system airflow. Furthermore, fan control is the most practical option for parameter optimisation because variable speed drives (VSDs) are already installed. Minimising airflow by reducing fan VSD inverter setting (%) is straightforward; however, an optimum oven pressure negativity must also be maintained to ensure that harmful flames do not exit the oven and to limit the ingress of cold air into the oven, which has a detrimental effect on temperature uniformity. All three fans affect oven negativity which is determined by the supply and exhaust flow rates.

Detailed process optimisation using measurements and control experimentation has been performed for the fan settings for reduced energy consumption and improved temperature uniformity. It suggests to alter inverter settings on the supply, recirculation and exhaust fan while measuring the exhaust and slot flow. Figure 8 shows the
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Fig. 8 Optimisation plot for fan speed configuration

Optimal D = 0.39877 m

Desirability 0.39877 %

Exhaust minimum
\( y = 3.9803\)
\( d = 0.22095\) m

Slot Flow
\( y = 1.3807\)
\( d = 0.99068\) m

Supply % 100.0

Recirc % 100.0

Re 100.0

Recommendations

Understanding the interaction between heat energy and the product is necessary in oven improvement projects. Actual and ideal thermal regimes should be compared in the product understanding phase, which can help to evaluate the effectiveness of the oven and identify areas for potential process improvement. Furthermore, it is important for process engineers to interact with both product developers and operators during all the phases of an improvement project. Developers have a detailed knowledge of the product and its components, while operators have greatest familiarity with how the process behaves on a daily basis.

Product quality is often the limiting factor within energy-reducing modifications. Therefore, establishing optimal thermal regimes from both quality and energy perspectives can indicate how oven improvements can be aligned to manufacturing strategy. Key opportunities for process improvement are often in the areas of temperature uniformity, effect of thermal mass and equipment reliability.

Conclusion

This paper presents an approach for industrial manufacturing ovens to reduce energy consumption and enhance product quality, simultaneously. The methodology develops product understanding, process improvement and process parameter optimisation. An iterative approach is practical in industrial scenarios where the knowledge gained from each phase can impact on observations made.
Previously, the link between product quality and energy consumption should have greater emphasis as it is a vital factor for manufacturers to tackle their energy consumption. A manufacturer places greater emphasis on generating a profit by creating superior quality products rather than by reducing energy consumption; therefore, emphasizing the link between energy and product performance can help in more energy-reducing activity within the process.

The iterative approach has been applied to a 1 MW industrial festoon oven that cures a layer of adhesive resin to a backing. Generat...
Generic Approach to Sustainability Improvements in Manufacturing Ovens

Frederick Pask, Peter Lake, Aidong Yang, Hella Tokos and Jhuma Sadhukhan

Abstract Improving industrial ovens is an important objective for sustainable manufacturing due to their significant energy consumption and impact on final product quality. A generic approach for sustainable oven development is presented that focuses on reducing the environmental impact of the oven and manufacturing superior product. The approach focuses on developing product understanding, process improvement and process parameter optimisation. An application example for an oven is presented, in which understanding of cure was developed to highlight how temperature variation affects product quality. This led onto process improvements that developed temperature uniformity and system responsiveness by lowering the thermal mass of the oven structure; resulting in 89% reduction in heating and cooling times respectively, saving 202 h of annual downtime. Process parameter optimisation was applied and saves 25% of natural gas consumption per year. The approach is flexible and can be replicated throughout the manufacturing industry.

Keywords Industrial oven • Sustainability • Optimisation • Energy saving • Product variation
1 Introduction

Industrial ovens are commonly found throughout the manufacturing industry and are used for curing, drying, or baking. They are used for continuous or batch operations, with energy being supplied directly or indirectly. An oven’s performance, compared to the best available practice, decreases over time due to structural/mechanical degradation, technology advancements or changing process requirements. There is potential for sustainability improvement in many existing industrial ovens.

Heating applications consume almost 1/5 of all industrial energy [1], and as ovens are an important heating process they have a substantial energy footprint. Energy saving within heating processes is relatively common throughout literature [2, 3]. However, research mainly focuses on minimising energy across an entire manufacturing process, rather than within a unit. Although very beneficial, site wide process improvement is often unfeasible due to limitations in existing technologies, space availability, layout restrictions, heat losses, disruption on production, financial viability, etc. Reducing energy consumption of oven units offers a focused and feasible approach to energy saving. But consideration of how it affects efficiency of the other assets in the factory is needed.

Creating a sustainable oven system considers social, environmental and economic factors. Increasing efficiency and decreasing waste has a positive effect on the environment while improving the oven’s capability to manufacture quality product has economic impacts. Process variation impacts product quality and should be reduced. Inconsistent processes impact on performance, cost, safety of a product and efficiency. Safety of workers being a key social impact of oven operation. Understanding process variation has many benefits, and is critical for a manufacturer to be competitive. It can be used to develop better products, avoid excess precision, minimise defects, allow for faster transition between products, deliver cost reduction and to reduce scrap [4]. Tools such as Total Quality Management, and specifically Six Sigma, are used to highlight areas of an oven process which need improving, but can also establish modification plans [4]. The same principals have been applied to reduce energy within industrial ovens by 29 % [5]. Research has highlighted the important link between product quality and energy reduction [6].

Throughout literature, there is a lack of focus on improving industrial oven performance from a holistic viewpoint, as well as industrial operability analysis and clear improvement techniques which can be applied in practice [7]. This paper presents a general management approach for industrial ovens that aims to increase the oven’s sustainability. By following the approach it is more likely to achieve energy saving, process variation reduction and product quality enhancement. The paper is structured by presenting a methodology for holistic oven improvement, followed by a description of each stage. An application example is presented to demonstrate the intended use.
Generic Approach to Sustainability Improvements ...

2 Methodology

A generic approach to improving industrial ovens includes three stages:
1. Product understanding
2. Process improvement
3. Process parameter optimisation

Each stage of the approach should be completed in order and highlights the importance of product understanding for enabling oven improvement projects. The order of activities is important for correct decisions to be made at the correct time, allowing for maximum benefit.

2.1 Product Understanding

Product understanding provides insight into what is required from the process to deliver a product which performs to specification. It aims to understand what affects product quality, which can be the determining factor for many modification projects. This work acts as an enabler to determine the viability of future projects, by understanding risks associated with projects or by quantifying potential quality improvements. It is important to establish this knowledge at the beginning of the improvement approach, because it will enable the right decisions to be made quickly.

