



**A Framework for Waste Heat Energy
Recovery within Manufacturing**

by

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A Doctoral Thesis

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Synopsis

This thesis reports on the research undertaken to recover the inevitable thermal energy loss within manufacturing processes and their related activities required to support the operation of a manufacturing system. The principle objective of this research is to develop a framework which describes a methodology to identify various opportunities for recovery of waste heat energy throughout a manufacturing facility and production processes to provide decision support for selection of an appropriate heat recovery technology.

The research contributions are divided into three major parts:

(1) The first part reviews the relevant literature across broad spectrum of energy management approaches, state of art heat recovery technologies and current waste heat recovery research in industry.

(2) The second part introduces a 'Waste Heat Energy Recovery' framework which consists of following four steps:

- i. Waste heat sources and sinks are identified through a waste heat survey from both the plant and process perspectives.
- ii. A quantitative and qualitative assessment is used to evaluate a number of defined parameters for the identified waste heat sources and sinks.
- iii. These quantitative and qualitative descriptors are then used to match sources and sinks to optimise potential heat recovery which can support the selection of appropriate heat recovery technology.
- iv. Final recommendations are provided for manufacturers to identify an appropriate technology to recover waste heat energy.

(3) This final part of the thesis describes the development and implementation of a software tool based on this framework to support technology selection for minimising thermal loss in a manufacturing environment.

The applicability of the proposed research concepts have been demonstrated via two industrial case studies; a compressed air system for a PCB manufacturing plant and a cupola at an engine block casting plant. The detailed analysis of available waste heat energy enables a systematic approach to minimising thermal losses cross manufacturing processes and associated supporting activities allows the assessment of heat recovery technologies for heat recovery and reutilisation. Although the scope in this thesis is targeted towards the existing manufacturing facility, the flexibility offered by

the waste heat energy recovery framework and associated decision support software tool allow for their employment to other scenarios such as, reconfigurable manufacturing systems or at the design stage of a manufacturing system.

In summary, the research has concluded that energy minimisation within a facility is not limited to technological process improvement or operational changes, but can also be achieved by taking a more holistic view of energy flow. It is envisaged that this methodical approach to implementing waste heat energy recovery within manufacturing should form part of a standard practice for new and old facilities striving to reduce overall energy demand.

Abbreviations

AE	Auxiliary Energy
CES	Cambridge Engineering Selector
CH ₄	Methane
CO ₂	Carbon Dioxide
CRC	Carbon Reduction Commitment
DE	Direct Energy
DfEM	Design for Energy Minimisation
EPE	Embodied Product Energy
EMS	Energy Management Systems
ER	Efficiency Ratio
ESDU	Engineering Science Data Units
HVAC	Heating Ventilation Air-Conditioning
IE	Indirect Energy
KERS	Kinetic Energy Recovery Systems
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Analysis
LMTD	Logarithmic Mean Temperature Difference
RI	Recovery Index
RMS	Reconfigurable Manufacturing System
RTD	Resistance Temperature Devices
UI	Utilisation Index
WHER	Waste Heat Energy Recovery
WHRS	Waste Heat Recovery Software
WI	Waste Index

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Chapter 1 Introduction

Energy in its various useable forms is an essential part of life in 21st Century. It has become a significant concern for governments, industry and the public because of increasing consumption, depletion of energy carrying resources, and the contribution to climate change. Global energy demand is expected to increase by 50% by 2040 compared to current levels (IEA, 2013). The manufacturing sector is a particularly important consumer since it is directly and indirectly responsible for one-third of global energy use (IEA, 2014). UK industry takes up about one quarter of the national final energy consumption and generates 32% (DECC, 2014a) of heat-related CO₂ emissions, mostly through deriving energy from fossil fuels. The development and proliferation of alternative renewable energy technology is considered to be too slow to fill the energy requirements of industry.

Heating or heat related processing treatment is one of the largest energy consumers in UK industry, accounting for about 72% of total energy demand according to the Digest of UK Energy Statistics (DUKES). Of the processes, the publication indicates that 31% of which is used for low temperature processes and 22% is used for high temperature processes (DECC, 2013). Furthermore, the most heat intensive processes have been identified to be within the cement, ceramics, iron and steel, glassmaking, chemicals, refinery, paper and pulp and food and drink industries.

It has been shown in numerous industries that the improvement of site energy efficiency or reduction of CO₂ emissions could reduce overall operating costs and improve competitiveness of UK businesses (Worrell *et al.*, 2009; Mori *et al.*, 2011). Indeed, targeting energy efficiency improvement is often a cost effective measure, leading to reduced CO₂ emissions, improved productivity and improved energy security. Energy efficiency is generally defined as using less energy while maintaining the same level of services (Sengupta & Pike, 2012), which can be achieved either by decreasing total energy use, or increasing production rate per unit of energy used. In the UK, the Carbon Trust designed the Industrial Energy Efficiency Accelerator (IEEA) programme to work collaboratively with various industrial sectors to support and deliver energy efficiency improvements in manufacturing processes (Carbon Trust, 2014). Also, performance indicators like the Carbon Trust Standard have been developed to measure carbon emissions and energy use reduction by organisations in industry, commerce and the public sector (Carbon Trust, 2014). Performance indicators such as these focus on quantifying carbon emissions as an end point impact of energy consumption, thus serving as a proxy for measuring energy efficiency indirectly.

For manufacturers to improve environmental performance through increased energy efficiency there are two major approaches: the use of renewable energy and the reduction of energy consumption. The development of renewable energy technologies has been relatively slow and is considered a costly option (Turner, 1999). The more cost effective solution would be to reduce energy demand, which can be further divided into three options: (1) reduction in total activity (Sorrell, 2015), (2) energy management to minimise energy consumption (Seow & Rahimifard, 2011) and (3) recovery and use of waste energy (Vallack *et al.*, 2011). The first two options are considered to be proactive approach because they allow manufacturers to identify not only goals and objectives but will determine what they want to achieve in the short- and long-term and anticipate possible challenges whilst the last option is classed as a reactive approach because waste energy is inevitable (Schobert, 2013) after the manufacturing processes are undertaken and manufacturers can respond to this issue with waste energy recovery solutions. A reduction in activity is not an ideal solution as manufacturing activities are mostly driven by make to sell business models and would thus impact profitability. Research activities have focussed on improving energy efficiency through energy management (Thollander *et al.*, 2007), but have had limited success. This may be because they require substantial time investment (Sandberg & Söderström, 2003), effort and expenditure (Doty & Turner, 2012). Although some of the activities may be beneficial in the short term, the impact may be insignificant. There has been research (Antizar-Ladislao *et al.*, 2010) into energy recovery yet it may be considered to be the least developed option of the three (see Figure 1.1).

There are several perspectives to efficient energy consumption within a manufacturing system, as depicted in Figure 1.2. These include energy supplies, minimising energy consumption and waste energy recovery. These three areas do not stand in isolation, but are inherently connected. It has been observed in many industries that available energy supplies influences production scheduling, requiring planning for when energy will be required to manage energy sources accordingly. The ability to recover waste energy will depend on the type of processes used and frequency of use (Ammar *et al.*, 2012).

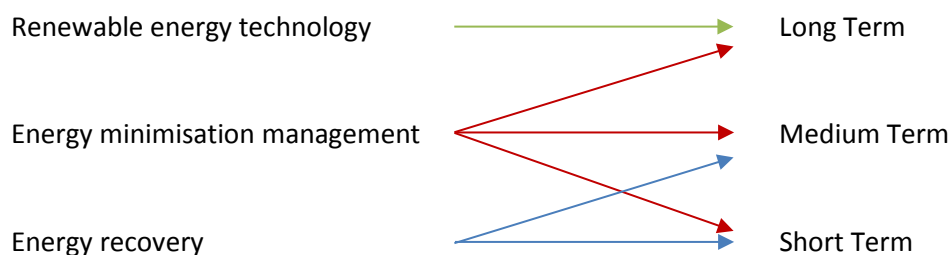


Figure 1. 1 Approaches to improvement of energy efficiency within manufacturing

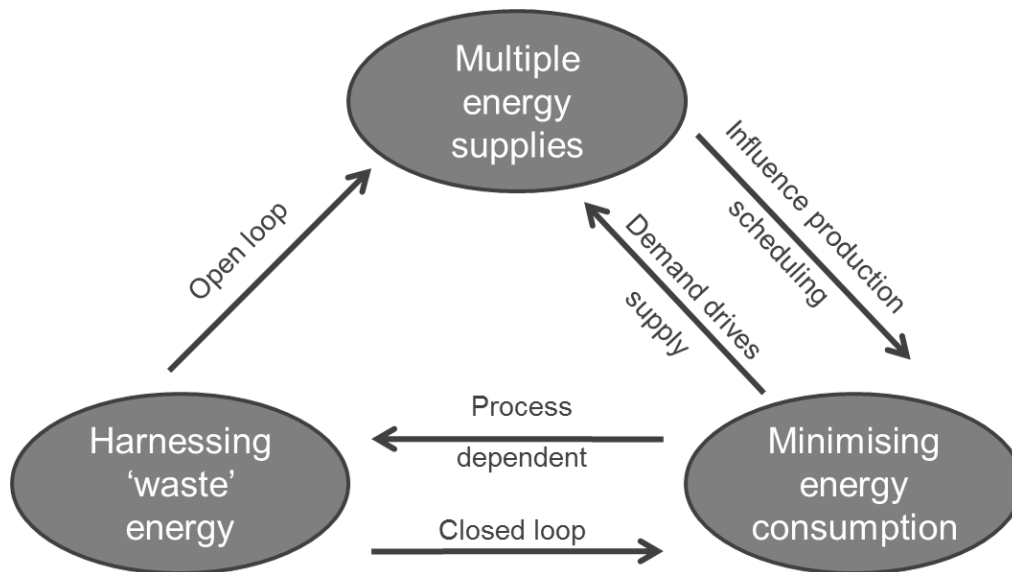


Figure 1. 2 Three perspectives of energy lifecycle in manufacturing systems

Another important opportunity for minimisation of energy is the reutilisation of waste energy, by feeding back directly into the process from which it is extracted, or by feeding indirectly into the main factory supply. The research presented in this thesis examines how waste energy recovery can play a part in energy efficient manufacturing.

Waste energy recovery in manufacturing applications is a complex subject and covers a wide range of issues from identification of waste energy sources, suitable energy demand and the practical implementation of appropriate waste energy recovery technology. Many of the existing analysis tools that focus on energy recovery are either very broad in scope, such as the McKenna model; a techno-economic model that aims to establish the economic potential for heat recovery in UK industry (DECC, 2014b). Industrial case studies are very specific in their attribution of energy recovery, for example low-grade heat recovery in UK food and drink industry undertaken by Law *et al.* (2012) and Ammar *et al.* (2012), where energy recovery was focused on very specific processes, with a limited range of technologies considered. This highlights the need for a decision support tool based on a systematic framework, applicable to a generic industrial environment, but that can also be applied specifically in manufacturing systems. As such, the scope of the research reported in this thesis focuses on the development and application of this framework.

The research reported in this thesis investigates the recovery of waste heat energy in a manufacturing environment. This includes identifying both source and sink for waste heat energy. This requires the ability to assign a number of quantitative and qualitative attributes to it, so as to provide environmental engineers with an indication of what, where, when and how much waste

heat energy is available during the production phase. This provides a systematic approach to recover waste heat energy and enhance overall energy efficiency improvements. This is achieved through:

- Development of a framework to identify waste heat sources and potential sinks, defining them quantitatively and qualitatively define them by assigning a number of attributes to highlight the most beneficial and economical solutions for improvement.
- Development of a software tool to handle the complexity involved in modelling according to the framework. This includes facilitating the calculation of waste heat energy lost through processes, selection of appropriate waste heat recovery technologies to be implemented and to support “what if” scenarios, through varying process parameters, production campaign, temperature, flow rate and temporal profile.

The structure of this thesis comprises three main sections: (1) research background and overview, (2) theoretical research, software development and case studies, and (3) research discussion and conclusions (Figure 1.3).

The research background and overview section consists of five chapters. Chapters 2 to 6 provide a review of a range of research issues regarding the use of energy and methods for improving energy efficiency, as well as specific examinations of where energy is lost in a manufacturing environment and how it can be recovered. The research context, aims and objectives and scope are defined in Chapter 2. This research definition is supported by a detailed literature survey, which reviews energy management in Chapter 3, state-of-the-art technologies in energy recovery in Chapter 4 and the latest waste heat recovery research in Chapter 5. Chapter 6 provides a brief review of common research methodologies and explains in detail the methodological approach adopted within this thesis.

The theoretical research and development section comprises five chapters and highlights the thesis’s main contributions to research. Chapter 7 provides a brief overview of the waste heat recovery framework and the structure for which the research chapters are presented. Chapter 8 details the first step of the waste heat recovery framework, developed to allow manufacturers to identify where unutilised waste heat sources occur and corresponding potential sinks where demand can be met with recovered heat energy. Chapter 9 provides detailed analysis of the identified heat sources and sinks, with a number of assigned quantitative and qualitative attributes defined in this research. Chapter 10 describes the development of a software tool to aid manufacturer’s decision making for selection of the most appropriate technology according to calculated environmental and economic benefits. Chapter 11 describes case studies that demonstrate the use of the waste heat energy

recovery software tool and illustrating the extent to which energy efficiency can be improved using this framework.

The final section of the thesis presents the conclusions from the research. Chapter 12 provides a summary of the research findings and assesses the outcomes of the research against the objectives set out in Chapter 2. In Chapter 13, a number of conclusions are drawn and opportunities for further development of the research are outlined.

Additional calculations and programing data to support the case studies are included in the appendices, along with three papers based on research reported in this thesis; one published and two provisionally accepted.

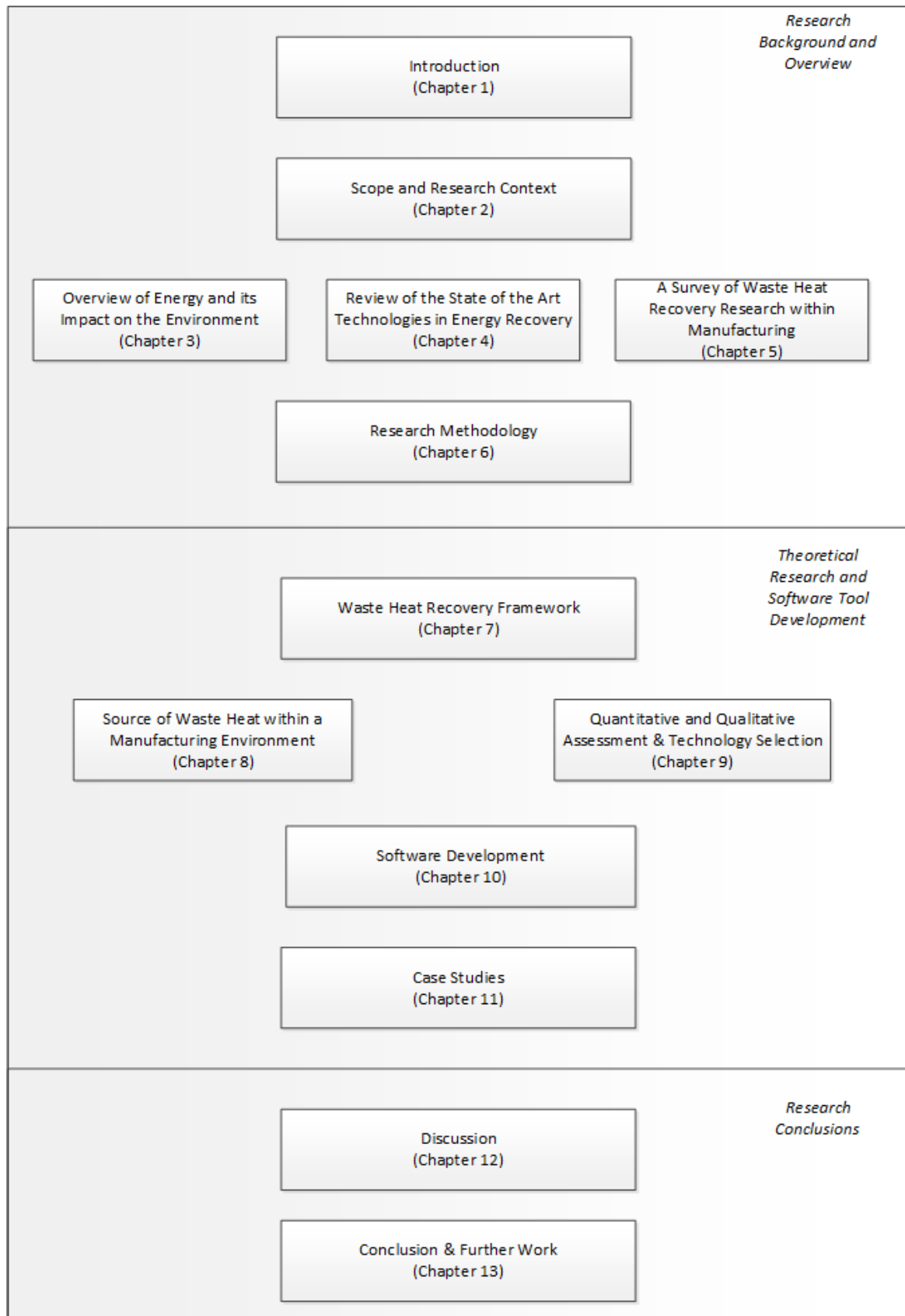


Figure 1. 3 Thesis Structure

Chapter 2 Aims and Scope of Research

2.1 Introduction

This chapter describes the research context and questions, the overall aims, objectives and research scope of the work presented in this thesis. Sections 2.2 and 2.3 describe the research context and the primary research questions considered in this research whilst sections 2.4 and 2.5 highlight the research objectives and their scope.

2.2 Research Context

In the 21st Century, fossil fuels remain the dominant component of the global energy grid. The depletion of these natural resources and increased environmental damage resulting from their use concerns governments, industry and the public. Coupled with the growing energy demand and the influence of emerging economies such as China and India, it has been projected that worldwide energy consumption will increase by more than 40 percent by 2035 (Chevron, 2014). Taking all new technology developments and policies into account, the world is still failing to put the global energy system onto a more sustainable path, currently over 80% of the global primary energy demand is met by fossil based fuels (Figure 2.1) (IEA, 2014). The problem is compounded by increased populations, development of ‘comfortable countries’ and industrial development based on economic drivers which hardly relegates energy or environmental consequences. New policy development, the introduction of economic incentives, widespread publication of environmental concerns has been ineffective (Blackman & Harrington, 2000).

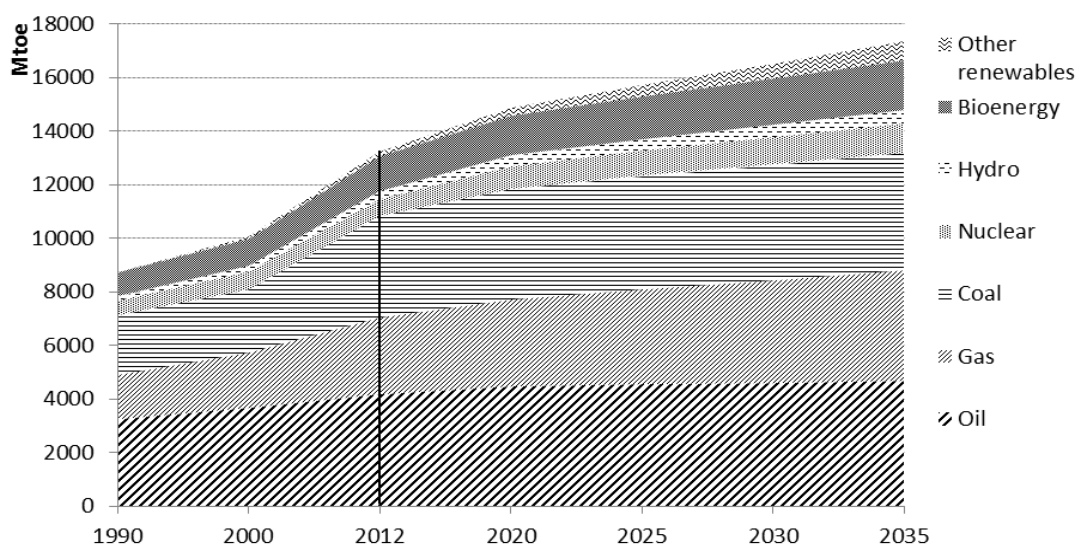


Figure 2. 1 World Primary Energy Demand, adapted from (IEA, 2014)

For the manufacturing industry, a reduction in activity is not an ideal solution as manufacturing activities are typically driven by production and sale business models (Spring, 2013). Reducing productivity would thus impact profitability, the primary objective of businesses. A large number of research programmes have sought to improve energy efficiency (Boyd *et al.*, 2008; Carbon Trust, 2014), but have not been hugely successful at achieving radical reductions on overall consumption. This is due to difficulties in implementing new technologies and operational procedures in companies, especially where the renewal of equipment happens only over long timescales. In general, it is often difficult to justify the time, expenditure and effort required to implement energy efficiency improvements in light of the financial cost against energy gains achievable. The third option described in Chapter 1, recovery of waste energy, has not been studied extensively in research. This may be due to the perceived low return in energy saving in comparison to the required effort and expenditure to implement such solutions. Energy recovery as an energy efficiency approach is consequently under-developed and forms the focus of this research.

As the research focusses on recovery of Waste Heat from various aspects of the manufacturing system, it is essential to clarify the manufacturing levels and energy recovery from 'plant', 'process' and 'product' perspectives.

'Plant' in this thesis refers to the factory buildings and associated infrastructure required in maintaining optimal production environment, i.e. space heating, lighting, compressed air systems, pressure etc.

'Process' in this thesis refers to the operational processes which includes the actions undertaken by the machines or equipment that aid the creation of value, i.e. material transformation, transport and storage etc.

'Product' in this thesis refers to 'materialised, artificially generated objects or groups of objects which form a functional unit, as defined by Krause *et al.* (1993). The product may contain different parts and maybe made up different materials and processed with different equipment.

In manufacturing, energy consuming activities generally fall under five levels ranging from detailed turret scale energy requirements to broad enterprise scale activities. These are useful for describing different energy requirements across various manufacturing activities, including enterprise, facility, machine cell, and turret levels (Vijayaraghavan & Dornfeld, 2010). Based on these five levels, the literature includes a significant amount of research has been carried out to improve energy efficiency of a wide range of manufacturing activities (for review of research work in these areas refers to Chapter 3).

At the enterprise level, Kara & Ibbotson (2011) identified that supplier location was a major factor that can increase overall energy requirements for the raw materials. Thus by selecting local rather than international suppliers, the use of energy intensive transport can be avoided. At the facility level, investment of capital in energy-saving equipment such as insulation and waste-heat recovery could reduce overall energy demand with little or no effect on product quality (Despeisse, *et al.*, 2012). At the machine cell level, most of the work involves process planning for improved energy performance. For example, Tan *et al.* (2006) combined manufacturing process planning and environmental impact assessments using check list analysis, proposing an optimal decision making method for new components that includes energy consumption as part of the sustainable development evaluation. At the machine level of manufacturing, Dahmus & Gutowski (2004) reported that machine tools with increasing levels of automation have higher basic energy consumptions which result from the amount of additional integrated machine components required. For example, CNC machines carry a number of key components such as pumps, hydraulic systems, and numerical control systems which dominate the energy consumption of the process. Turret level of the manufacturing system represents the actual material transformation process and is typically studied based on theoretical analysis. examples include the work of: Sarwar *et al.* (2009) who carried out a detailed analysis on the specific energy consumption of bandsawing different work piece materials; Rajemi *et al.* (2010) have looked at the minimal energy required for turning and the optimal conditions for machining a product and finally Kuzman (1990) who carried out an energy evaluation of the cold forming process.

There has been a substantial amount of work carried out across these different manufacturing levels to improve energy efficiency. However, it is sensible to suggest that energy recovery should not be applied to one manufacturing level only. WHE is potentially recoverable from facility level activities, from individual processes and from actual products as they leave their respective processes. Here, a focus on discrete manufacturing levels described by Vijayaraghavan & Dornfeld (2010), become less useful. Instead it may be useful to adopt another set of terminologies defined by Rahimifard *et al.* (2010) called the '3P perspective' which describes energy modelling techniques which use either the Plant, Process or Product as the central perspective. These three perspectives can be used to define potential sources of WHE and may be useful for identifying possible waste heat flows within a manufacturing facility (Figure 2.2). WHE available from plant level activities might include flue gases from boiler systems, heat generated by air compressors, or heat from lighting, all of which can be either concentrated or disperse.

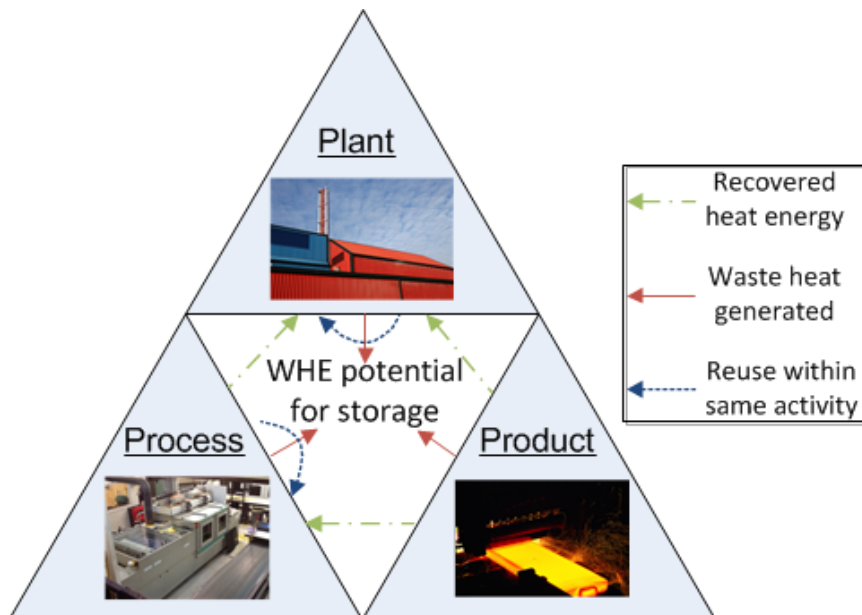


Figure 2. 2 Plant, Process and Product Perspective for WHE recovery

WHE available from process level activities may include sources such as heat from pumps and cooling fluids, exhaust gases as well as conduction and convection from hot castings (e.g. furnace). Finally, WHE from products will typically be in the form of heat emanating from hot bodies (e.g. cooling cast or kilned parts).

Within these categories it is then possible to identify potential sinks for where the waste heat can be reutilised. As shown in Figure 2.2, WHE is typically suitable for use at either the same manufacturing level, or cascaded to a level above. This is with the exception of the product level, in which case it is generally not feasible to reuse the energy outside of the context of a process.

2.3 Research Questions

This research addresses the inevitable thermal energy loss within manufacturing processes and related activities required to support the operation of a manufacturing system. The fundamental research question in this thesis is “How do we identify the quantity, quality and availability of waste heat from a manufacturing process, determine the maximum potential, and selection of the most appropriate technology for recovery of this energy?”

To be able to answer this fundamental research question, the following questions also need to be answered:

- What are the current obstacles for waste heat energy recovery and how should a taxonomy be developed for heat energy recovery within the manufacturing environment?

- How can we quantitatively and qualitatively describe waste heat energy in a way that allows systematic judgment for optimised recovery?
- How can waste heat sources and sinks be systematically compared for the most beneficial energy recovery opportunities? and
- Given the identification of the most suitable technology for heat energy recovery for a particular application, what information is required by manufacturers in order to implement the identified solution taking into account environmental and financial considerations?

2.4 Aims and Objectives

The overall aim of this research is to assign quantitative and qualitative descriptive attributes to potential WHE and to support manufacturers select the most suitable heat recovery technology for their specific applications.

In order to achieve this aim the following research objectives have been defined:

- 1) To review literature on energy management across various industrial sectors especially in the manufacturing discipline, on the state of art in energy recovery technology as well as the latest research in WHE recovery and software tools.
- 2) To generate a framework to systematically identify the waste heat energy sources, associated quantity and quality, ways of comparing the parameters with technology specification.
- 3) To develop a decision support software for the optimisation of heat energy recovery through examining the suitability of potential technology options.
- 4) To investigate the viability of using the WHE recovery framework and the decision support software by demonstrating the applicability through two case studies.
- 5) To document the result generated in form of a PhD research thesis

2.5 Scope of Research

The scope of this research is in line with its objectives, as defined in the remaining sections of this chapter.

2.5.1 To review literature on energy management across various industrial sectors especially in manufacturing discipline.

In order to position the research in the appropriate context, a comprehensive review of the research that comprises an overview of energy system in industry specifically study energy efficiency in the manufacturing sector, an overview of energy management related research, which includes Life-

cycle analysis, Life-cycle energy analysis and Cambridge Engineering Selector (CES), a review of energy management strategies in manufacturing sector in which an overview of five levels of manufacturing is considered, and also an understanding of exergy and its associated analysis. These will be discussed as part of the literature survey in Chapter 3.

2.5.2 To review the state of art in energy recovery technology and latest heat energy recovery research

To gain a better understanding of the Waste Heat Energy (WHE) Recovery, Chapter 4 & 5 takes a closer look at various energy recovery technology and latest waste energy recovery research on the 'Plant', 'Process' and 'Product' perspectives is required. There are many different methods and technologies for recovering waste energy in a manufacturing environment, such as kinetic energy from movement of the machine parts, chemical energy from reactions, thermal energy as a result of combustion and some other well established engineering cycles which enable heat energy recovery. The review will include various heat exchanger technologies, thermodynamic cycle, and some of the state of the art technology. In addition, the review examines currently existing waste heat recovery researches such as low grade waste heat energy recovery, energy recovery system for electric motor drive system and energy harvesting from vibration.

2.5.3 To generate a framework to systematically identify the waste heat energy availability and its potential demand

A framework for waste heat energy recovery will be developed to provide a structured approach by which opportunities and challenges arising in the manufacturing environment can be explored. The framework describes a methodology to identify various sources of waste heat throughout a manufacturing plant, production processes and product levels, and provides an overview of waste heat hotspots within the production system. This analysis is used to highlight opportunities for heat recovery, by capturing available waste heat with suitable recovery technologies and reuse, recycle or energy storage options in order to improve overall energy efficiency. This will be described in Chapter 7, 8 and 9.

2.5.4 To develop a decision support software for the optimisation of heat energy recovery through examining the suitability of potential technology options.

Based on the framework generated, a software tool that enables manufacturers to have a quick and simple implementation of such framework and access to decision making. The software tool designed for this framework allows data to be input into the program which is fed into the calculation module of the software. The software carries out mathematical operations to determine some of the key values which will then be utilised alongside the technology database to suggest a

number of waste heat recovery technologies for manufacturers to consider. A detailed description and demonstration of the software tool will be in Chapter 10.

2.5.5 To investigate the viability of using the WHE recovery framework and decision support tool by demonstrating their applicability through two case studies.

In order to investigate the viability of the research concepts and to highlight the applicability of the framework, the software tool will be assessed through a number of case studies. In this thesis, two industrial case studies of which one represents waste heat energy in the low temperature band whereas the other is associated with high temperature applications will be investigated using theoretical data, complemented by empirical data. Case study and analysis data will also be used to populate the software tool and provide opportunities for improvement. This will be discussed in Chapter 11.

2.6 Chapter Summary

In this chapter the context of the research has been identified, and research assertions are stated. Aims have been set and respective objectives have also been defined. The defined aims and objectives have been used to generate the scope of the research. The following three review chapters present an overview of energy management in manufacturing, state of art technology and latest research in WHE recovery.

Chapter 3 Review of Energy Management within Manufacturing

3.1 Introduction

Energy is playing an important role in our everyday lives, providing us with warmth, light, transport and production capabilities, amongst many other useful applications. With recent interest in future energy security, carbon emissions and associated concerns over rising fuel costs, there has been a significant escalation of research into energy saving strategies within industry. This section provides some fundamental knowledge of the role energy plays in our everyday lives and a detailed review on the various researches that has been conducted on measuring, analysing and modelling energy consumption within manufacturing. The current research in this field is divided into two main domains: 1) product perspective, and 2) manufacturing systems perspective. Both domains are described in detail.

3.2 Overview of Energy in Industry

Global demand for energy has risen inexorably in the last 150 years in step with industrial development and population growth. At the present time, we are totally dependent on an abundant and uninterrupted supply of energy for living and working. It is a key ingredient in all sectors of modern economies. Effectively, society as we know it is underpinned by this crucial resource, with energy demand predicted to continue to rise by at least 50% by 2030, (IEA, 2013). This is due to developing countries like China and India seek to fuel their rapid economic growth (see Figure 3.1).