2.2 Process Improvement

Process improvement develops operability and oven capability under current process settings. Analysis of the system evaluates how close to its original specification the current process performs, which can identify areas of process improvement. This can then be developed to exceed and enhance the oven’s original capability. Improvements are likely to be physical changes to the oven system e.g. upgrading equipment or installing additional hardware. Reducing process variation, increasing operability, controllability and energy efficiency are all important aims of this stage. Process settings are set based on product understanding. Therefore, the development of product understanding can identify process constraints and potential process improvements.
2.3 Process Parameter Optimisation

Process parameter optimisation is the final step of this approach. The optimisation procedure questions whether the existing process settings can be altered in order to give benefits to process variability, product quality as well as energy consumption. Optimisation involves detailed analysis of process variables through empirical or theoretical approaches. Energy reduction is a key target in this stage, with the optimisation of process variables often being cost effective. This is the final stage because optimisation of a process should only be completed once satisfied with the physical set up of the system.

3 Case Study: Industrial Oven Improvement

In order to demonstrate the intended use, the approach has been applied to a festoon oven that cures adhesive resin to a backing film. Energy is supplied to the oven with direct fired gas burners with fumes exhausted to atmosphere. The oven performs its task reliably, however it was identified as an area of improvement and energy saving because a significant proportion of the site’s gas consumption is consumed within it, and it is the first oven in the process line, thus significantly impacting on cure.

3.1 Process Specific Flowchart

Figure 1 presents a flowchart which interprets the high level generic approach for this specific manufacturing application. It shows the specific steps taken through this oven improvement project.

![Flowchart](image)

Fig. 1 Process specific flowchart
3.2 Product Understanding

A gap in product understanding was knowledge of how temperature variation affects adhesive resin curing. The webbed product is in repeating loops as it moves through the oven. Temperature profiling was conducted to understand existing variation. Probes were attached to the web as it moved through the process. Figure 2 shows the average cross web temperature deviation for one product above and below its set point. As well the average temperature variation, the analysis also determined that there was greater variation at the start and end of the process than during the middle stages.

Knowledge of cure was required to understand the impacts of temperature variation on product quality. The cure of a resin is represented on a scale of 0-1, and is a measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive [8]. Understanding cure can help identify the most appropriate process strategies. In this particular case, it was not known what level of cure was being achieved in the process, or the level of cure that should be targeted. The resin was analysed using Differential Scanning Calorimetry (DSC); an established technique for the modelling of curing kinetics of epoxy based resin formulations. The Arrhenius nth order equation is one of the most common kinetic curing equations; shown in Eq. (1).

\[
\frac{dx}{dt} = Z e^{\left(\frac{E_a}{RT}\right)}(1 - x)^n \tag{1}
\]

where \(x\) is the conversion of cure, \(t\) is the time, \(Z\) is the reaction constant, \(E_a\) the activation energy, \(R\) the gas constant, \(T\) is the absolute temperature, and \(n\) is the order of reaction. Equation (1) is used for data fitting and regression, and is deemed to be generic for modelling cure kinetics [9]. Figure 3 displays the exothermic...
region of heat flow from DSC plots for different heating rates, which determines parameters for the Arrhenius nth order kinetic model (numerical values have been removed due to confidentiality). The total enthalpy of the curing reactions (area under the curve) for each heating rate would be the same if the reactions were identical. Figure 3 shows this is not the case highlights how heating rate variation results in different final cure levels; important for product quality.

Alternative kinetic curing models were considered [10–12], but given the complex nature of the adhesive formulation being analysed, it was determined that Arrhenius is the most robust model, and provides sufficient information for this study. As the heating rates A, B and C represent a feasible variation in the oven, this study has demonstrated process temperature variation can significantly affect product cured when exiting the oven, and thus significantly impacting quality. This indicates that consistent heating rates decrease quality variation (e.g. product life), which has important economic and environmental benefits due to reduced waste and customer satisfaction. Product understanding highlights an aspect of the process that needs improving and can be used as justification for process modifications.

3.3 Process Improvement

Process improvement aims to improve system controllability, process variation and energy consumption. Product understanding highlighted the importance of delivering a uniform temperature profile which includes vertical temperature variation and system responsiveness to temperature change. Products are run sequentially (there may be 8 product changes per week) and discrete run sections can be exposed to different temperature profiles (hottest profile 50% higher than the coolest). Structural thermal mass limits the oven’s ability to change temperature resulting in long start up periods, unnecessary downtime during breakdowns. The existing wall structure consisted of thermal blockwork, insulated cavity, and an external block skin. A modification to install a 50 mm insulation layer to the inside of the oven wall is being proposed. Insulation to the inside oven wall will develop a uniform temperature profile. The aim is that this will improve the environmental and economic performance of the oven due to energy saving in heat loss and unnecessarily long downtime and also improve product quality.
Appendix E

Generic Approach to Sustainability Improvements ...

A model was used to calculate the conductive heat flow through the wall structure using the common heat transfer equation shown in Eq. (2); where \( \rho \) is the density, \( C_p \) is the specific heat capacity, \( T \) is the temperature, \( t \) is the time, \( k \) is the thermal conductivity, and \( x \) is the layer thickness. The boundary conditions assumed a constant internal oven temperature, and a constant external ambient air temperature. For heating, the initial condition was an ambient oven wall temperature. Numerical solutions were obtained by discretising the model with a time interval of 1 s, and a layer thickness of 5 mm. Once a steady state temperature profile was reached, this profile was taken as the initial condition to model the cooling effect. For cooling, burners are turned off and the fans replace warm air with ambient air. Ambient temperature external air was the boundary condition.

\[
\rho C_p \frac{dT}{dt} = k \frac{d^2 T}{dx^2}
\]  

(2)

Figure 4 displays the output from the model for the wall cooling temperature profiles with and without a 50 mm insulation facing (numerical values have been removed due to confidentiality). The model output reduces heat up is reduced by 9 h (90 % reduction), and as shown in Fig. 4 the cooling time for the inner wall temperature to a safe temperature is reduced by 3 h 30 min (88 % reduction). These reductions will save an estimated 202 h of downtime per year. Furthermore, the energy held within the fabric of the structure will also be reduced by 64 %. This work benefits operation, productivity and deliver a consistent thermal regime to the product, ensuring uniform product quality. Process improvement has increased system capability which positively impacts on economic and environmental aspects.