This upward trend in energy consumption however is not replicated in every country. In the UK, industry accounted for 25% of the energy consumed, 2.22 quadrillion Btu, in 2007, with transport at 28% and the domestic sector being the largest consumer at 30% (Figure 3.2). In primary energy equivalents, industrial consumption accounted for 47,620 ktoe (thousand tonnes of oil equivalent) in 2011, some 1,076 ktoe (or 2%) lower than 2010 (DECC, 2013). This reduction shows efficiency improvements in electricity generation, changes in the structural nature of the industrial sector, and efficiency of final use in industry during the transformation of primary into secondary fuels for final consumption.

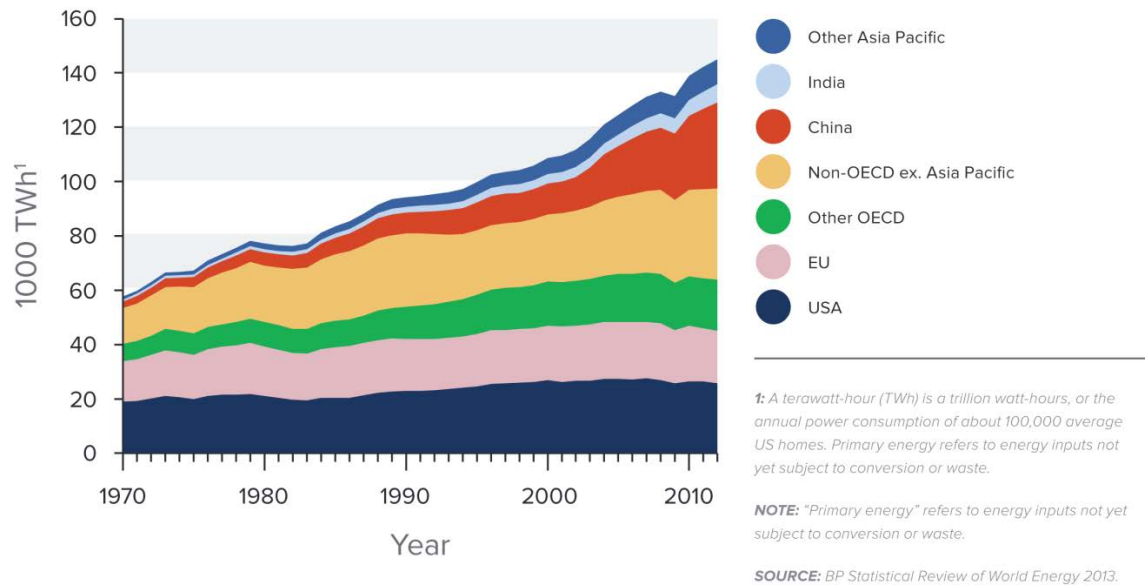


Figure 3. 1 Global primary energy consumption by region 1970-2012, adapted from Review of World Energy (2013)

Despite this recent reduction in UK industry energy consumption, the manufacturing sector still represents a major source of demand. Energy efficiency in the manufacturing industry is becoming an increasingly important issue due to the rising costs of electricity and fossil fuel resources (The Global Commission on the Economy and Climate, 2014), as well as the tough targets for the reduction in greenhouse gas emissions outlined in the Climate Change Act 2008 amongst other UK and EU legislations. More recently, organisations are becoming increasingly proactive in being environmentally responsible with respect to their processes and products, and now consider the environmental challenge a competitive business opportunity rather than as an obstacle (Singer, 2013). According to the latest updated data from the Department of Energy and Climate Change (DECC) annual publication in 2015, heat use (space heating, drying/separation, high temperature processing and low temperature processing) was responsible for 72% of total industrial consumption (DECC, 2014b). Low temperature processes being the most significant at 31% of the total energy consumption by industry (Figure 3.3).

Different sectors have different energy needs, for example within the industrial sector, high temperature processing dominates energy consumption in the iron and steel, non-ferrous metal, bricks, cement, glass and potteries industries. Low temperature processes are the largest end use of energy for the food, drink and tobacco industry. Space heating and lighting are the main end uses in engineering (mechanical and electrical engineering and vehicles industries). Compressed air processes are mainly used in the publishing, printing and reproduction of recorded media sub-sector (Pellegrino *et al.*, 2004). Refrigeration processes are mainly used in the chemicals and food and drink industries.

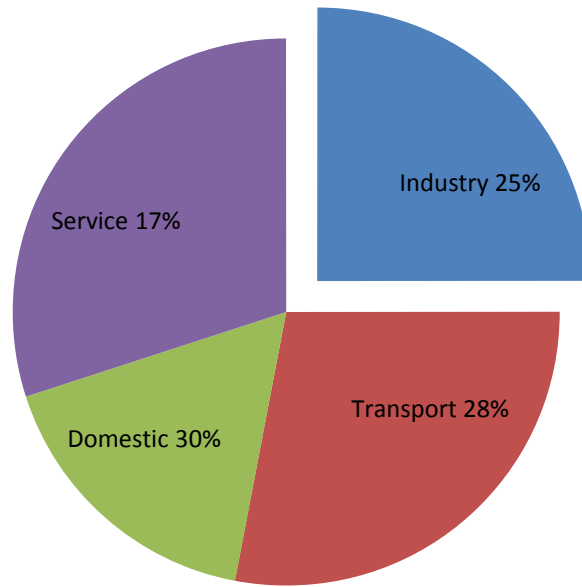


Figure 3. 2 Final energy consumption of various sectors in primary energy equivalent (Source: DECC, 2014)

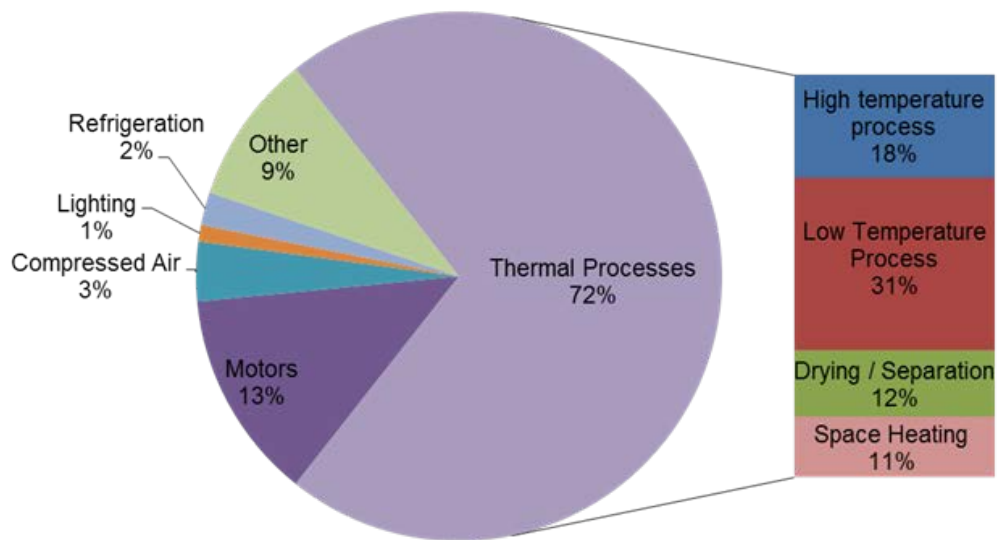


Figure 3. 3 Energy consumption in UK manufacturing industry by type (source: DECC, 2015)

3.2.1 Energy Efficiency in the Manufacturing Sector

There are four primary sectors that consume energy: manufacturing, households, transport and services. The manufacturing sector covers the manufacture of finished goods and products, mining and quarrying of raw materials and construction. Directly or indirectly, manufacturing industry accounts for more than one-third of the global energy use and CO₂ emissions (IEA, 2013). This figure is higher in developed countries where most of the energy is allocated to industrial and transportation sectors (Moan & Smith, 2007). The worldwide industrial energy consumption is predicted to grow from 175.0 quadrillion Btu in 2006 to 245.6 quadrillion Btu in 2030 (IEA, 2006).

The energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of thermodynamics (Intergovernmental Panel on Climate Change, 2007). In energy intensive industries such as paper, chemicals, steel and cement manufacturing, cost-effective efficiency gains are possible in the order of 10%-20% using commercially available technology (Vallack *et al.*, 2011). In processes where efficiency is close to the practical maximum, innovations in materials and processes would enable even further gains.

Using energy more efficiently can not only be a cost cutting exercise and an effective way of reducing CO₂ emissions but also improves productivity and contributes to the security of our energy supplies by reducing reliance on imported energy and ensuring our own and global energy resources are maximised. More importantly it helps to conserve energy derived from non-renewable sources.

Reduction in energy consumption has historically been promoted within manufacturing as a means of saving money, with figures estimating that a 20% cut in energy costs representing the same bottom line benefit as 5% increase in sales (Carbon Trust, 2015). Hence, while historic energy reduction measures have been borne out of the need to improve profitability (Ptasinski *et al.*, 2006) future improvements will be driven by the need to avoid taxations.

From the industrial aspect, a study by Worrell *et al.* (2009) shows there are important benefits of energy efficiency and productivity. A methodology for assessing productivity benefits of energy efficiency investments was proposed which was incorporated into assessments of energy saving potential across an industry.

3.3 Overview of Energy Management Related Research in Industry

Industrial systems encompass the design, manufacture and sale of products including any directly associated activities (e.g. building management and administration). Although difficult to measure precisely, it is suggested that the industrial system can account for 30% or more of greenhouse gas generation in industrialised countries (Evans *et al.*, 2009). Therefore, in light of the threats posed by climate change and the need for sustainable industrial systems, there has been a growing body of research aiming to explore opportunities for energy reduction in this area. Within industrial systems

there are two recognised approaches to analysing energy flows, 1) on a product level, and 2) on a manufacturing systems level. There are different challenges with each approach.

3.3.1 Life-Cycle Analysis

As previously identified, the most common method of assessing the energy associated with the production of a product is by using Life-Cycle Analysis (LCA). An LCA is essentially carried out as a comparison between two products of directly comparable functionality, and consists of identifying each and every manufacturing phase required to produce those products. Rebitzer *et al.* (2004) provides a detailed explanation of the LCA framework and procedure as well as providing an overview of available methods and tools for tabulating and compiling associated emissions and resource consumption data in a Life Cycle Inventory (LCI).

The environmental consequences of quantifying and assessing the environmental impacts of a product by the energy and materials used and wastes released to the environment has been carried out by Jiménez-González & Overcash (2000). They present a methodology to help establish gate to gate LCI data for chemical substances and show the method helps to obtain fair and transparent estimate of LCI data when information is not readily available from industry or literature.

So the disadvantage of LCA is its time consuming inventory analysis which the industry also found to be too complex and requiring a great deal of effort (McAloone, 2000; Guinée *et al.*, 2001; Fitzgerald *et al.*, 2007; Knight & Jenkins, 2009). It is also expensive and time consuming mainly due to the lack of consensus among practitioners on all LCA issues and techniques and exacerbated by the lack of comprehensive publicly available data sources.

Ciceri *et al.* (2010) have improved on the LCA and developed a tool that can be quickly and transparently used to estimate the energy requirements and checked against existing LCI so that new products can be estimated at the design stage. Essentially the tool proposes a methodology to estimate the materials embodied energy and manufacturing energy for a product. The tool uses the products 'Bill of Materials' and the knowledge on how these materials are processed to produce an output that represents the sum of all the energy inputs into a product system. The tool presents the results in the form of a value range on the energy requirements of the product during its beginning of life, including the extraction of materials, processing and the manufacture of the final product.

3.3.2 Life-Cycle Energy Analysis (LCEA)

LCEA uses the guidelines and methodology in a typical LCA but uses energy as the only measure of environmental impact. Typically the use of LCEA is not to replace a broader environmental assessment method, such as LCA, but to facilitate decision making concerning energy efficiency (Fay

et al., 2000). Figure 3.4 shows a representation of the energy flows throughout the lifecycle of a product.

Comparing the embodied energy of a product to its operational energy for example can indicate potential life cycle energy efficiency and conservation strategies. It can also be used to demonstrate the life cycle benefits of strategies designed to optimise the operational energy or embodied energy of a product. For example insulation on a kettle would require additional embodied energy cost – energy to make the insulation – but savings in operational energy will provide greater savings in the longer term. LCEAs are also useful for distinguishing the alternative solutions or technologies in terms of energy performance (Keoleian & Lewis, 1997).

3.3.3 Cambridge Engineering Selector

Ashby *et al.* (2009) together with Granta Design Ltd have developed a commercially available software based on the Cambridge Engineering Selector (CES) technology called the CES Selector. The software provides the rational selection of engineering materials and of manufacturing processes. The systematic selection tools allow the application of graphical and numerical criteria to identify materials that meet a specific design objective. The specialist edition of the CES Selector, the CES EcoSelector, provides quick estimation of the energy usage and CO₂ footprint of a product design at each phase of the product lifecycle.

3.4 Review of Energy Management Strategies in Manufacturing Sector

Energy efficiency is a general term that does not define a particular set of actions or equipment and so can be misleading if used in isolation. To address this, and to provide some structure to research carried out in this field, a variation of the ‘Shop Floor Production Model’ as developed by International Organisation for Standardization (ISO) can be used to categorise research conducted on various levels.

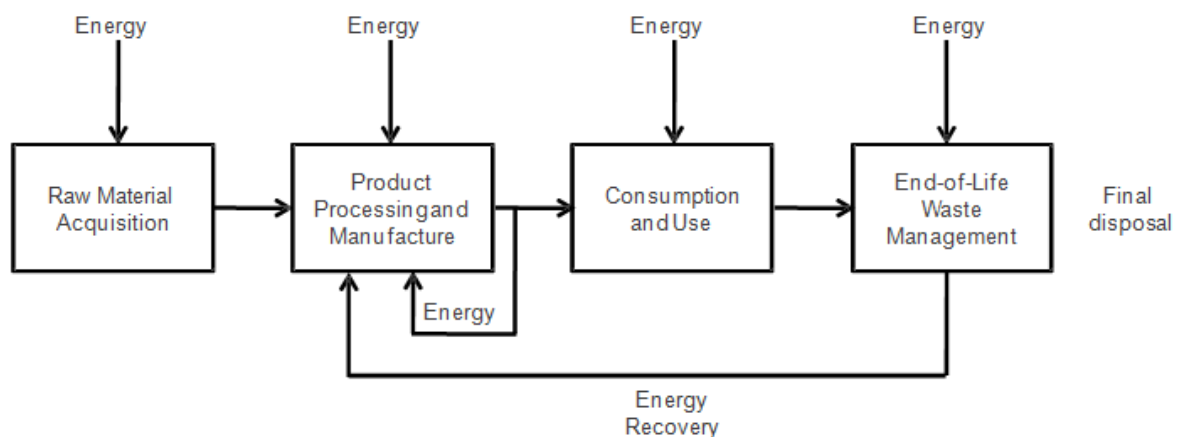


Figure 3. 4 Energy flows at various stages of the lifecycle (Fay *et al.* 2000)

In manufacturing, energy using activities generally fall under five levels ranging from the detailed turret scale energy requirements to the broad enterprise scale activities (Figure 3.5), and are useful for describing different energy requirements across the various manufacturing activities.

The considerations for each level are summarised here:

- Enterprise level – supply chain of materials or components, network of production sites, inventory hubs, sales and distribution centres, R&D and the integration of various plants.
- Facility level – building envelope, HVAC, infrastructure of the facility and site energy generation.
- Production/machine cell level – planning, production engineering and management, supply of material resources and maintenance.
- Machine level – operation and control of equipment, lighting, cooling, work done on material and communication systems.
- Turret level – actual transformation of material.

3.4.1 Energy Management on an Enterprise Level

On the highest level, manufacturing enterprises extend beyond the walls of a factory that just produces goods; it encompasses a range of activities from, supply chain of materials or components, manufacturing processes to the logistics of the finished product. This involves a network of production sites, suppliers, inventory hubs as well as sales and distribution centres.