![Fig. 4](image)

Fig. 4 Heat transfer model output for cooling through the wall structure, a cooling of existing blockwork, b cooling of insulation faced blockwork.
of an oven. Process improvement builds on knowledge gained from product understanding to identify areas of the process which can be improved. In this industrial case study, installing insulation to the inside of the oven wall will help increase productivity, save energy and assist in the development of a uniform and consistent temperature profile.

3.4 Process Parameter Optimisation

The final stage of the holistic approach is process parameter optimisation. The aim is to identify optimal settings that reduce energy consumption while also helping to create a uniform temperature profile. Pask et al. [5] outlined an optimisation methodology for industrial ovens which was used for process parameter optimisation. This systematic approach follows the Six Sigma principles and applies them for an oven scenario. Figure 5 displays the system under consideration; showing a direct fired gas burner heater box, three fans (F), five dampers (D), and the ducting and recirculation system. The dashed line passing through the oven represents the web path. Baseline air studies found that the system exhaust flow was 16 kg/s, it was decided that process capability would allow for this to be reduced and still

Fig. 5 Oven system under considering; showing fans (F), dampers (D), ducting, and the oven chamber with web path (dashed line)
Table 1 Optimised settings for three process fans

<table>
<thead>
<tr>
<th>Fan</th>
<th>Existing setting %</th>
<th>Optimised setting %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Recirculation</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Exhaust</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>Exhaust flowrate (kg/h)</td>
<td>16</td>
<td>12</td>
</tr>
</tbody>
</table>

deliver sufficient cure to the product (flowrates at all points in the system omitted due to confidentiality).

Analysis of all process variables outlined that three fans (supply, recirculation and exhaust fans) had the largest impact on system air flow. Oven negativity ensures furnaces stay within the oven and impacts the ingress of cold air into the oven, which has a detrimental effect on temperature distribution. The goal is to establish a fan setting to minimise system air flow while maintaining a very slightly negative pressure within the oven. Three experiments were conducted to achieve a minimum exhaust flow and a target slot flow. Table 1 displays the existing and optimised settings for the three process fans in the oven system. Here, the recirculation fan has been increased to maintain flow through the burner and the exhaust fan has been minimised. The optimal fan settings would decrease system exhaust flow by approximately 25%, thus reduce gas energy consumption within the direct fired burners by 25%. Uncertainty is due to the unpredictable nature of the oven negativity; affected by local atmospheric conditions and process temperature. Process optimisation has been demonstrated to save energy and reduce process temperature variability therefore enhancing product quality.

Optimal settings for key fans were identified which, along with insulating the inside of oven walls, reduce energy and develop temperature uniformity. Interaction between the three stages of the generic approach must be considered. In this study, it was ensured that reducing system airflow does not negatively impact on cure. Increased product understanding should allow for product quality to not be harmed, and hopefully improved, during process improvement and process parameter optimisation.

4 Recommendations

The approach outlined in this paper is adaptable to many scenarios and highlights the importance of establishing thorough product understanding before embarking on any modification plans. Assessing which process variables (e.g., oven pressure negativity) affect quality (e.g., product life) indicates areas of the possible improvement. It is also important to understand how the heat energy is required by the product. Oven performance should be evaluated to identify opportunities for process improvement by looking at: temperature uniformity, effect of thermal mass, equipment reliability etc.
Appendix E

5 Conclusion

This paper presents a general approach to industrial oven improvement which starts with developing product understanding, leading on to process improvement and finishing with process parameter optimisation. Improving the sustainability of ovens should be an important strategy for manufacturers due to their high energy consumption, effect on product quality and potentially hazardous work environment for employees. Such a methodology has not previously been applied to industrial ovens.

Generating product understanding identifies conditions necessary to create the desired product, thus highlighting areas of quality improvement. In the industrial case study presented, cure characterisation using DSC analysis of adhesive resin has been presented. The data showed that a feasible heating rate variation within the oven can result in dramatically different cure conversion when material exits the oven impacting on product quality and affecting economic and environmental dimensions of the oven. Process improvement involves ensuring the system hardware is performing well under the current process settings, while also establishing a way to enhance process capability. In the industrial case study, it was identified that the process could be improved by installing an insulation layer to the inside of the oven wall. This would result in 89% reduction in heating and cooling times, saving 202 h of annual downtime. Process parameter optimisation alters the process settings to maximize performance. In the industrial case study, process parameter optimisation was conducted and identified fan setting that reduce energy consumption by minimising system flow and oven pressure negativity for better temperature uniformity and energy saving. The optimisation has reduced fuel gas consumption by 25%.

This research looks to increase the sustainability of industrial ovens by improving the environmental and economic aspects of an industrial oven system. By providing an industrial case study example, the applicability of the proposed approach has been demonstrated. Further work is necessary to link product understanding to energy consumption, as this concept is a tool that can enable further sustainability enhancement in the manufacturing industry.

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References

Appendix E

Appendix F: Journal Paper in Cleaner Production

Sustainability indicators for industrial ovens and assessment using Fuzzy set theory and Monte Carlo simulation

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ABSTRACT
Industrial ovens play a significant role in many manufacturing and process industries. Despite the desire to enhance sustainability throughout this sector, research looking to improve the sustainability of industrial ovens is in its infancy. This paper presents seven sustainability indicators to assess potential oven investment; these include system air flows, production efficiency, operating costs, quality, capital investment, toxicity and employment opportunity. The indicators are straightforward and can be scored with readily available data and have been weighted by industrial experts. A hybrid multi-criteria approach using Fuzzy set theory and Monte Carlo simulation has been developed to help evaluate the sustainability of alternative improvement options. The approach is required as previous methodologies only present desirability as a singular figure and therefore decision makers are not provided with sufficient information on associated risk. The presented approach incorporates uncertainty throughout, and gives option desirability in terms of mean, standard deviation and variance. The risks using this method are better understood and can significantly aid industrial decision makers. The sustainability indicators and hybrid approach have been demonstrated using a case study in the manufacturing industry, to identify the most sustainable way to increase cure conversion within an oven. Amongst the three options: increasing oven size, increasing oven temperature and new product formulation, increasing oven temperature shows the highest desirability while new product formulation though has a lower desirability has the highest certainty. Furthermore, a cumulative desirability distribution plot gives a basis to select option that is aligned with the business’s risk strategy.

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1. Introduction

Sustainable development concepts and practices are becoming increasingly common throughout the manufacturing industry, however research focused on increasing the sustainability of industrial ovens is still in its infancy. Ovens consume a sizeable portion of industrial energy (IEER, 2013), and significantly affect the performance capability and environmental impact of a manufacturing process. The three dimensions of sustainability can be applied to have specific relevance for industrial ovens. For example; environmental concern can result in pollution and waste. The ability to manufacture quality product affects economic performance, and employee’s safety falls within the social dimension of sustainability. This research aims to enable cleaner and more responsible production in the manufacturing environment.