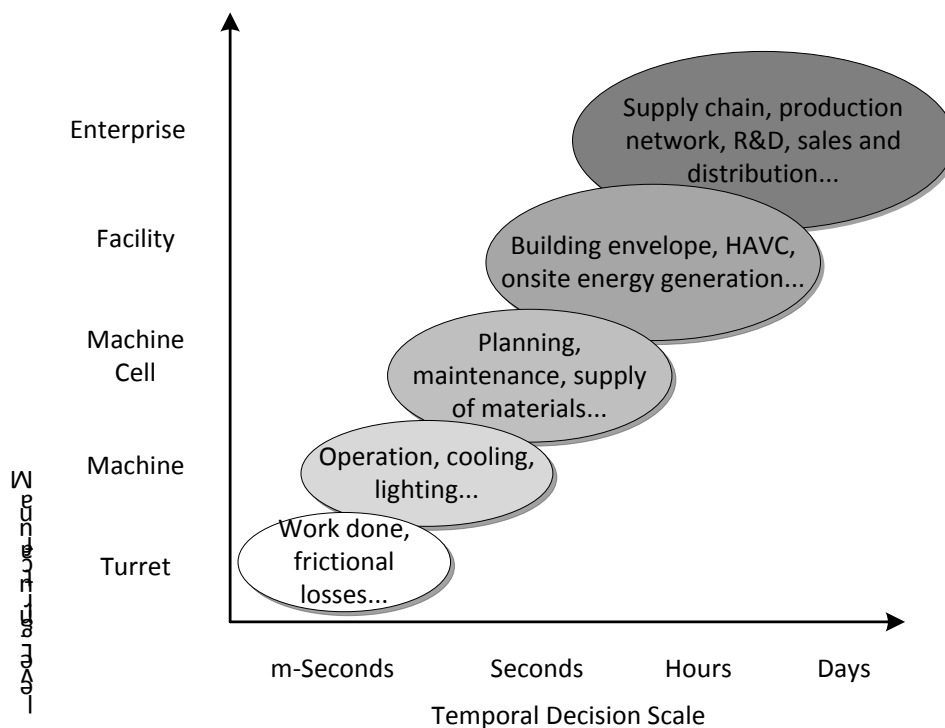


Figure 3. 5 Energy considerations at the various manufacturing levels and the defined scope of this research, adapted from Vijayaraghavan & Dornfeld, (2010)

Strategic decisions are often taken on this level and the activities are usually concerned with supply chain management, sales and marketing, research and development and integration of various plants. Energy flows involve the various interactions within the supply chain.

A number of studies have been undertaken to help address this complexity and enable businesses to make better informed decisions regarding improving their sustainability. Quite notably, Seuring & Müller (2008) have undertaken a comprehensive review of peer reviewed papers published between 1990 and 2007 (inclusive) that look at improving sustainability at the enterprise level. One of the key findings, and that has some relevance here, is that whilst all papers considered economic aspects, some papers focused mainly on social aspect whilst some focused on the environment with a growth in later years of papers considering all three strands of sustainability. This reflects the increase in global understanding of the requirements of sustainability but also that it is often best to tackle one aspect well than all aspects not so well. In general, there has been a larger focus on environmental aspects than on any other aspect of sustainability.

It has been found that embodied energy of products could be reduced by selecting local suppliers and avoiding use of road transport for transporting the large quantities of raw materials over long distances (Kara *et al.*, 2010). The model produced by Kara and Manmek focuses on energy, materials and emissions and waste with considerations for how each of these are used or produced within lengthy supply chains. Supplier location was shown to be a significant factor that can increase or reduce the embodied energy of the raw materials. (Kara & Ibbotson, 2011) advances a methodology for assessing the impact of global manufacturing on the embodied energy of the products. The study was done with six different products manufactured from various raw materials in a global manufacturing network and found that product, material and key supply chain parameters played a crucial role. Careful selection of local suppliers and avoidance of long distance road transport are key considerations.

Other research on the enterprise level has identified the energy improvements can be obtained by changing business models. For example, Seliger *et al.* (2006) showed that less energy consumption is required for a phone that is remanufactured rather than a phone that is sent to a land fill, over the production, use and end of life phase. This is because the remanufacturing pathway, despite requiring energy input into the reverse logistics, avoids repeating manufacturing steps with characteristically high energy consumption and environmental emissions. The results indicated that the difference between land filling and remanufacturing a mobile telephone represents approximately 10 days of energy consumption for the average German household and 9 months of CO₂ sequestration potential for an average tree.

A further study by Pearce *et al.* (2007) used Google maps to carefully plan and optimise the embodied energy of transportation at the enterprise level. This enabled manufacturers to optimise the life cycle of their products by minimising embodied energy of transportation.

Because globalisation of businesses has led to long and multi-tiered supply chains, it has proven difficult to introduce improvements across the enterprise level because of the complex communication requirements and varying levels of legislation across different countries and regions. This has been reflected in the number of studies that have been carried out at the enterprise level with most publications focusing on case studies and observed trends rather than new methodologies (Seuring & Müller, 2008). In general, the higher costs, coordination effort and complexity and communication difficulties of implementing sustainable supply chains has led to companies focusing on internal activities which present far more achievable environmental (and financial) gains over shorter time periods. Indeed, such changes have been shown to lead to equal or greater benefits with smaller financial and time investments.

3.4.2 Energy Management on a Facility Level

Energy management can be achieved at the facility level with little or no capital expenditure. It involved measures such as better monitoring and control of heating and lighting, better planning and scheduling of energy intensive processes, switching off or dropping running rate of equipment when it is not in use or running at idle state and improved maintenance of boilers, furnaces and steam distribution systems.

Additional energy efficiency measures could be achieved at the facility level, which involved the investment of capital on energy-saving equipment such as insulation and waste-heat recovery. These measures can either be retrofitted to an existing plant or installed in newly built plants. Since their main purpose is to save energy, they have little or no effect on product quality (Despeisse *et al.*, 2012). Investigation of the energy saved in proportion to the capital cost has to be carried out and correctly justified. For example, improvements by replacing worn out and less efficient equipment with newly developed equipment of modern design could be made however this will also result in higher capital outlay. The benefit includes the reduction in maintenance costs, improvement in production efficiency, product quality and increased throughput. Integrating equipment with new process technologies is similar to replacement equipment measures with more radical changes in the process, for example, the change from wet to a dehumidified process in iron making, or continuous usage of blast furnace.

Ball *et al.* (2013) have developed the conceptual modelling approach and introduced the prototype as applied to industrial studies to provide information towards sustainable manufacturing. The

innovation was the combined simulation of production and building energy use and waste in order to reduce overall energy consumption and improve energy efficiency.

3.4.3 Energy Management at a Machine Cell Level

At the production/machine cell level, the activities considered include, planning, production engineering and management, supply of material resources, transport of waste material and processing and maintenance. Energy flows are closely related to the running of these activities which may be affected by production plans, scheduling times and parameters.

Most of the research carried out on this level involves process planning for improved energy performance. Most research has focused on costs and cycle times due to the complexity of process flow decisions. In order to overcome the lack of tools for optimising process flow based on sustainable development purposes and to address the issue, Tan *et al.* (2006) reported their work of combining manufacturing process planning and environmental impact assessments using check list analysis and proposed an optimal decision making method for new component that includes energy consumption as part of the sustainable development evaluation (Figure 3.6).

A green manufacturing process planning and support systems (GMPPSS) have been developed by He *et al.* (2007), which enables the raw materials, secondary materials and energy consumption, and other environmental impacts of process planning to be optimised. This was supported with databases and model repositories. Integration of the optimisation of energy consumption of processes as part of the process selection algorithm in a process planning program is possible as demonstrated by He *et al.* (2007). Figure 3.7 shows how green factors can be integrated within the process planning support systems for green manufacturing.

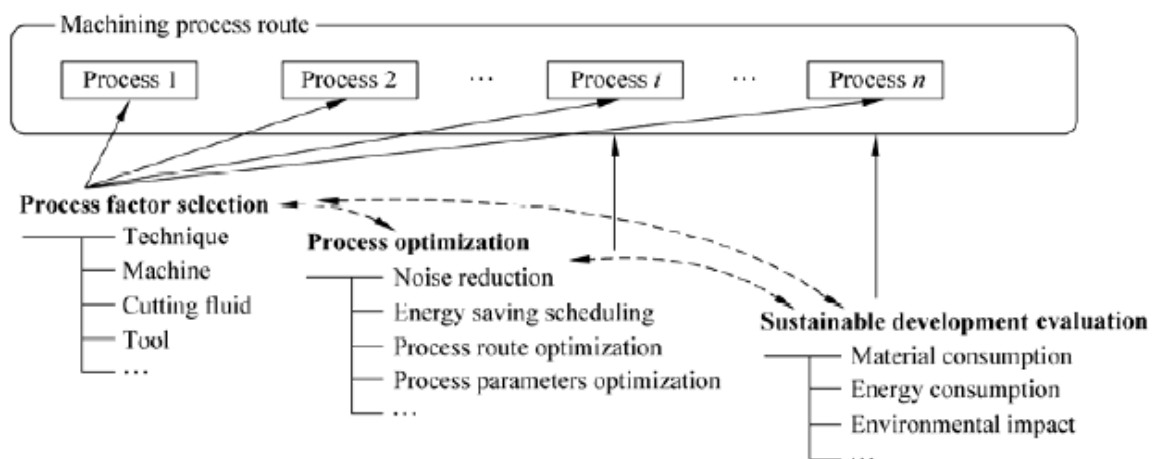


Figure 3. 6 Optimization decisions for production process planning in terms of sustainable evaluation, adapted from (Tan *et al.*, 2006)

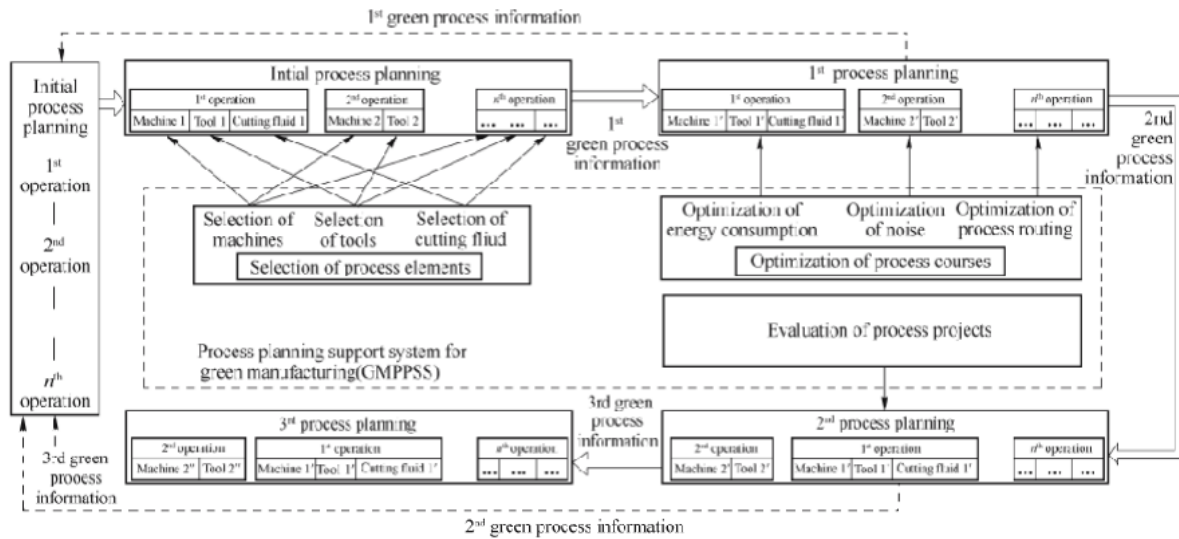


Figure 3. 7 Integration of green factors in process planning, adapted from (He et al. 2007)

At the machine cell or production level, information is very important. Thiede *et al.* (2012) have applied smart metering for industrial purposes like production planning. First applied in private households, smart metering substitutes analogue metering and reading of the consumed electrical work, by computerising the process, tracking not only the electrical work but also the characteristics of specific power consumption. Industrial smart metering comprises of sensors, processors and analysers to capture, transfer and resolve energy and resource flows in manufacturing systems. They also have assigned energy and resource flows to hierarchical levels starting top-down from factory, process chains, and to machine tool level, and have provided guidelines for energy metering requirements on each of those levels. As data volumes will increase exponentially as you move lower down the levels, it is important to set the correct resolution and address them through appropriate hardware and software systems (see Figure 3.8). They believe that the effective metering of energy flows provides detailed information on energy flows that improves the management of the manufacturing system. It also provides the foundation for energy efficient planning.

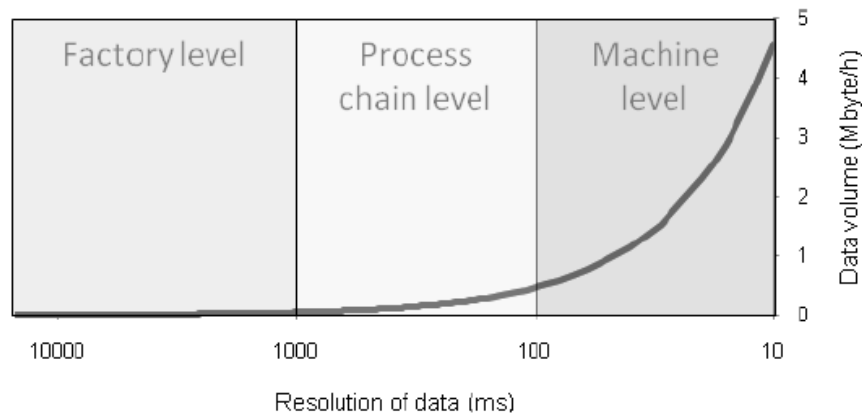


Figure 3. 8 Resulting data volume from 64-bit measurement values depending on its temporal resolution (ranging from 1.5 min up to 10 ms) from a single data output, adapted from (Kara et al. 2010)

3.4.4 Energy Management associated with Production Machines and Equipment

Energy efficiency has a precise technical meaning when applied to a machine: it is the ratio of the work done compared to the input energy, defined by Langley (1987). In this respect, energy efficiency could be defined as energy input relative to a theoretical minimum energy requirement. For a given product or process, the energy consumption per unit of physical output is also recognised as 'Specific Energy Consumption' (SEC) (Langley, 1986). This enables the comparison not only between individual factories, but of the factory over different periods of time.

At the machine level of manufacturing, Dahmus & Gutowski (2004) reported that machine tools with increasing levels of automation have higher basic energy consumptions which result from the amount of additional integrated machine components. For example CNC machines carry a number of key components such as pumps, hydraulic systems, and numerical control systems which dominate the energy consumption of the process.

Seow & Rahimifard (2011) have gathered information of power generation and trends in energy consumption within the industrial sector and engineering context in energy management and modelling research and software tools. A framework has been developed to model Embodied Product Energy (EPE), to give a clear indication of where energy consumption hotspots are in manufacturing process chains and to gauge whether energy is used efficiently. The research also looked into a particular simulation technique which would help design and implement a prototype energy simulation model that integrates some of the features included in the EPE so to support energy efficiency optimisation. The EPE framework allows the breakdown of energy consumption for each process to be attributed to a product as it moves through a number of processes and this approach enables each process to be evaluated individually and brought together to give an overview of energy consumption. In the EPE framework, the energy consumed by various activities within a manufacturing application is categorised into two groups: Direct Energy (DE) and Indirect Energy (IE). The DE is defined as the energy used by various processes (e.g. casting, milling, machining etc.) required to manufacture a product, whereas the IE is the energy consumed by activities (e.g. heating, lighting, ventilation, air conditioning etc.) to maintain the general environment in which the production processes are carried out within a manufacturing plant, which is further divided into Theoretical Energy (TE), Auxiliary Energy (AE). TE is defined as the minimum theoretical energy required to carry out the process while AE is the energy required by the supporting activities and auxiliary equipment for the process (Rahimifard *et al.*, 2010).

Three main methods have been recognised to collect data for these individual energy components including, empirical measurements, published data and, via appropriate mathematical approaches, although the most preferred way would be metering directly at each production process and the

supporting activities within the manufacturing facility however the complexity of these process and activities usually makes this unpractical. The energy simulation model was then developed to support the application of the EPE modelling framework within complex manufacturing systems. This model can be used for consideration of ‘what-if’ scenarios for optimisation and improvement in energy efficiency and a user graphical interface was also offered, showing energy consumption values, option to change parameters, allowing output and plotting graphs etc. These features deliver a better vitalisation of issues and allow little effort to use. Rahimifard *et al.* (2010) established efficiency relationships between DE and IE within EPE Framework and efficiency ratios for processes. These figures help to demonstrate the Process Efficiency Ratio which reflects how well processes perform, whether they are efficient or not. Comparisons can also be made between multiple processes to give a better illustration.