Sustainability indicators can be used to inform decisions and provide insight into complex issues by balancing the three sustainability dimensions (Kwatra et al., 2016). They can be used to compare differences between potential oven improvements, and therefore help to develop a sustainable industry. Application of indicators for technology assessment can be used in two ways; a) to assess the overall performance of a particular technology system, or b) to compare at least two technology systems. Indicators should be applied using ‘fit for purpose’ approach rather than making a generic set of indicators fit for all applications (Dewulf and Van Langenhove, 2008). Indicators can be quantitative or qualitative, and can fall within the categories of descriptive, performance or efficiency indicators (Hallstedt, 2015). A UN report (Nations, 2007) sets a number of guidelines when selecting appropriate indicators.
Appendix F

Nomenclature

\[ c \] sustainability indicator
\[ A \] Alternation option
\[ w \] Weight factor
\[ x \] Score of indicator
\[ n \] Number of indicators
\[ m \] Number of alternative option
\[ f(A, B) \] Triangular fuzzy number
\[ x_{ni} \] Normalized score for each indicator
\[ w_{ni} \] Weighted fuzzy number
\[ c_{ni} \] Normalized weighted score for each indicator
\[ \alpha_{ni} \] Randomly generate number
\[ D \] Desirability

In summary, they should be simple and informative and approaches should be uncomplicated and without a large number of sub sets. Indicators should be responsive to changes in the environment and related human activities. They should be clear, unambiguous and provide basis for comparison.

Environmental indicators may include greenhouse gas emissions, energy consumption, re-usability of resources, toxicity of emissions, re-use of materials, recoverability of waste materials and efficiency (Dowoff and Van Langenhove, 2005). Proposed economic indicators relevant to industrial owns involve net sales, operational production costs, gross margin and overhead costs (Pannell and Glenn, 2000). And finally, social indicators tend to be toxicology or safety related (Al-Shammari et al., 2007; 2010).

As well as identifying a suitable set of sustainability indicators, it is also important to analyze the indicator set with a method of multi-criteria analysis appropriate for that particular application. For instance, Tokics et al. (2012) were able to develop a methodology for integrated sustainability performance assessment specifically for processing industries. Multi-criteria analysis is used to aid decision making by gathering information on a variety of criteria, or indicators, to understand how multiple objectives can best be achieved. It enables for indicators with different units to be assessed alongside each other. Fuzzy set theory is a long established field within multi-criteria analysis which presents a way to deal with problems which had previously been unsolvable by traditional multi-criteria analysis. It deals with approximation rather than exact reasoning (Zadeh, 1965), allowing for uncertainty to be assessed rationally by associating a grade of desirability to quantitative and qualitative data (Begic and Aljan, 2007; Nielsamp et al., 2015; Fu, 2008). Fuzzy optimization is seen to be more robust than crisp optimization with Pareto optimum analysis as no iterative steps are required (Tay et al., 2011).

Fuzzy indicator sets including both qualitative and quantitative indicators have more recently been demonstrated as a method to assess sustainability indicators (Mendoza and Prabhu, 2004; Ducey and Larson, 1999), by enabling objective decision making of indicators, which may themselves be subjective. Uncertainty can result from imprecise measurements, average or outdated data using proxies and incomplete data, approximations in modelling, normalisation and weighting (Sathukhan et al., 2014) assessment and linguistic descriptors by experts and their assigned values, in case of qualitative indicators. Uncertainty in the assessment of sustainable development causes issues when trying to solve problems using conventional multi-criteria analysis. Probabilistic theory is based on classical set theory which is defined by yes or no statements, and requires hard thresholds. Whereas fuzzy theory is based on multi-valued logic and relates to events which have no well-defined meaning, allowing for the fuzziness to describe a degree to which an event occurs (and soft thresholds) (Cornelissen et al., 2001). Fuzzy sets do not have to be in or out, but are rather given a degree of membership. Fuzzy methods are useful when assessing complex or ill-defined problems, and can therefore be very useful for sustainability indicators. Fuzzy indicator uncertainty is not due to error or randomness, but attributed to generally, ambiguity or vagueness.

Monte Carlo simulation is a sampling technique used for result generation that depends on parameters given from probability distributions. Studies have been conducted that utilize both Monte Carlo simulation and Fuzzy set theory to evaluate sustainability indicator sets (Sadeghi et al., 2010; Lodj, 2004). Monte Carlo simulation requires the generation of random values to input into the model, where the model variables have a known range (as determined from a distribution type) but uncertain values in a particular event. Model variables can be provided by the triangular distributions generated in Fuzzy set theory. This technique is commonly used as a way to incorporate uncertainty into quantified risk assessment. Additionally there are guidelines for uncertainty analysis using Monte Carlo simulation for estimation and mitigation of uncertainty during environmental impact assessment (ECC, 2006).

Although there has been valuable research into improving different aspects of industrial owns (Pask et al., 2014; Khatri et al., 2015; Miah et al., 2014; Pask et al., 2016), an indicator set to assess overall owns sustainability has not previously been developed. This research is to provide a specific set of sustainability indicators that can be used to inform investment decisions for own improvement and therefore provide a useful tool for manufacturers and process industries. The indicators are designed so that two or more alternative options can be evaluated to prioritize investment to deliver a more sustainable own. To achieve this, a method of multi-criteria analysis using Fuzzy set theory and Monte Carlo simulation has been developed which aims to assist decision makers by incorporating uncertainty into a final desirability level, thus providing information so that investments can be aligned with risk strategies. The applied methodology is an adaptation of previous approaches, and has been tailored to present findings in a way which is particularly useful for decision makers in the manufacturing and process industries. The indicator set and methodology have been demonstrated using an industrial case study.

2. Methodology

A set of sustainability indicators for industrial owns is to be identified in Section 3. This section details a hybrid method of multiple criteria decision making using Fuzzy set theory and Monte Carlo simulation to analyze sustainability indicators. Fig. 1 outlines all important stages of the methodology, while the rest of this section details each step fully.

The methodology entails a multi-criteria decision analysis tool to identify a preferred option, \( A_m \), amongst \( m \) alternatives. The method evaluates alternative options through the use of indicators, Equation (1) displays the multi-criteria decision analysis matrix, where \( C_i \) is the sustainability indicator, \( x_{ni} \) is the indicator score, \( m \) is the number of alternative option, and \( n \) is the number of indicators. When using such an approach, the sustainability indicators and alternative options for system improvements should be defined by expert insights. The list should not be exhaustive; the indicators should be the most important ones without overlap between them and those that make a difference in the overall sustainability performances between options and thus help in the selection of the overall best option (Sathukhan et al., 2014). The sustainability indicators of industrial owns are presented in
Appendix F

Fig. 1. Flowchart of approach used for assessment of criteria using fuzzy optimization.

Section 3.

Specific criteria C₁, C₂, …, Cₙ
Weighting alternatives W₁, W₂, …, Wₖ

\[
x = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1k} \\ x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mk} \end{bmatrix}
\]

(1)

As previously stated, fuzzy set theory is applied to multi-criteria decision problems to handle uncertainty of quantitative and qualitative criteria (Fu, 2008). It is likely that sustainability indicator sets will have both quantitative and qualitative information, and will inherently have a degree of uncertainty; thus highlighting why fuzzy theory is appropriate for sustainability indicator analysis. The indicator score \( \hat{x}_{im} \) is presented as a triangular fuzzy number \( (\hat{x}_{min}, \hat{x}_{mid}, \hat{x}_{max}) \). A triangular fuzzy number describes the membership grade function that a value for an indicator will occur; \( \hat{x}_{mid} \) is the lower limit membership grade equal to 0, \( \hat{x}_{max} \) is the most possible value membership grade equal to 1 (can be interpreted as the mean), and \( \hat{x}_{min} \) is the upper limit membership grade equal to 0.

Fuzzy numbers for quantitative indicators can be identified in measurable units. The task is to then convert quantitative scores \( x_{im} \) to normalized values between 0 and 1, so that indicators can be directly compared to each other. Indicators are either a benefit or a cost having positive or negative effects on the system performance, respectively; benefit indicators should be maximized, while cost indicators should be minimized. Equation (2) shows the calculation to normalize scores for benefit indicators, and Equation (3) for cost indicators. The normalized score \( \hat{x}_{im} \) is calculated using \( \hat{c}_i \) as the maximum score for \( c_i \), and \( \hat{c}_b \) the minimum score for \( c_i \).

\[
\hat{x}_{im} = \left( \frac{\hat{c}_i}{c_i} \right) \hat{x}_{im}
\]

(2)

\[
\hat{x}_{im} = \left( \frac{\hat{c}_b}{c_i} \right) \hat{x}_{im}
\]

(3)

Qualitative assessment can be used for indicators where it is difficult to use numerical figures due to uncertainty or the nature of indicator. Fuzzy set theory is advantageous as it can analyze quantitative and qualitative data simultaneously. Table 1 displays the linguistic variables and associated fuzzy numbers used in this study. Linguistic variables are used in standard fuzzy partition to enable for an indicator score to be given a linguistic term, which then corresponds to a fuzzy set and numerical value. The numerical value for each linguistic variable was chosen to provide the necessary range of desirability on a scale of 0–1, and also to provide sufficient resolution and distinction between the potential indicator scores that are seen in the case study example in Section 4.

Weighted fuzzy numbers \( \hat{w}_i \) and the normalized scores \( \hat{x}_{im} \) are used to determine \( \hat{c}_{im} \) using Equation (4). The weighting factors are necessary as the indicators will not all have equal importance when creating a sustainable system. Weights should be determined objectively through consultation with experts working in relevant fields. For each alternative option, \( \hat{c}_{im} \) values provide a triangular distribution of desirability of each sustainability indicator.

\[
\hat{c}_{im} = \hat{w}_i \cdot \hat{x}_{im}
\]

(4)

The Monte Carlo simulation is now used as a tool to evaluate \( \hat{c}_{im} \) values simultaneously and to determine which alternative option is favourable while understanding uncertainty in the final results. \( \hat{c}_{im} \) values are fuzzy numbers and therefore represent a triangular distribution that can be used as the model input variables for Monte Carlo simulation. Each alternative option now has a number of distributions of desirability. The aim is to combine all these distributions into one meaningful level of desirability for each alternative option. Monte Carlo simulation is used to numerically solve the problem by aggregating information in a stochastic way.

Random numbers are generated using the distributions provided by \( \hat{c}_{im} \); the lower, mode and upper inputs for the triangular distribution are provided by fuzzy numbers \( (\hat{c}_{min}, \hat{c}_{mid}, \hat{c}_{max}) \). The count of random numbers generated must be deemed sufficiently large; 10,000 random numbers is reasonable (Gani and Talib, 2015).

The next task is to identify the transfer linking equation; used to combine all the indicators into one, enabling for overall desirability of each alternative option to be calculated. As the data is normalized and weighted, the indicators can be directly assessed against each other. Equation (5) displays the transfer linking equation, where \( \hat{D}(A_{im}) \) is the total desirability for alternative option \( A_{im} \) and \( \hat{r}_{im} \) is a randomly generate number for a given indicator.

\[
\hat{D}(A_{im}) = \frac{\sum_{i=1}^{n} \hat{r}_{im} + \hat{r}_{i2} + \hat{r}_{i3} + \ldots + \hat{r}_{in}}{n}
\]

(5)

Equation (5) is used to generate a data set of the total desirability for each alternative option. A normal distribution plot of the desirability can be created which determines the mean, variance and standard deviation; used to rank each alternative option. The higher the mean, the more desirable the option. The spread of data is used to indicate result certainty, which is a key advantage of using the proposed methodology. Furthermore, a cumulative distribution plot of each alternative option can be created to provide decision makers which outcome findings that can be aligned to a
business's risk strategy. This is a development on previous methodologies as it provides decision makers with information of the desirability uncertainty.

Fig. 2 demonstrates why knowledge of desirability uncertainty is essential. Each triangle represents the triangular distribution of desirability for alternative options A1, A2, A3 and A4 with the peak showing the mean, and the edges showing the variance. A2 has a greater mean desirability than A1, however there is more uncertainty in A2's results. A business may decide that it prefers A1 despite the decreased mean, because they have more confidence that the desirability will be within an acceptable range. Therefore Monte Carlo simulation presents the spread of data rather than just the mean, thus providing decision makers with all available information.

A hybrid approach has been presented for the analysis of multiple criteria/indicators using fuzzy set theory and Monte Carlo simulation. It requires basic statistical software and can be used across a wide range of industrial scenarios. The following sections identifies specific sustainability indicators for industrial ovens, and then the intended use of methodology and indicator set is demonstrated in Section 4.