3.4.5 Energy Management on a Machine Tool Level

Turret level of the manufacturing system represents the actual material transformation process and is typically studied based on theoretical analysis such as in the work of Sarwar *et al.* (2009) who carried out a detailed analysis on the specific energy consumption of bandsawing various materials. While Rajemi *et al.* (2010) has looked at the minimal energy required for turning and the optimal conditions for machining a product, whereas Kuzman (1990) has carried out an energy evaluation of the cold forming process.

3.5 Energy and Exergy

3.5.1 Difference between Energy and Exergy

The term exergy is often confused with energy. Exergy was first called “availability” or “available energy”, since then following the proposal of Rant (1956) it is referred to as “exergy”, and explains quality of energy (Yantovski, 2004). A complete definition was given by Baehr (1965) which is briefly described as: Exergy is that part of energy that is convertible into all other forms of energy.

It emphasises the maximum work output attainable in the natural environment, or a minimum work input necessary to realise an opposite process. The exergy of a system is the maximum work done by the system during a transformation which brings it into equilibrium with the surrounding, as defined by Karellas *et al.* (2012). The relationship between energy and exergy was summarised as:

$$\text{Energy} = \text{Exergy} + \text{Anergy} \quad [\text{Equation 3.1}]$$

In contrast to the property of energy, exergy accounts for the irreversibility of a process due to increase in entropy and consequently exergy is always destroyed when a process involves a

temperature variation. The destruction of exergy is proportional to the entropy increase of the system together with its surroundings. The destroyed exergy is also known as anergy (Honerkamp, 2002). Unlike energy which measures the ability to do work, exergy is much more dependent upon the reference state, which means the exergy of a system in equilibrium with the environment is zero. Gong & Wall (1997) summarised the main differences between energy and exergy in table 3.1.

Table 3. 1 Energy versus Exergy, adapted from (Gong & Wall, 2001)

Energy	Exergy
The first law of thermodynamics	The second law of thermodynamics
'Nothing disappears'	'Everything disperses'
Energy is motion or ability to produce motion	Exergy is work, i.e. ordered motion, or ability to produce work
$\Delta Q = \Delta U + \Delta W$ Where: ΔQ is added energy as heat to the system, ΔU is the change of the internal energy U of the system, ΔW is extracted energy as work from the system	$E_x = T_0 \Delta S^{tot}$ Where: E_x is the exergy, T_0 is the temperature of the environment, ΔS^{tot} is the change of the entropy of the total system S^{tot} , i.e., the system and the environment
Energy is always conserved, i.e., in balance; it can neither be produced nor consumed.	Exergy is always conserved in a reversible process, but reduced in an irreversible process, i.e., real processes. Thus exergy is never in balance for real processes.
Energy is a measure of quantity.	Exergy is a measure of quantity and quality

The difference between the input and output exergy is often referred to as irreversibility of a process which is related to its entropy change. The irreversibility always results in an unrecoverable loss of exergy and its value is proportional to the sum $\sum \Delta S$ of entropy increases of all the bodies taking part in the process:

$$E = T_0 \Delta S^{tot} \quad \text{[Equation 3. 2]}$$

The equation is termed the law of exergy loss or the law of Gouy-stodola (Szargut *et al.*, 1987).

The use of energy as a measure for understanding and improving the energy efficiencies can be confusing and misleading. A new concept of exergy can however, be used to assess and improve the energy efficiencies, and can help better appreciate the energy losses in energy systems by providing a more precise definition and explanation than energy provides. Exergy is defined as the maximum work that can be produced from a system or a flow of matter or energy relative to a reference environment (Rosen & Bulucea, 2009). In other words, exergy is a measure of the potential of the

usefulness of a system or flow. Exergy is also defined as a measure of the potential to cause change, as a result of being out of equilibrium relative to the reference environment (Rosen & Bulucea, 2009). Exergy has an important role to play in increasing efficiencies of energy systems and technologies not only because of its unique ability to clearly identify efficiency improvements and reductions in thermodynamic losses, but also because it better identifies environmental benefits and economics of energy technologies than that of energy provides. Nevertheless, the full value of exergy is not achieved because many researchers regard that exergy is applicable only to systems or studies involving extensive thermodynamics, in areas like mechanical, chemical and electrical engineering whereas it is neglected or underutilised in other research areas.

This section goes on to describe exergy and exergy methods and their applicability to the waste heat recovery research established in this thesis. Examples are also used to illustrate the use of exergy as a tool to understand and improve energy efficiency.

3.5.2 Energy and Exergy Analysis

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Gundersen, 2011). Exergy is a measure of the ability of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment (Çengel & Boles, 2008). Unlike energy, exergy does not follow the law of energy conservation, rather exergy is consumed or destroyed during transfer or conversion in any real process due to irreversibility. In addition, the exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process (Rosen & Bulucea, 2009).

Exergy analysis is a methodology that utilises the principle of conservation of energy (which is embodied in the first law of thermodynamics) together with non-conservation of entropy principle (which is embodied in the second law of thermodynamics) for the analysis, design and improvement of energy and other systems (Szargut *et al.*, 1987). It is identified that the exergy method is useful for improving the energy efficiency by clearly quantifying the locations, types and magnitudes of waste and losses.

A unique characteristic of exergy analysis is that the reference environment must be readily specified before analysis is carried out. This is normally done by providing the temperature, pressure and chemical composition of the reference environment. Therefore, the results of exergy analyses are relative to the specified reference condition which in most cases is modelled after the actual local environment.

3.5.3 Exergy of Various Systems

3.5.3.1 Power Generation

Common electrical conversion devices include transformers, alternators, generators, motors and static converters which are widely used in the power generation industry. In such devices, electrical energy is being converted to other type of electrical energy. Since electricity and work are considered to have same quality on energy and exergy bases (Kotas, 1985), the overall energy and exergy efficiencies for such devices are the same. However, the losses differ greatly as all energy losses are associated with waste heat. Most exergy losses are associated with exergy destroyed or internal consumption of exergy due to irreversibilities. Resistive losses usually dominate the electrical losses, as a result which appear as waste heat.

3.5.3.2 Electrical storage systems

Electrical storage systems are used to store electricity, the most common of which are batteries. The energy efficiency of an electrical storage device is usually determined as the ratio of the quantity of electricity obtained from the storage while discharging divided by the electrical energy supplied to the storage while charging. For a battery, the energy loss is observed as heat, which causes the battery and its surrounding temperature to rise. Low charging and discharging rates help keep a battery cool and improve the battery life. Given that the inputs and outputs are both electricity for electrical storage systems, the energy and exergy efficiencies are equal.

3.5.3.3 Electrically Driven Systems

i. Industrial Furnaces and Heaters

Energy efficiencies for industrial process heating can vary depending upon the heat retention characteristics of the heater. Exergy efficiencies for industrial process heating vary significantly, depending primarily on the temperature of the product heat. Typically, the exergy efficiency is greater when a high-quality input such as electricity is used for an energy intensive task (like producing high-temperature heat). Therefore, the use of energy efficiencies and losses is quite misleading for industrial heating.

The exergy losses for such system can also be broken down into more detailed level which often reveals that the exergy losses are divided among those due to irreversibilities associated with the combustion reaction and those due to heat transfer from the peak theoretical combustion temperature to the actual temperature of the working fluid.

ii. Refrigeration Systems

Refrigeration systems operate like heat pumps, but with the heat removed from the cold space, rather than the cold being rejected, being the product. As for trigeneration systems which involve a cold product, the energy and exergy efficiencies for such systems vary due to the dependence of the exergy of the cold thermal product on temperature. The energy of the cold product is also difficult to determine, so the energy-based figure of merit used for refrigeration systems is the Coefficient of Performance (COP), which is simply the energy efficiency divided by 100. The energy and exergy efficiencies differ markedly for refrigeration systems, but the exergy efficiencies are more intuitively meaningful.

The energy and exergy losses for such systems are identified to be in different locations and due to different causes. The main losses occur in the motor and compressor, the condenser, the heat exchangers and the throttle valve.

iii. Pumps and Fans

Electric pumps and fans convert electricity to mechanical energy in the form of pressure rise and kinetic energy. The energy and exergy of the products are usually similar, leading to similar device efficiencies.

iv. Lights

Lighting consumes a significant amount of energy in society, and it is also extremely inefficient. Light bulbs convert electricity to visible light. As the product electromagnetic radiation can be taken to have similar energy and exergy contents, the energy and exergy efficiencies of lighting are similar. Lighting efficiencies differ markedly from the efficiencies of many home appliances. The potential for energy and exergy savings from lighting is large, due to its inefficiency and large contribution to societal energy use.

3.5.4 Numerical Illustration

Typical values of energy and exergy efficiencies for the electrical devices and systems considered in the previous section are illustrated in Table 3.2. In addition, exergy losses are broken down in that table into internal exergy consumptions and waste exergy emissions.

A detailed review of the efficiencies in Table 3.2 shows that in some instances the energy and exergy efficiencies are equal, while in other cases they differ significantly. Where they differ, the exergy efficiencies provide an indication of how close the process approaches theoretical value whereas energy efficiencies can cause confusion. Where the efficiencies are similar, the energy efficiencies can be treated as good approximations of the more meaningful exergy efficiencies. The efficiencies tend to be similar where the energy input and product energy outputs are of the same quality. The

efficiencies differ when energy inputs and outputs are of significantly different quality (e.g., electricity as opposed to heat at high temperature).

A typical example can be seen are electrical resistance heaters, as industrial heaters have the higher exergy efficiency because it delivers heat of a higher quality, as reflected by its temperature. Space and hot water heaters deliver lower quality heat.

The refrigeration and heat pump systems are difficult to assess using energy efficiencies as the values exceed 100%. The energy efficiency for trigeneration is not a true efficiency as it includes the cold product energy, which is normally evaluated with a Coefficient of Performance (COP) as a figure of merit. In both these cases, exergy efficiencies are rational and meaningful.

The energy loss can be found using the corresponding energy efficiency as 100% minus the energy efficiency. The exergy loss can be found similarly. The overall energy loss is made up entirely of waste energy emissions from the system. The overall exergy loss differs significantly, as it consists of both waste exergy emissions from the system and internal exergy consumptions (or destructions) due to irreversibilities.

Table 3.2 is a brief summary of data from different sources, which has been modified to be comparable and illustrative. Some details not presented in the table are as follows:

- The ideal thermal power plant is taken to be operating using a heat source at a temperature of 550 °C, which roughly corresponds to the temperature of the high-pressure superheated steam exiting the steam generator of the coal-fired Nanticoke generating station.
- The fuel cell system is based on an automotive fuel cell system assessed previously by Cownden et al. (2001). The system includes the fuel cell stack and the balance of plant, which includes pumps, compressors, heat exchangers, etc.
- Wind turbine system energy efficiencies vary significantly with wind speed, and are usually designed for highest efficiency operation at a given wind speed. Values are reported here for typical operating energy efficiencies for wind turbine systems at wind speeds that are reasonable in terms of systems operation. The main component of the system is the wind turbine itself, which has energy efficiencies typically ranging from 75% to 94% (Hau, 2013). The device is assumed to emit waste heat at 30 °C, a temperature near the ambient condition.
- Energy efficiencies values for photovoltaic electricity generation are based on confirmed efficiencies for terrestrial solar cells and modules, measured under the global AM1-5 spectrum (1,000 W/m²) at 25 °C (Crabtree & Lewis, 2007) (Humphreys, 2008). These devices are assumed to emit waste heat at 60 °C, a temperature between ambient conditions and waste heat flows for industrial heating.

- Solar thermal energy conversion devices use the energy in sunlight to heat a working fluid to a temperature sufficiently high to drive a thermal power cycle. Such systems usually utilize concentrating solar collectors so that reasonably high temperatures can be attained. The mean annual efficiencies reported are about 10–20% for systems built over the past two decades and 30% for more recent systems (Crabtree and Lewis, 2007). The devices are taken to emit waste heat at a temperature of 145 °C, which is typical for industrial heating systems and some solar thermal systems.
- The electrical storage systems considered are common lead-acid batteries, with and without a charging circuit. The energy efficiency represents the percentage of electricity supplied to the battery system that is recovered on discharging. Energy efficiency values for typical lead-acid batteries and charging circuit can be obtained from the manufacturing company (Lawrence, 2005). For the battery, the charging circuit and the combination of the two, the exergy efficiency is identical to the energy efficiency.
- The electrical hot water heater is assumed to deliver product heat at a temperature of 55 °C, and to emit waste heat at 45 °C.
- The electrical industrial heater is assumed to deliver product heat at a temperature 800 °C, and to emit waste heat at 145 °C.
- The heat pump taken to be same as refrigeration system, except that the heat delivered is the product. Waste from the heat pump system includes miscellaneous heat releases from all devices and assumed to be small (10% of the exergy loss), which are assumed to occur at 40 °C. The plant efficiency is relatively low compared to available systems.

Table 3. 2 Energy and exergy efficiencies and breakdown of exergy losses for selected electrical devices, adapted from Rosen & Bulucea, (2009)

Device	Efficiency (%)		Breakdown of exergy loss (%)*	
	Energy	Exergy	Consumptio	Emission
Electrical generation systems				
Ideal thermal power plant	64	100	–	–
Coal-fired power plant	37	36	9	8
Nuclear power plant	30	30	9	2
Hydroelectric power plant	90	90	8	12
Fuel cell system	33	33	8	11
Wind turbine system	80–97	80–97	9	3
Solar photovoltaic system	6–25	6–25	8	12
Solar thermal power generation	10–30	10–30	7	30
Cogeneration and trigeneration systems				
Cogeneration system	74	31	9	1
Trigeneration system	94	28	9	8
Electrical storage systems				
Battery (lead–acid)	75–85	75–85	9	8
Electrically driven devices and systems				
Resistance space heater	99	6	9	3
Heat pump	380*	19	9	6
Hot water heater	90	10	9	8
Industrial heater	70	51	7	30
Refrigeration system	310*	24	9	5
Pump	70	70	9	3
Fan	90	90	9	3
Lighting (incandescent)	5	5	9	8
Lighting (fluorescent)	20	20	9	3

*Conventionally expressed as COP by dividing by 100.

3.5.4.1 Calculating Exergy of Heat

The maximum work potential of a heat stream, Q , is limited by the *Carnot factor*. Its exergy content Ex_Q , can therefore be calculated by the Carnot factor multiplied with the energy content of the heat stream (Cornelissen & Hirs, 2002).

$$W_{max} = Q \left(1 - \frac{T_0}{T} \right) \quad \text{[Equation 3. 3]}$$

Where,

W_{max} is maximum ability to perform work, T_0 is absolute ambient temperature, $(T - T_0)/T$ is dimensionless Carnot-factor characterising the quality of heat taken from the source with a constant temperature. Although Equation 3.3 applies the concept of exergy to thermal energy, it is a useful concept for all other forms of energy (Figure 3.9).

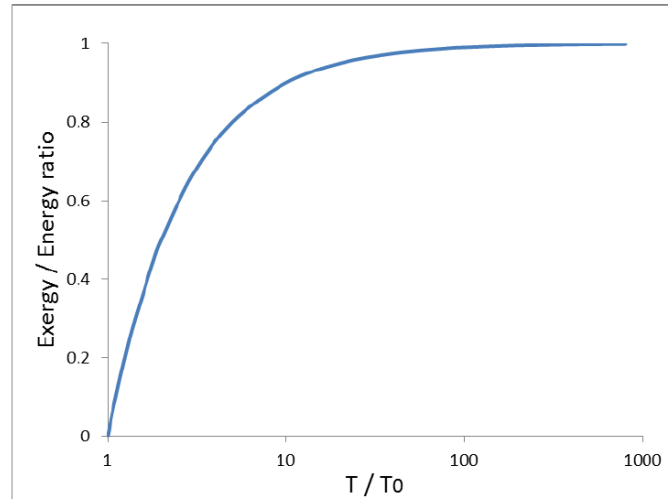


Figure 3.9 Variation of exergy content of heat with temperature (Cooper S., 2013)

3.5.4.2 Exergy Losses

Exergy losses happen due to irreversibility of a system process, thus it is useful to differentiate between types of exergy losses in order to study where irreversibility occurs. Exergy loss can be grouped into two categories, internal and external exergy losses (Szargut, 1980). Internal exergy losses occur inside the analysed process corresponding to the losses of quality due to internal inefficiencies within the process (Alej *et al.*, 1998). This internal irreversibility may be of technical limitation within the plant, e.g. friction or lack of insulation, or due to their structural nature. External exergy losses represent the remaining exergy contents of waste and emissions that are dissipated or ejected from the process, therefore regarded as unused exergy. Structural exergy losses are losses determined by the principle and design of the system (Cornelissen & Hirs, 2002), e.g. the use of heat for electricity production is structurally limited by the Carnot Factor. Whereas technical exergy losses can be reduced through operation optimization, structural losses can be reduced by redesigning the system.

Internal and external exergy losses depend on each other as a change in process design or optimization influences the exergy content of waste material and emissions and thus the external exergy losses (Szargut *et al.*, 1987). Many exergy analyses have been carried out in order to reduce internal exergy losses, however little effort has been found in the research of harnessing external exergy losses to feeding it back into the manufacturing processes. Here it is essential to define system boundaries that are broad enough to understand the opportunities of this unused exergy, for example, the unused exergy can be cascaded down further to processes with lower exergy requirements, and a reduction of external exergy losses of the first process would increase the environmental performance of the entire system.

3.6 Chapter Summary

In this review, a number of the energy management strategies have been surveyed. The main points of the findings include: energy management can be defined at different manufacturing levels from the very detailed turret level, looking at energy measurement of tool heads, up to the more broad enterprise level, for example focusing on supply chain, product network, R&D and product distribution. There are also some studies that have been carried out from different perspective, such as the EPE framework which have focused on decreasing energy per product by minimising non-productive energy. However, very little literature is found on regarding management of waste energy, which could have significant potential. In the next section, a review of the latest technology and innovations of waste energy recovery is surveyed to gain an understanding of what energy recovery methods are currently available.

The exergy efficiencies and losses describe the efficiencies of the electrical technologies and systems better and provide more meaningful information. With these insights, a better understanding is attained of the factors affecting efficiency, and efforts to improve performance can be better allocated and directed.

In particular, low values of exergy efficiencies, or high exergy losses, indicate that a significant margin for efficiency improvement exists in theory. Realising this efficiency improvement requires ingenuity and creativity, and involves trade-offs with other factors such as economics and environmental impact. The breakdown in exergy losses allows the causes, locations and magnitudes of the exergy losses to be understood better, so that efficiency-improvement efforts can focus more directly on those factors likely to be causing efficiency losses.

Chapter 4 State-of-the-Art Technology

4.1 Introduction

In the previous section, a review of energy management in the manufacturing environment has highlighted that it is insufficient to explore the problems at the higher manufacturing levels and a closer look at the energy recovery technology at process and machine level is necessary. There are many different methods and technologies for recovering waste energy in a manufacturing environment, such as kinetic energy from movement of the machine parts, chemical energy from reactions, thermal energy as a result of combustion and some other well established engineering cycles which enable heat energy recovery.

Despite the variation in technology, they all have the same aim, which is to collect and reuse or recycle waste energy arising from any process that would otherwise be lost. The process might be inherent to a factory building, such as space heating, ventilation for example, or could be something carried out as part of manufacturing activity, such as the use of ovens, furnaces etc. Waste energy recovery can help to reduce the overall energy consumption of the process itself, or provide useful energy source for other purposes.

In this chapter, an overview of the currently available technology for energy recovery system within manufacturing is discussed.

4.2 Heat Exchanger Technology

A heat exchanger is a piece of equipment built for heat transfer from one medium to another. The media may be separated by a solid wall to prevent mixing or they may be in direct contact (Kakac & Liu, 2002). A wide range of heat exchangers are available on the market from manufacturers around the world and are widely applied in space heating, refrigeration, air conditioning, power plants etc. The merits of a number of heat exchangers are discussed in the following sections.

4.2.1 Gas-gas Heat Exchangers

Several gas-gas heat exchangers are on the market to facilitate the transfer of heat between gas/vapour streams. One of these is the rotating regenerator also known as heat wheel. Heat is transferred between two separate streams flowing through a slowly turning wheel. The matrix material of the wheel is alternately heated and cooled allowing heat transfer. One disadvantage of the equipment is that large differential pressures are not tolerable and leakages are often apparent

between the two streams, thus affecting performance (Law *et al.*, 2012). This unit has been used to good effect in various dryer exhaust applications (Worrell *et al.*, 2010).

The gas-gas plate heat exchanger is another efficient option, which operates by hot and cold stream flowing in a cross or counter flow configuration between plates through which heat is transferred. The units are suitable for a wide range of low-grade heat (Temperature range of ambient up to around 260°C) recovery applications. The advantage of this type of unit is that no cross contamination occurs, so they can be used as an alternative choice when such contamination cannot be tolerated. This heat exchanger has been used in many fields including the recovery of heat from exhaust lines for warm-air space heating (NBS, 1994).

For example, heat exchangers made of heat pipes are one of the most effective devices for waste heat recovery (Noie-Baghban & Majideian, 2000). The advantage of using a heat pipe over conventional methods is that large quantities of heat can be transported through a small cross-sectional area over a considerable distance with no additional power input to the system (Faghri, 1995). Other merits include the simplicity of design and manufacturing, wide temperature application range and the ability to control and transport high heat rates at various temperatures (Bar-Cohen *et al.*, 2009). The heat pipes exchangers can also be used for other type, such as gas-liquid and liquid-liquid heat exchangers.

4.2.2 Gas-liquid Heat Exchangers

Gas-liquid heat exchangers are available for the heating of liquids using waste gas streams, the most common of which is the economiser which is widely available for both domestic and industrial applications. An economiser is a mechanical device that consists of a tubular heat exchanger in which the hot gas flows over finned tubes containing a liquid. It is most commonly used in the pre-heating of feed water going into a boiler. This in effect increases the thermal efficiency of the steam raising process as less energy is required to heat the pre-warmed feed water.

Spray condensers are also used as heat exchangers with various merits for different applications. The basic principle of this direct contact heat exchanger is to spray the liquid, most commonly water, into a hot, humid gas steam. The gas steam then condenses creating a stream of hot water from which the heat can be recovered by using a further heat exchangers unit, or used directly depending on the gas steam contents.

4.2.3 Liquid-liquid Heat Exchangers

The most common of all liquid-liquid heat exchangers is the shell and tube heat exchanger. The design of this heat exchanger is to allow for working fluid to flow across the outside of several tubes

a number of times before exiting the exchanger. This increases the areas of contact of fluids and increase the amount of energy transferred. Figure 4.1 shows a typical cut away view of a shell and tube exchanger.

The plate heat exchanger is first of a few compact units to be accepted in the process industry and was originally used in the dairy industry to allow precise control of heating and cooling during pasteurisation (Proctor *et al.* 2011). It allows large area of contact in excess of $200\text{ m}^2/\text{m}^3$, and has high thermal efficiency of up to 95%. However the disadvantage of this heat exchanger is the susceptibility to fouling, with the unit allowing only around 25% of the fouling capacity of shell and tube heat exchangers (NBS, 1994).

4.3 Thermodynamic Engineering Cycles

There are a wide variety of different cycles which enable heat energy recovery in manufacturing industry. This section demonstrates some of the commonly utilised cycles.

4.3.1 Rankine Cycle

The Rankine cycle is a simple and widely used thermal cycle for thermal power generation, amongst other processes. A simplified set up of a thermally driven power generation process that utilises a Rankine cycle is shown in Figure 4.2. It consists of four main parts including the water pump, boiler, turbine to carry out external mechanical work and a condenser. The optimal conditions that the cycle can operate over include: turbine entry temperature typically of 565°C and the condenser temperatures of around 30°C .

There are four fundamental stages of a Rankine cycle (Singh, 2006), which are:

- Stage 1-2: the working fluid is pumped under pressure.
- Stage 2-3: the working fluid is then heated in a boiler by an external supply of energy (usually burning coal or flue gas) to raise steam pressure.
- Stage 3-4: the steam is allowed to expand to drive a turbine in order to produce mechanical work
- Stage 4-1: the rejected steam is cooled and returned to water in a condenser

A temperature verses entropy plot of this process is shown in Figure 4.3 and each plotted point on the graph corresponds to the respective process stages above.

Based on this basic principle, some variations of the traditional Rankine cycle have also been developed to recover heat energy where high grade steam or flue gases are unavailable (Huang *et al.*, 1998).

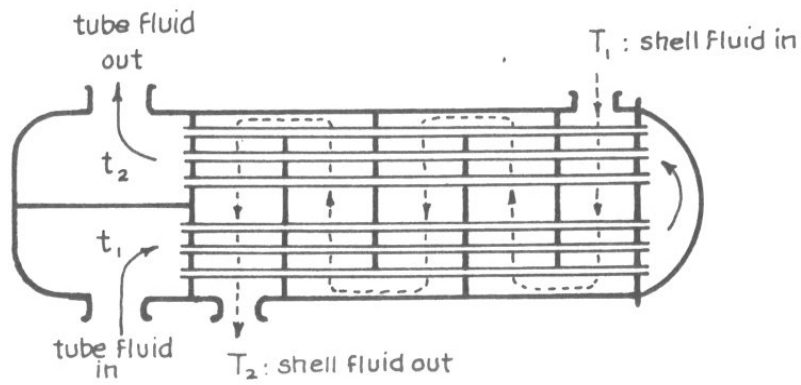


Figure 4. 1 Shell and tube heat exchanger, two tube pass design (Thulukkanam, 2013)

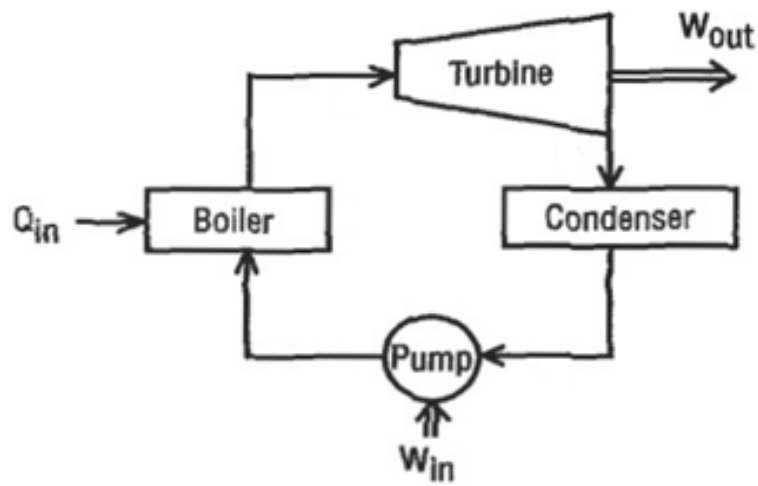


Figure 4. 2 Schematic of the Rankine cycle (Rajadurai, 2003)

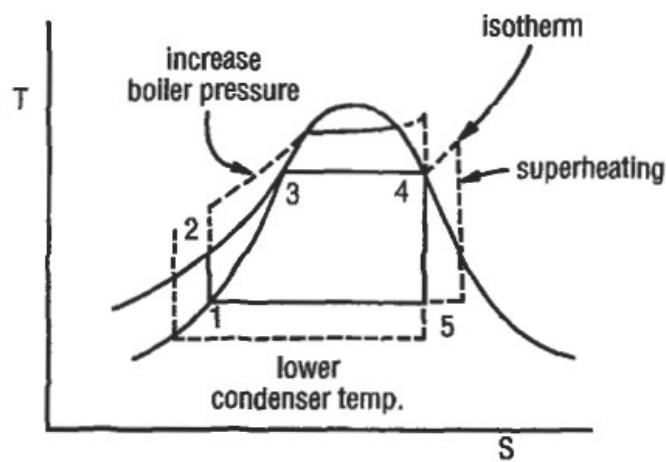


Figure 4. 3 Temperature vs. entropy graph of a simple ideal Rankine Cycle (Rajadurai 2003)

4.3.2 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) differs from the traditional Rankine cycle that its working fluid is changed from water to an organic, high molecular mass fluid, which improves the system by taking advantage of lower-grade of waste heat. Typically, the ORC is considered to be perfectly adapted for the temperature range from 50 to 350°C (Saleh *et al.*, 2007). The qualified working fluid must have characteristics that enable it to be vaporised at a lower temperature than water, so a turbine can be driven to produce mechanical work (Liu *et al.*, 2004).

Many researches have shown the interest in the working fluids for ORC, and some of the working fluids being used at the present time, include the “R” series of refrigerants. Yamamoto *et al.* (2001) stated that physical properties of the working fluid should be used to evaluate and select a fluid that will allow efficient operation.

Dossat & Horan (2001) studied a number of “R” fluids in typical refrigeration scenarios. It is noted that important characteristics of the fluid include its boiling point at standard atmospheric pressure, the evaporator pressure at 258K and 303K, specific volume of the suction vapour, refrigeration effect, and the mass flow of refrigerant per ton, compressor ratio, compressor discharge temperature, power consumption and the coefficient of performance. Data tables of major “R” fluids are readily available from manufacturers, to allow for property comparison and decision making.

There are a variety of turbines based on the ORC technology in the market; companies such as Infinity Turbine®, ORMAT Technologies Inc., Clarke Energy, and General Electrics are the leading ORC based turbine providers.

4.3.3 Kalina Cycle

According to Madhawa Hettiarachchi *et al.* (2007) a significant development in the choice of working fluids for ORC is the Kalina cycle (see Figure 4.4). Instead of using a single boiling point working fluid such as one from the “R” series of refrigerant fluids Karimi *et al.* (2016), which are typical of the working fluids of choice for an ORC, the working fluids that were found to be viable in the Kalina cycle is a combination of water and ammonia. The differences between an ORC and the relatively new Kalina cycle are summarised by Henry & Mlcak (1996):

- The ammonia water mixture has a variable boiling point
- The thermal properties of the mixture are adjustable by altering the ratio of ammonia to water composition.

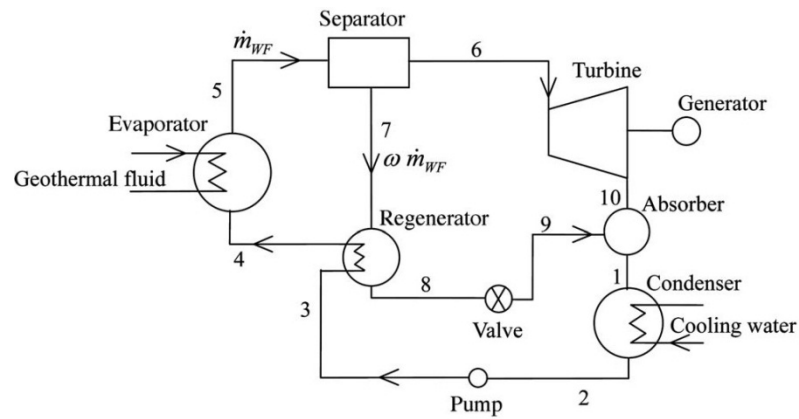


Figure 4. 4 Schematic of Kalina cycle (Madhawa Hettiarachchi et al., 2007)

- The combined mixture allows for change in temperature without a change in the enthalpy content of the fluid. Thus taking full advantage of the temperature difference between the particular heat source and sink, and enabling applications in reuse of industrial process heat, geothermal energy, solar energy, and use of waste heat from power plants.
- Due to the lower freezing point of ammonia at 195K, temperatures below the freezing point of water at 273K can be used as a heat sink in terms of improving the Carnot efficiency.

There is however a couple of potential drawbacks to a Kalina cycle operation. First being the risk of handling the ammonia and water mixture, despite many years of the development of safe handling regimes and operational requirements for ammonia (Ogriseck, 2009). Pilavachi (2000) highlighted a disadvantage of the Kalina cycle is that the absorption and distillation equipment required for the system creates further complexity and potentially significant increase in the cost of plant installation.

The Kalina cycle has been implemented commercially at a number of sites around the world, including in Japan, the US, Germany and Iceland (Fridleifsson *et al.*, 2009). However wide spread application of the process has not been seen so far (ZKG International, 2011), since current operations have not established favourable returns. According to Ogriseck (2009), at the present time, the Kalina cycle has a small market share of low temperature Rankine cycle projects.

4.3.4 Brayton Cycle

The Brayton cycle is primarily a closed engineering cycle with two constant pressure parts to the cycle. Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery.