3. Sustainability indicators for ovens

A generic schematic diagram of an oven system is shown in Fig. 3. This understanding, sustainability indicators for industrial ovens have been identified. Table 2 shows the overview of the seven sustainability indicators chosen for industrial ovens. The table highlights the primary sustainability theme for each indicator, indicator name, ID, suggested units, type of indicator, a short description and a rational behind the indicator selection. To keep the assessment framework simple, it has been intended that each indicator affects a primary sustainability theme (i.e. environmental, economic or social), although it is worth noting that in reality some indicators will impact more than one sustainability dimension. For instance, toxicity affects humans who interact with the oven process, and will also have environmental impacts e.g. as in the case of toxic airborne particulates which interact with local environmental receptors. The remainder of this section then goes into further detail describing all seven indicators.

These seven indicators are directly related to industrial ovens, and the indicator scores are practically obtainable in real life industrial scenarios. A limited number of indicators increases the practicality and ease of use in an industrial setting. Greenhouse gas emissions as a potential indicator was not chosen because the system airflow and production efficiency indicators either control, or are determining factors for, GHG emissions and would capture any changes in GHG emissions. Similarly, other cost items such as gross margin and overhead costs are not separate indicators as the operating cost indicator captures the majority of this information.

![Fig. 2. Graphical representation of desirability for alternative options A1, A2, A3, A4.](image)

![Fig. 3. Generic schematic diagram of oven system.](image)

3.1. Detail for specific indicators

3.1.1. System air flow

The target is to minimize the system air flow which passes through the oven system to a safe level while ensuring oven performance; resulting in reduced energy demand and environmental impact. This indicator is linked to the total energy and gas emissions and is a suitable measure for the industrial setting of this study. Low energy consumption is desirable to minimize an oven's impact on the environment as well as being cost effective for the business. There will be a lower limit for system air flow, and this can be determined by oven function or safety constraints (i.e. drying force, humidity, lower explosion limit). The physical setup of an oven can impact this indicator and optimization techniques can be used to minimize system air flow.

3.1.2. Production efficiency

Production efficiency is how efficient the system is in terms of production time compared to downtime. The downtime incorporates breakdowns, stoppages, heat up, cool down and can be affected by many aspects of the oven hardware, software, automation and interaction. A reliable and robust oven system can be constructed, and a well planned maintenance regime can ensure the oven equipment is working effectively. This ensures safety for workers, and has a large impact on the profitability of the process. Minimal unplanned downtime results in more manufacturing opportunity and positively impacts the production efficiency.

3.1.3. Operating costs

Operating costs are classified in two categories: fixed and variable operating costs. Fixed costs are independent of production rate/quantity and include maintenance, labor, taxation, insurance, overheads etc. Whereas variable rates are dependent on production and includes raw material and utilities (Sahlström et al., 2014). This is an economic performance indicator and in many instances the operating costs are easily obtainable. The main aspects of oven modification which impact this indicator are the energy consumption, heating technology, materials for product formulation and human interaction.

3.1.4. Quality

Product quality is significantly affected by oven temperature uniformity and distribution. Product formulation can also affect the product quality. Quality is monitored within a manufacturing facility, however quality improvements can be overlooked when reviewing project options due to difficulty attributing quantitative improvement of a final product to a single unit oven process. In such cases, a linguistic description of quality improvement can be a suitable method of qualitative assessment. Table 1 displays the linguistic descriptions, and associated fuzzy numbers that can be used for this indicator. On top of the obvious waste issues resulting from poor quality, inconsistent products (that are still within quality tolerances) affect customer satisfaction and loyalty. This quality indicator captures both the economic and environmental
Table 2
Sustainability indicators.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Name</th>
<th>ID</th>
<th>Units</th>
<th>Type</th>
<th>Description</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Env.</td>
<td>System air flow</td>
<td>$c_1$</td>
<td>kg/h</td>
<td>Cost</td>
<td>The mass flow rate through the system</td>
<td></td>
</tr>
<tr>
<td>Production Efficiency</td>
<td>$c_2$</td>
<td>%</td>
<td>Benefit</td>
<td>The efficiency of the system to produce product compared to operation time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Econ.</td>
<td>Operating costs</td>
<td>$c_3$</td>
<td>£/hr</td>
<td>Cost</td>
<td>Cost of running the oven, including labour, energy, materials.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quality</td>
<td>$c_4$</td>
<td>–</td>
<td>Benefit</td>
<td>Quality improvement to product (High, medium, low, or no impact)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Capital investment</td>
<td>$c_5$</td>
<td>£ (10000)</td>
<td>Cost</td>
<td>Capital investment needed to get project off the ground</td>
<td></td>
</tr>
<tr>
<td>Soc.</td>
<td>Toxidity</td>
<td>$c_6$</td>
<td>ppm</td>
<td>Cost</td>
<td>Residual monomer in formulation and exhaust used to assess the impact on humans and environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Employment Opportunity</td>
<td>$c_7$</td>
<td>–</td>
<td>Benefit</td>
<td>The employment opportunities generated from an oven, job numbers and skill level required</td>
<td></td>
</tr>
</tbody>
</table>

dimensions of sustainability.

3.1.5 Capital investment

Although improvements should result in financial benefits to the business, there is often an initial capital investment required which has negative consequences to cash flow. The capital required for a modification should be estimated to a good degree of accuracy during an option appraisals phase of a process. This indicator influences the economic performance of a business. It is clear that any business would want to have highest economic margin and minimize costs. Thus, it is important to understand the direct costs of expenditure for a modification option.

3.1.6 Toxidity

Toxic materials or exhaust emissions are common in many industrial heating processes and can be harmful to humans and the environment. At the very minimum toxicity must comply with regulations, but exceeding regulatory standards is beneficial. This indicator signifies the potential health impact by the evaluation of the extent of residual monomers in the product. The product formulation has the highest effect on the toxicity of the industrial oven process. In the authors' industrial setting, the level of residual monomers is a suitable measure of this indicator. This indicator is primarily assessing the social aspect of industrial ovens.

3.1.7 Employment opportunity

The employment opportunity is an indicator of social performance and is viewed as a benefit. Employment opportunity can be increased by creating more jobs, or by increasing the skill level of existing jobs so that personnel have greater responsibility. Increasing the number of jobs can only be achieved if production demand increases, which can benefit a business, but also the individual. Increasing the skill level increases job satisfaction, responsibility, and development. The head count required to operate an oven needs to be carefully calculated to ensure sufficient, but not excessive, manpower; this indicator ensures that workers are viewed as important stakeholders in such decisions. Linguistic descriptors are used to evaluate the potential change in employment opportunity, with the descriptions and associated fuzzy number found in Table 1.