Figure 4.5 shows the schematic of a Brayton cycle and its 4 working stages are described by Moran (1998):

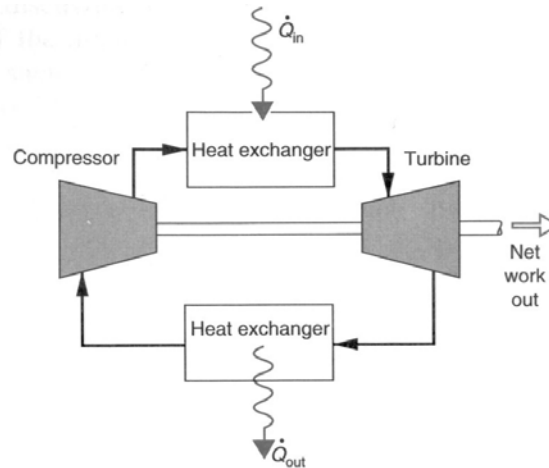


Figure 4. 5 Gas turbine using the Brayton cycle (Shapiro et al., 1998)

- The working fluid in the closed system is compressed by a compressor
- External heat energy is added to the closed loop
- Work is carried out at the turbine by the expansion of the working fluid to produce net mechanical work out and drive the compressor back to the first stage
- Heat is dissipated from the working fluid via a second heat exchanger

A temperature, T against entropy, S graph of the Brayton cycle is shown in Figure 4.6.

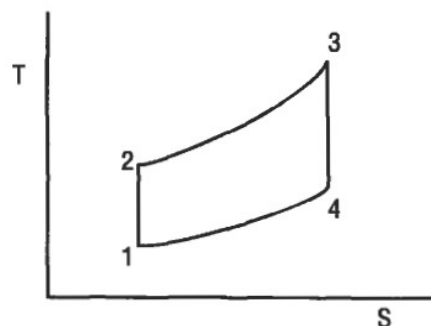


Figure 4. 6 Brayton cycle T-s graph (Rajadurai, 2003)

The Brayton cycle is the most basic application of a closed loop gas turbine, though there are further refinements using recuperates and intercoolers.

4.3.5 Absorption Refrigeration System

The absorption refrigeration system works on the principle of an absorption heat pump system, in which the traditional mechanical compressor is replaced by a ‘thermal compressor’ and absorption liquid. The absorption liquid is desorbed as a vapour upon heating and then condensed to flow through an expansion valve to be evaporated, hence producing a refrigeration effect (Srikhirin et al., 2000).

UK government's Good Practice Guide (Energy Efficiency Enquiries Bureau, 2008) reviewed two commercially available systems; lithium bromide/water and ammonia/water. They are able to achieve refrigeration temperatures of around 7°C by using a common heat sources such as low pressure steam.

4.4 Other Energy Recovery Systems

4.4.1 Heat Energy Recovery with Thermoelectric Systems

Thermoelectric devices are semiconductor systems that can directly convert electricity into thermal energy for cooling or heating or recover waste energy and convert it into electrical power. The advantage of these devices compared with more traditional engineering cycles based on heat recovery systems is the direct conversion of temperature differences to electrical power and vice-versa. Therefore it is simpler than systems that must compress and expand a two-phase (gas/liquid) working fluid, which improves efficiency in conversion (Bell, 2008). A Thermoelectric device creates voltage when there is a different temperature on each side of the semi-conductor; this is because semi-conductor responds differently to the temperature difference, creating a current loop and magnetic field when electrons move from p-node to n-node. Conversely, when a voltage is applied to it, it creates a temperature difference (Figure 4.7).

In order for this process to be efficient, it is necessary to find materials that are good electric conductors, otherwise electron scattering generates heat on both sides of the barrier and throughout the material. Also, the materials must be poor thermal conductors, otherwise the temperature difference that must be maintained between the hot and cold sides will produce a large heat backflow.

In addition, the semi-conductor materials must be selected to optimise the thermoelectric effect of the specific temperature operating ranges. It is difficult to optimise all three of these parameters because they are affected by the electronic properties of the materials and electrons conduct unwanted heat as well as electric current, and the thermoelectric effect decreases as the electrical conductivity increases.

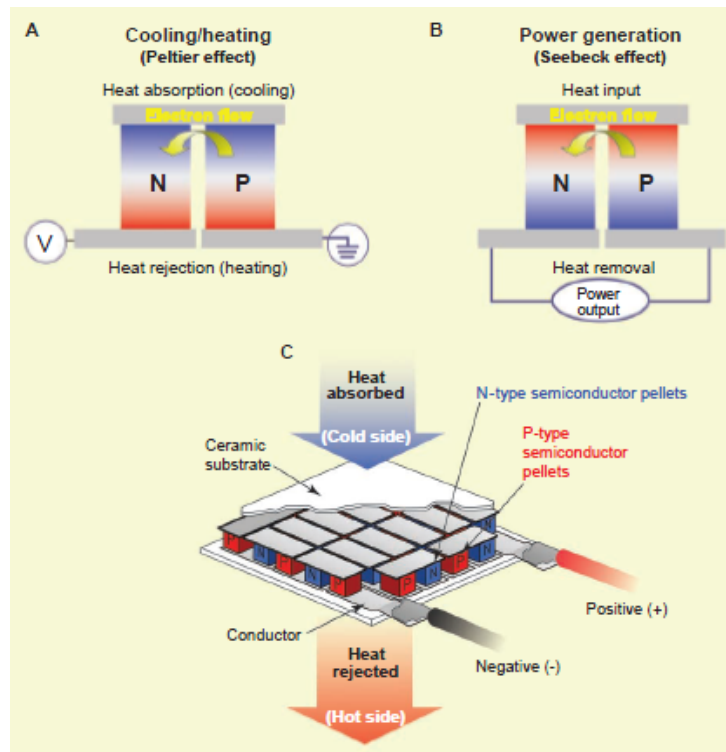


Figure 4. 7 Thermoelectric heat engines. (A) When current is run across a thermoelectric junction, it heats or cools through the Peltier effect, depending on the direction of the current flow. (B) When heat flows across the junction, electrical current is generated through the thermoelectric effect (Bell, 2008).

Over the years, thermoelectric waste heat recovery has been investigated for materials with advanced heat exchangers. Numerical heat exchanger models integrated with models for bismuth telluride (Bi_2Te_3) thermoelectric modules are validated against experimental data from previous cross flow heat exchanger studies as well as experiments Crane & Jackson (2004). Results from the validation studies show that a net power output of 1 kW can be achieved for a modestly sized heat exchanger core such that the net power density based on heat exchanger volume is approximately 45 kW/m^3 . Biswas *et al.* (2012) have recently confirmed that the highest performance is achieved with p-n junctions made from Bi_2Te_3 .

Bell (2008) developed an alternative stack thermoelectric configuration, see Figure 4.8. This can benefit from lower parasitic losses from the electrical connections between thermoelectric elements than traditional configurations. As a result, thermoelectric material volume can be lower and the weight of thermoelectric material used can be reduced by a factor of 6 to 25.

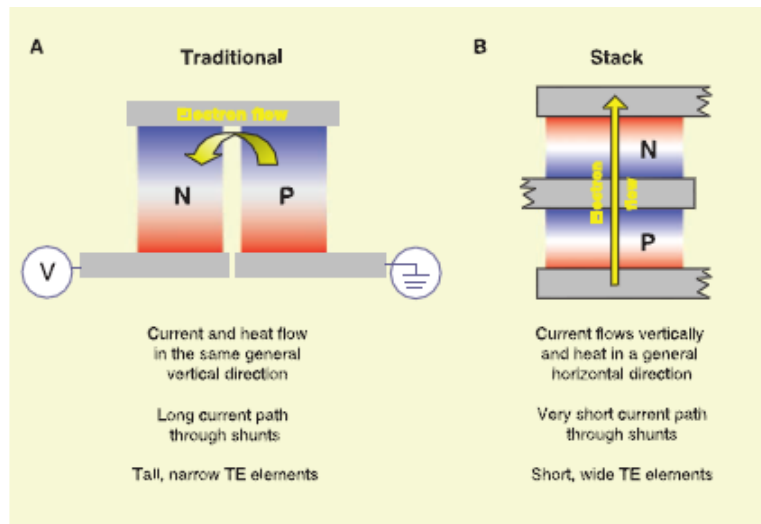


Figure 4. 8 Alternative TE junction geometries. (A) A traditional junction. Current and heat flow in the same general direction, and there is a long current path through shunts and tall narrow TE elements. (B) A stack; (Bell 2008)

4.4.2 Kinetic Energy Recovery System

A regenerative brake is a mechanism that reduces vehicle speed by converting some of this kinetic energy into another useful form of energy (Cibulka, 2009), for example, electric current or compressed air. The captured energy is then stored for future use or fed back into a power system. In battery electric and hybrid electric vehicles, the energy is stored in a battery or bank of twin layer capacitors for later use. The vehicle's electric traction motor is operated as a generator in the braking phase and its output is supplied to an electrical load, (Figure 4.9).

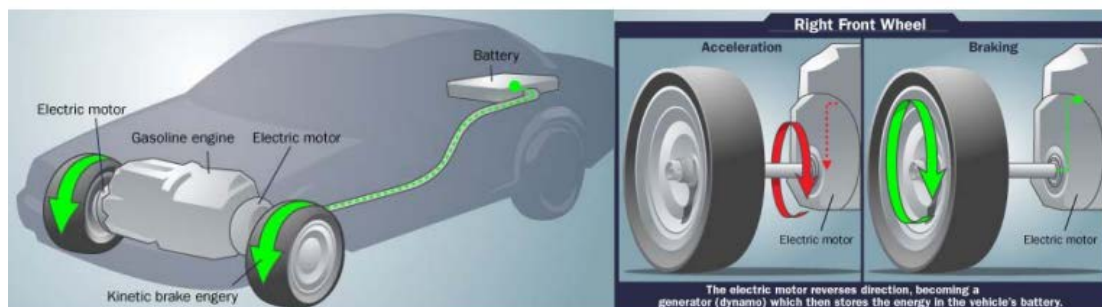


Figure 4. 9 Regenerative braking – Kinetic energy stored in a battery (Cibulka, 2009)

In recent years, design of Kinetic Energy Recovery System by means of Flywheel Energy Storage is current under tremendous development both for motor sport and road hybrid vehicles. In comparison to the battery storage, kinetic energy is allowed to accelerate an inertial mass to a very high rotational speed and maintained the energy in the system as rotational energy. The energy is converted back by slowing down the flywheel (Cibulka, 2009).

4.4.3 Energy Harvesting from Mechanical Vibrations

Vibration-powered generators are typically inertial spring and mass systems. There are three main transduction mechanisms employed to extract energy from a system, they are Piezoelectric, electromagnetic and electrostatic (Beeby *et al.*, 2006). Piezoelectric generators employ active materials that generate a charge when mechanically stressed. Electromagnetic generators employ electromagnetic induction arising from the relative motion between a magnetic flux gradient and a conductor. Electrostatic generators utilize the relative movement between electrically isolated charged capacitor plates to generate energy (Despesse *et al.*, 2008; Boisseau *et al.*, 2010).

Despesse *et al.* (2008) presented a small scale mechanical vibration harvester, having a 100g of tungsten moving mass. This structure was made with rectangular and triangular fingers (Figure 4.10). One of the most difficult challenges is maximising the capacitance variation and efficiency, and to achieve this, researchers used a geometrical non-linearity in the beams used as springs and guidance between the mass and the support. This non-linearity gives to the beams the property to amplifying the low amplitude input vibrations and to constrain the high relative displacements and to enlarge the band of frequency where the resonance is active.

4.5 Chapter Summary

In this chapter, an overview of the technology for energy recovery within manufacturing is discussed. A number of methods and technologies for energy recovery from a range of energy forms, such as kinetic energy, thermal energy, mechanical energy etc. have shown to be promising in terms of viability and effectiveness. However, comparing with the relatively mature technologies in thermal energy, kinetic and mechanical energy recovery is considerably under developed due to the facts that only a small percentage is present and is unlikely to make significant impact to the overall process and be reasonably beneficial.

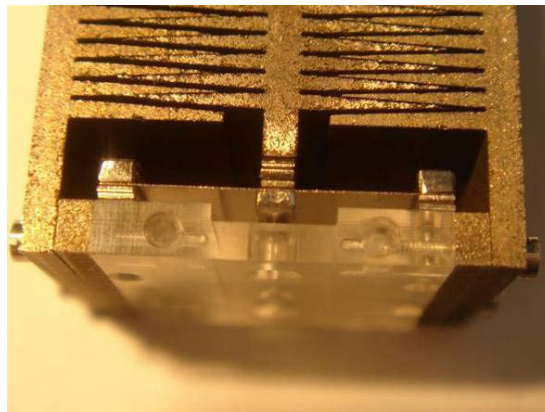


Figure 4. 10 Rectangular and triangular fingers made up the structure (Despesse *et al.*, 2008)

Chapter 5 Waste Energy Recovery Research

5.1 Introduction

Energy efficiency in the manufacturing industry is becoming an increasingly important issue due to the rising costs of both electricity and fossil fuel resources, as well as the tough targets for the reduction in greenhouse gas emissions outlined in the Climate Change Act 2008 (IEA, 2014). A significant amount of research has been done on the proactive approach to improve energy efficiency optimisation in manufacturing; however, reactive approach of energy minimisation such as recovery and utilisation of waste energy back into the main energy supply of production facilities should also be emphasised.

Waste heat recovery is a topic near and dear to many economies. The industrial sector has depleted energy tenets creating a stark shortage of energy resources. Non-renewable sources of heat remain the most preferred because of their efficiency and performance. Unfortunately, these sources pose a range of challenges to the atmospheric, aquatic and terrestrial environment. The other fold of energy is the renewable sources. This presents one of the best sources of energy including solar energy, wind and hydropower. Unfortunately, the inconsistency and the undeveloped nature of these sources of energy continue to limit uptake in industries that demand large inputs of power. Up to this end, energy is a challenge. Despite the need for industrialization and development, energy remains a precious commodity. There is therefore the need to recover waste heat and re-use it for myriad purposes including domestic and commercial needs. This review section examines a previous research performed on the recovery of waste heat giving a critical analysis of scientific literatures and scholarly sources.

5.2 Recovery from Waste Heat Energy

According to The Department of Trade and Industry (DTI)'s figure in 2014, heat related processes dominated the UK manufacturing industry, accounting for 72% of all energy consumption (DECC, 2014), within this figure, high and low temperature process represent a large share of the energy consumed of 18% and 31% respectively (Figure 3.3). There is a wide variety of waste heat in an industrial context, the main forms of waste heat that are usually available for energy recovery are exhaust gas, steam or warm liquid. In addition, heat temperature is categorised into high-grade heat and low-grade heat, in which the former represents the heat temperature range from 260°C and above while low-grade heat is defined as from ambient up to 260°C (Fox *et al.*, 2015).

A study of the current situation of recovery and reuse of surplus industrial heat carried out by the UK department of Energy and Imperial College London offers insights into heat recovery. The concept of re-capturing already used heat and channelling it to significant use is attractive. However, to achieve efficient energy recovery and ensure it serves existing demands, there is need to identify opportunities and create an economic-model that will successfully ‘bridge’ available waste heat source with a useful heat sink. The research by DECC's report argues the future will depend on how well the present recovers waste heat and use it to meet both upcoming and existing needs (DECC, 2013). To achieve this, there is need to identify the potential available in recovering the heat derived from commercial, technical and economic activities.

5.2.1 High-Grade Waste Heat Recovery

Solheim *et al.* (2009) highlighted in their research that a modern aluminium cell utilises about 50% of the total energy supplied in the form of electric work. The “useful” part consists of the chemical energy needed for conversion of alumina and carbon into aluminium and carbon dioxide, while the rest is dissipated as heat. The concept was to deploy active cooling of the anode yoke using compressed air. The amount of heat extracted by active cooling was collected to produce electricity, however as this is a Carnot process, the theoretical maximum energy efficiency (η , ratio between work out and heat in) is governed by,

$$\eta = 1 - \frac{T_{min}}{T_{max}} \quad [Equation 5.1]$$

where T_{min} and T_{max} [K] are the minimum and maximum temperature in the cycles, respectively. In order to improve efficiency, a thermally insulated anode top is also used since this gives the higher amount of heat recovered. The air from the yokes can be recycled in a closed loop. It will therefore be clean, which enables the use of a simple heat exchanger design with a high efficiency.

Ladam *et al.* (2011) have also done a preliminary study concerning the possibilities of recovering waste energy in aluminium electrolysis and use for electrical power production. Three main heat sources in the process (cathode sides, anode yokes and gas) were combined in different ways, using different types of power cycle. The performance of a large number of thermal cycles, layouts and combinations of heat sources were studied and results have shown that the potential for electrical power production is significant. This is achieved by having two power cycles, through both distributed open Brayton cycle based on a turbo charger and through centralised power production with a Rankine cycle.