3.2 Weighting of indicator

The importance of each indicator to sustainable decision making has been assessed by experts in the field of industrial oven management and sustainability. Fifteen individuals were asked to score each indicator between 0 and 1 for its importance when developing a sustainable oven (0 being least important, 1 being of most importance). This method of identifying indicator weightings is appropriate because it reflects the opinions of decision makers in industry and has sufficient input from experts across all three dimensions of sustainability. Fifteen opinions were deemed an appropriate number for the purpose of this study because of the balance of individual knowledge background. Fig. 4 displays the results with the box plot showing the median, lower and upper quartiles for each indicator. Triangular fuzzy number weightings, shown in Table 3, are given to each indicator which are then used in the multiple criteria analysis; the lower quartile becomes $f_1$, the median becomes $f_2$ and the upper quartile becomes $f_3$.

4. Case study

To demonstrate applicability, the indicator set and methodology has been used to evaluate three different modification options to improve the sustainability of an industrial oven system. The oven’s purpose is to treat an adhesive resin. It was identified that insufficient treatment was occurring in the current process, and therefore options were developed that would ensure sufficient treatment. The aim is to identify which of the three options outlined in Table 4 is the most sustainable.

Using the sustainability indicators for ovens provided in Section 3, Table 5 displays the initial indicator scores for each alternative option. Furthermore, in Table 5 the values for $c_2$ (maximum score for $c_1$ and $c_2$ minimum score for $c_4$) are given. These are used in Equations (2) and (3) depending on whether the indicator is a cost or a benefit; therefore, the cost criteria have 'n/a' in the $c_2$ column, and the benefit criteria have 'n/a' in the $c_4$ column. Using the sustainability indicators for ovens provided in Section 3, Table 6 shows the normalized quantitative and qualitative indicator scores $(x_{n,q})$ for each alternative option using Equations (2) and (3). These were determined using product and process understanding of the existing oven, as well as knowledge of how the alternative option would impact on each indicator. Linguistic values were used to generate fuzzy numbers for indicators $c_4$ and $c_5$.

The weightings for each indicator, $w_i$, is multiplied by $x_{n,q}$ using Equation (4) for the $c_{n,q}$ values, which are displayed in Table 7. Using the triangular distribution given by the fuzzy numbers $(f_{n,q})$ for each indicator and option, 10,000 random numbers were...
Table 3
Weighting of indicators using fuzzy numbers.

<table>
<thead>
<tr>
<th>Name of indicator</th>
<th>Criteria ID (εs)</th>
<th>Weighting using Fuzzy numbers (fL, fM, fU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System air flow</td>
<td>c1</td>
<td>(0.3, 0.7, 0.9)</td>
</tr>
<tr>
<td>Production Efficiency</td>
<td>c2</td>
<td>(0.4, 0.5, 0.6)</td>
</tr>
<tr>
<td>Operating costs</td>
<td>c3</td>
<td>(0.7, 0.8, 0.9)</td>
</tr>
<tr>
<td>Quality</td>
<td>c4</td>
<td>(0.3, 0.7, 0.9)</td>
</tr>
<tr>
<td>Capital investment</td>
<td>c5</td>
<td>(0.5, 0.6, 0.7)</td>
</tr>
<tr>
<td>Toxicity</td>
<td>c6</td>
<td>(0.9, 0.8, 0.7)</td>
</tr>
<tr>
<td>Employment opport.</td>
<td>c7</td>
<td>(0.3, 0.5, 0.7)</td>
</tr>
</tbody>
</table>

Fig. 4. Box plot of weighted scores for sustainability indicators.

Table 4
Alternative descriptions.

<table>
<thead>
<tr>
<th>Alternative ID (A)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Increase the size of the oven to increase time the product is exposed to a thermal regime. The current process is constrained in terms of product throughput.</td>
</tr>
<tr>
<td>A2</td>
<td>Increase temperature within the oven. Increasing the temperature will result in more cure. This option will increase the temperature within the oven by 5°C.</td>
</tr>
<tr>
<td>A3</td>
<td>Change the product formulation. Use an additive in the product formulation in order to catalyze to the curing reaction.</td>
</tr>
</tbody>
</table>

Table 5
Individual indicator scores.

<table>
<thead>
<tr>
<th>Criteria ID</th>
<th>A1 (x1)</th>
<th>A2 (x2)</th>
<th>A3 (x3)</th>
<th>ε1</th>
<th>ε2</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c2</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c3</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c4</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c5</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c6</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>c7</td>
<td>(20, 21, 22)</td>
<td>(15, 16, 17)</td>
<td>(10, 11, 12)</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Generated using statistical software. The overall desirability of each alternative option was calculated by combining the information from all seven indicators, using the transfer linking Equation (5). Fig. 5 shows the histogram plot of desirability for each alternative option. It shows that the mean desirability of A1 is 0.38 (left hand side plot), the desirability of A2 is 0.48 (right hand side plot), and the desirability of A3 is 0.62 (middle plot). Therefore, A2 (to increase oven temperature) is the most sustainable option as it has the highest desirability. The advantage of presenting findings in this way is that the spread of data can be visualized; thus enabling more informed decision making. Fig. 5 shows the largest spread of data for A3 suggesting greatest uncertainty in the mean value of its desirability compared to the other two options. The narrowest spread of A2 suggests that this carries the greatest certainty. But it...
Appendix F

Table 6

<table>
<thead>
<tr>
<th>Criteria ID</th>
<th>Weight using fuzzy numbers (w_j)</th>
<th>A_1 (x_{1j})</th>
<th>A_2 (x_{2j})</th>
<th>A_3 (x_{3j})</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_1</td>
<td>(0.7, 0.7, 0.9)</td>
<td>(0.45, 0.48, 0.50)</td>
<td>(0.83, 0.89, 1.00)</td>
<td>(0.85, 0.95, 1.00)</td>
</tr>
<tr>
<td>c_2</td>
<td>(0.4, 0.6, 0.8)</td>
<td>(0.62, 0.77, 0.92)</td>
<td>(0.66, 0.85, 1.00)</td>
<td>(0.77, 0.85, 1.00)</td>
</tr>
<tr>
<td>c_3</td>
<td>(0.7, 0.8, 0.9)</td>
<td>(0.76, 0.73, 0.86)</td>
<td>(0.80, 0.84, 1.00)</td>
<td>(0.81, 0.88, 0.94)</td>
</tr>
<tr>
<td>c_4</td>
<td>(0.3, 0.7, 0.9)</td>
<td>(0.55, 0.70, 0.85)</td>
<td>(0.15, 0.36, 0.45)</td>
<td>(0.35, 0.56, 0.65)</td>
</tr>
<tr>
<td>c_5</td>
<td>(0.6, 0.8, 1)</td>
<td>(0.01, 0.08, 0.11)</td>
<td>(0.50, 0.60, 1.00)</td>
<td>(0.25, 0.33, 0.56)</td>
</tr>
<tr>
<td>c_6</td>
<td>(0.1, 0.2, 0.3)</td>
<td>(0.05, 0.15, 0.30)</td>
<td>(0.05, 0.15, 0.30)</td>
<td>(0.05, 0.15, 0.30)</td>
</tr>
</tbody>
</table>

Table 7

Normalized and weighted \( w_{ij} \) fuzzy matrix.

<table>
<thead>
<tr>
<th>Indicator ID</th>
<th>A_1</th>
<th>A_2</th>
<th>A_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_1 )</td>
<td>0.32, 0.33, 0.45</td>
<td>(0.58, 0.64, 0.80)</td>
<td>(0.58, 0.64, 0.80)</td>
</tr>
<tr>
<td>( e_2 )</td>
<td>0.25, 0.38, 0.55</td>
<td>(0.38, 0.42, 0.60)</td>
<td>(0.33, 0.40, 0.40)</td>
</tr>
<tr>
<td>( e_3 )</td>
<td>0.46, 0.56, 0.69</td>
<td>(0.02, 0.17, 0.30)</td>
<td>(0.59, 0.71, 0.85)</td>
</tr>
<tr>
<td>( e_4 )</td>
<td>0.28, 0.49, 0.77</td>
<td>(0.08, 0.21, 0.41)</td>
<td>(0.18, 0.35, 0.49)</td>
</tr>
<tr>
<td>( e_5 )</td>
<td>0.08, 0.09, 0.10</td>
<td>(0.25, 0.35, 0.45)</td>
<td>(0.01, 0.02, 0.05)</td>
</tr>
<tr>
<td>( e_6 )</td>
<td>0.47, 0.70, 1.00</td>
<td>(0.35, 0.56, 0.78)</td>
<td>(0.35, 0.51, 0.78)</td>
</tr>
<tr>
<td>( e_7 )</td>
<td>0.02, 0.08, 0.21</td>
<td>(0.02, 0.08, 0.21)</td>
<td>(0.02, 0.08, 0.21)</td>
</tr>
</tbody>
</table>

5. Discussion

There will inevitably be a degree of cross-over between indicators; however it is important to minimize replication in order to not skew findings. In the indicators presented, the operating cost includes fixed and variable costs. Fixed costs are those which do not change with sales or production, and it is important to try to separate these fixed costs from capital investment. Variable costs include the utility costs and will therefore be impacted on by the system air flow, which although is primarily an environmental measure, does impact on energy consumption. These have been taken into consideration and it was decided that the seven indicators are separate enough not to affect overall finding.

Indicator weighting can change depending on the desired purpose of the process being studied. A commodity business might have greater concern with initial capital or operating costs. However, a highly profitable industry would perhaps be less interested in costs and more interested in quality and throughput. The indicators and weightings presented in this paper have been designed for one particular industrial application, and there could therefore be industrial scenarios when they are not suitable. It is recommended that before any potential use, an evaluation of the industrial process and its supporting business should be conducted to fully understand the suitability of the presented indicator set.

Decision making when assessing sustainability from the perspectives of different disciplines is a difficult task. It is rare that one option can be definitively determined as more sustainable than another. There is often a significant degree of uncertainty, as well as cross-over, with the sustainability performance of alternative
options; therefore the method of multi-criteria analysis should reflect this. Being able to incorporate uncertainty using fuzzy set theory has enhanced the practical application of sustainability indicators, however many previous approaches have fallen short on presenting uncertainty in the final results. The methodology used in this paper aids the decision making process further by providing all the information so that decisions can be aligned to business strategy.

Overall desirability of an option gives an indication of the sustainability. As the model in Equations (1)–(5) incorporates scores of individual sustainability indicators given by experts as independent variables, these could be varied to examine their impacts on the sensitivity of the overall desirability of each option. If a particular indicator is found to impact desirability to an extent a different option becomes favourable, then the decision makers should investigate its uncertainty due causes (increasing the depth of the analysis) and involve more experts in the field (expanding the breadth of the analysis).

6. Conclusion

Sustainability indicators for technology assessment are essential to help decision makers identify suitable options. Having said this, the development of rigorous sustainability assessment for industrial ovens is in its infancy. In this study, a specific set of seven sustainability indicators has been developed for the assessment of an industrial oven, including system air flow, production efficiency, operating costs, quality, capital investment, toxicity and employment opportunity. Each indicator has been assigned a weighting through consultation with industrial oven and sustainability experts. The indicators have been chosen so that all aspects of sustainability are incorporated, and also with consideration of what information is readily available for industrial engineers. Such an indicator set for technology assessment of ovens has not previously been reported.

As well as identifying a specific set of sustainability indicators, this paper presents a hybrid method of multiple criteria decision analysis which can be used to evaluate the sustainability of alternative improvement options. The methodology incorporates fuzzy set theory and Monte Carlo simulation. Both techniques are established tools to help decision makers in multiple criteria analysis by incorporating uncertainty into the analysis. They are commonly used with sustainability indicators due to the inherent uncertainty which is common with many indicators, however the approach presented in this paper is more effective due to the fact that it incorporates uncertainty into the final desirability. This provides industrial decision makers with greater information than many previous methodologies.

The sustainability indicators and multiple criteria analysis has been demonstrated in an industrial environment by evaluating three alternative options for oven improvement at a manufacturing facility. It was identified that the level of adhesive cure being achieved in the oven was not sufficient. Consequently, three alternative options to increase cure conversion were developed. The predicted performance of each alternative option was scored against the seven sustainability indicators, before analysis was performed to determine its desirability. Using a histogram of normal distribution of desirability and a cumulative distribution plot, the most sustainable option to provide improved treatment of an adhesive resin was identified, which is increasing the oven temperature. The hope is that this research can help to increase sustainability of industrial ovens throughout the manufacturing and process industries.

Acknowledgments

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Appendix F

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