Energy recovery from high temperature slags has been actively discussed since the iron and steel industry is the largest industrial energy consumer (Bisio, 1997). In this research, waste energies in iron and steel works were grouped into four exergy categories (Tian & Zhao, 2013): (a) chemical exergies of outlet gases including Blast-Furnace Gas (BFG), converter gas and coke-oven gas; (b) pressure exergy of BFG; (c) thermal exergies of waste gases, refrigeration air and refrigeration water; (d) thermal exergies of outlet sinters, steel block, blast-furnace slags and converter slags. The last category represents the largest waste energy potential in the high-temperature range (1450 – 1650 °C) (Bisio, 1997).

Modern technologies and research has made a tremendous improvement in energy efficiency for metal manufacturing industry in the past several decades. Barati *et al.* (2011) claimed that waste heat of slags in metal manufacturing operations can be as large as about 220 TWh/year at temperatures in the range of 1200 – 1600°C, and currently the three types of commonly used technologies for energy recovery include use of hot air or steam, conversion to chemical energy as fuel and thermoelectric power generation.

However a fundamental constraint to recover energy from metallurgical slags is the low thermal conductivity of slag, ranging from 1 to 3 $W m^{-1} K^{-1}$ for solid to 0.1-0.3 $W m^{-1} K^{-1}$ for molten slags at 1400-1500 °C (Allibert *et al.*, 1995; Goto *et al.*, 1985). Numerical simulations (Barati *et al.*, 2011) and experimental measurements (Yoshida *et al.*, 1984; Yoshinaga *et al.*, 1982) of temperature distribution inside a slag droplet suspended in air indicate considerable temperature gradients. The data in Figure 5.1 show temperature difference of a 5 mm slag droplet between its surface and centre can be as high as 200°C. This has suggested that in order to achieve efficient heat recovery, the slag must be broken up into small droplets with a large surface area available for heat transfer.

Many designs of slag granulation have been implemented by research institutes and industries. Nippon Kokan (now JFE) (Yoshida *et al.*, 1984) and Mitsubishi Heavy Industries Ltd. and Nippon Kokan (1982) developed an air granulation system to recover heat from multiple stages of slag granulation including the flying slag drops and hot solid slag particles which can transfer heat to boiler pipes, by radiation and convection of exit air, which is then utilised for preheating combustion air. An energy recovery of 40 – 45% of the slag heat energy can be achieved (Works, 1983). A plant built by Kawasaki Steel used a cooling drum process to granulate liquid slag to particles smaller than 100 mm in stirrer, while water pipes are heated by radiation. The granulated slag is cooled in a tower to 250 °C while air is heated. The hot air produces steam in a closed cycle and this steam is utilised to produce electrical power (Maruoka *et al.*, 2004).

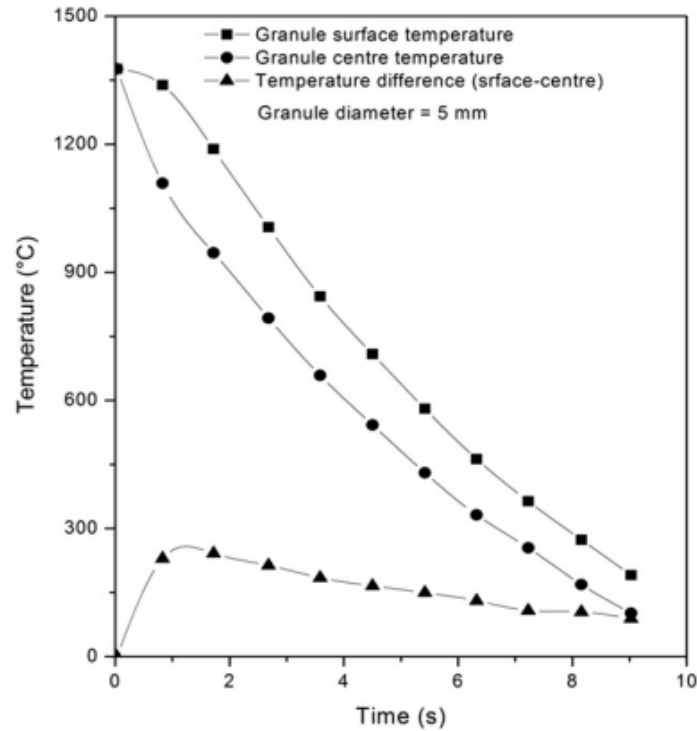


Figure 5.1 Temperature history of a 5 mm slag drop cooled in fluidized bed (Yoshinaga *et al.*, 1982)

Generation of fuels based on the utilisation of the slag thermal energy in endothermic reactions has been recently studied. Table 5.1 shows the reactions are proposed to generate CO, H₂ and their mixtures through gasification of coal (Akiyama *et al.*, 2000).

Energy recovery by methane reforming is one of the solutions proposed by Kasai *et al.* (1997), in a system in which heat from molten slag is transferred to a steam reformer to for the reaction between methane and steam, generating CO and H₂. The still molten slag is then transferred to the granulation stage, in which steam is generated by extracting the remainder of the sensible heat. The steam is fed back to the reformer, where hot CO and H₂ mixture is to go through a heat exchange to generate steam for power generation. On the other hand, the chemical energy of the gas mixture is partially recovered in the methanation reactor where the reverse reaction generates methane and steam. Water vapour is condensed in a second heat exchanger and methane is directed back to the reformer (Figure 5.2).

Table 5.1 Endothermic reactions for chemical recovery of waste heats (Akiyama *et al.*, 2000).

Reaction	Enthalpy (kJ/mol)	Exergy (kJ/mol)
(1) C + CO ₂ → 2CO	172	122
(2) C + H ₂ O → CO + H ₂	131	91
(3) CH ₄ + CO ₂ → 2CO + 2H ₂	247	171
(4) CH ₄ + H ₂ O → CO + 3H ₂	206	142
(5) C ₃ H ₈ + 3H ₂ O → 3CO + 7H ₂	498	298
(6) CH ₃ OH → CO + 2H ₂	90	25

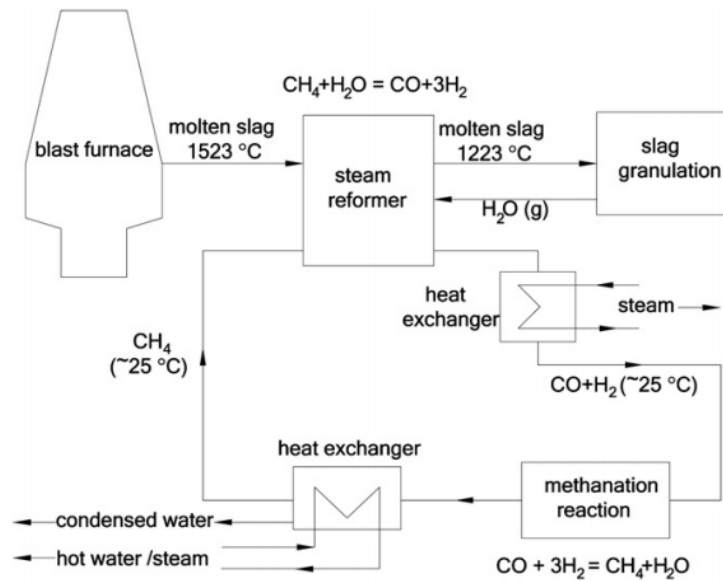


Figure 5. 2 Process flow diagram for energy recovery through methane reforming, adapted from Kasai *et al.* (1997)

Maruoka *et al.* (2004) designed a new system in which the slag is first granulated using a rotary cup and is then accumulated in a packed bed. The steam reforming of methane takes place with the aid of a Ni-based catalyst. The thermal energy required for the reaction is recovered by direct heat exchange between the gas mixture and slag granules.

Energy recovery by coal gasification was first studied by Li *et al.* (2010). In the proposed coal gasification system, CO₂ is injected together with coal into a molten Blast Furnace (BF) slag bath, generating CO through reaction $C + CO_2 = 2CO$. The heat of the emitted gas is recovered in a heat exchanger to make steam while the cleaned gas is used as fuel.

Direct electricity generation from waste heat has been recently studied by Rowe (2006) and reviewed by Barati *et al.* (2011), and is recognised as an environmental friendly, safe and reliable technology which can convert unused heat into electricity. The technology uses semiconductors with Seebeck coefficient in the order of several hundred microvolts per degree to convert heat directly to electrical power. This has been implemented for high quality heat sources such as molten slag, however, low temperature trials have also been successfully carried out on a laboratory scale and in prototype commercial systems.

5.2.2 Low-Grade Waste Energy Recovery

Yasmin Ammar is one of the pioneers of this concept of thermal heat recovery. The author, alongside a team of scholars, demonstrates that thermal heat can be recovered and channelled for use in manufacturing and processing industries. In a research study, the author observes that thermal energy is lost on a daily basis posing a great challenge to the atmosphere and the

environment at large. The multiple heat intensive practices involved in the generation of thermal heat remain a critical issue in waste heat harvest. Thermal heat, as much as it accelerates the rise of atmospheric temperatures, can be harvested and re-used to ensure economies meets rising industrial and commercial heat demands. The process of capturing and utilizing thermal heat, particularly the selective low-grade one, will help in efforts to conserve energy and move towards a sustainable future. Multiple waste heat recovery studies have explored suitable models of low-grade waste heat recovery.

One example is the work of Law *et al.* (2012) who advance this research on the available opportunities for low-grade recovered heat. This research finds out that the ever rising cost of fossil fuels and electricity provides an incentive for low-grade heat recovery. The research alludes to a number of scholarly sources revealing the estimated potential for heat recovery in United Kingdom as 11.4 TWh/year. This represents around 5% of the total consumption of thermal heat (Law *et al.*, 2012). The research by the three scientists projects that increasingly effective use of energy-sensitive technologies will make it easier to tap into the great potential of thermal heat. Thermal heat in United Kingdom is clearly available in food and beverage processing industries. This sector is perhaps one of the largest sources of thermal energy – it also offers increased opportunities for low-grade heat. Low grade heat recovery can be classified into generic unit operation or sector specific unit operation: processes such as air compressors, boilers and power plant are grouped as generic since they are common in all industrial sectors, and use low-grade heat to control the environment in the forms of hot gases etc., as well as accounting for a significant portion of plant electricity use. Typically a boiler flue gas gives off a gas/vapour stream at 200°C (Carbon Trust, 2014). This part of the waste heat is currently recovered using air pre-heaters, heat exchangers and condensing heat exchangers. However it is still common for smaller processing plants to send this heat through the stack which then dissipates into the environment.

Sector specific unit operations include cooking, drying, evaporation, washing and sterilisation, pasteurisation, distillation and refrigeration. Industrial ovens or fryers are most commonly used for cooking food and a certain amount of low-grade heat is produced besides that required for their primary operation, such as through oven exhaust gases at around 150-250°C, and 200°C for fryers (Wu *et al.*, 2012). Similar to cooking, food processes that involve drying also produce exhaust which has the capability to provide a low-grade gas/water vapour heat source, typically in the range of up to 160°C. Common recovery and utilisation of this heat source includes pre-heating the dryer air inlet (Atkins *et al.*, 2011). A summary of heat sources of each process is shown in Table 5.2.

Table 5. 2 Summary of heat sources and their nature, adapted from Good practice guide 141, (2002)

Source of heat	Nature		
	Gas	Liquid	Vapour
Air Compressor	X	X	
Boiler	X	X	X
Distillation		X	X
Drying			X
Evaporation	X	X	X
Kilns	X		X
Ovens	X		X
Pasteurisers		X	
Process Cooling	X	X	
Process Heating	X	X	X
Refrigeration	X	X	
Sterilisation	X	X	
Ventilation	X		
Washing		X	

It can be seen from the table that some sources of heat have the same nature or ‘carrier’. Therefore, selecting a most appropriate technology to match the quality of the heat source and efficiency of the sink has far more significance.

In general terms, it is more economical to recover the heat for transfer to a suitable heat sink by heat exchange or direct re-use as this equipment has the cheapest capital outlay. Inherently, it is also preferable to restrict the transfer of this heat to within the process from which it is emitted or to a nearby process as this saves the cost of transport and pipe work, ducts and auxiliary equipment (Law *et al.*, 2012). Solutions such as heat pumps and units to generate electricity or refrigeration require more capital outlay due to higher equipment costs (See Figure 5.3).

Selection criteria based on whether or not a suitable heat sink is available for heat change between source and sink and if it is also possible for refrigeration as an alternative use of the waste heat. Also cost effectiveness is another consideration as more complex recovery systems have higher capital outlays and are more complicated to install.

McKenna & Norman (2010) have identified the iron and steel sector in the UK as the largest user of heat with a load of approximately 213 PJ which indicates significant potential for heat recovery. In their case study, processes in a steelmaking plant were studied and a number of streams containing low-grade heat were identified for demonstration purposes, flue gas from the coke oven was chosen as being most suitable for recovery. The suitability comes not only from the consistent operation of the coke oven, but also from the reduced potential for process disruption (Walsh & Thornley, 2013). A flue gas stream with a temperature of 221°C and a flow rate of 66kg/s was estimated to yield 21 MW of recoverable power.

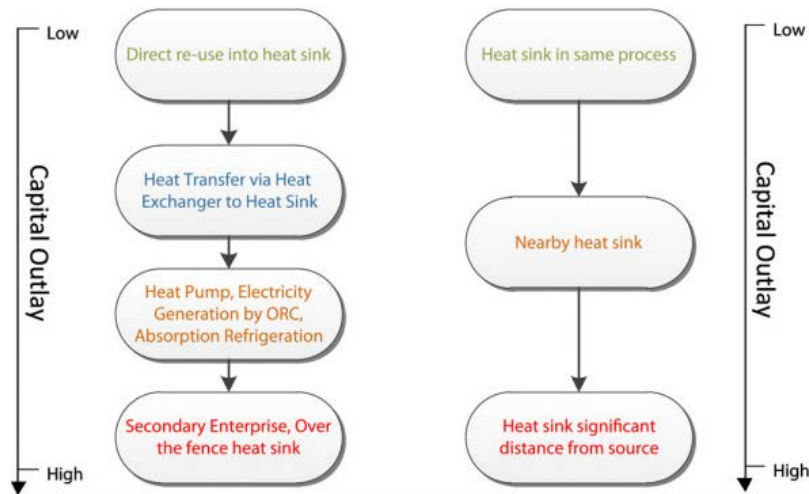


Figure 5. 3 Flow chart of capital costs of each type of project, from low to high, adapted from Law *et al.* (2013)

Walsh & Thornley (2013) studied two low-grade heat recovery options within manufacturing and carried out an industrial case-study for each one of them to reflect the findings. The two options carried out include Organic Rankine Cycle (ORC) and condensing boiler. In one of their case studies, a condensing boiler is used to recover latent heat from a waste gas steam in order to improve thermal efficiency. Condensing boilers can be used as direct or indirect systems which differ in the way that there are no boundaries isolating hot combustion gases from the stream to be heated, whereas an indirect system recovers heat from hot flue gases by passing them through one or more heat exchangers. Chen *et al.* (2012) performed a similar study examining the impact of a condensing boiler on a Finnish woodchip fluidised bed boiler which provides heat for a district heating system. It was estimated that the condenser improved the thermal output of the plant from 40 MW to 52 MW.

5.2.2.1 Recovering Low-grade Heat Energy

It is hard if not impossible to capture, store and re-use high-grade thermal energy (Gieré & Stille, 2004). However, it is possible and significantly practical to make use of low-grade heat. Low-grade heat refers to low-temperature heat that has a relatively low density. The heat can be captured and stored although this depends on the quality and property of waste heat, particularly in waste streams. As Ammar argues, the temperature stored in low-grade sources of heat is among the highest ranking parameters to consider when capturing (Ammar *et al.*, 2013). The author observes that the effective use of collected low-grade heat will depend on the temperature difference between the source and the sink. For instance, the significance of low-grade heat will be determined on where the energy is being collected and where it is channelled. More clearly, if a geothermal source of energy is tapped, the low-energy heat derived from this source might be slightly above domestic needs. This is to say the temperature difference between the sink (domestic needs) and the source (geothermal plant) must be compatible to allow effective use of harvested waste energy.

Additionally, tapping into the potential of this energy also goes a long way towards identifying potential sinks. From the research, common sinks in the industrial sector are expected to lower significantly the heat duty offered by these utilities. Oven air and drier inlets are classic examples of heat sinks. These technologies make it easier to exploit an economically cheap energy. When oven and drier inlets are used as sinks for recovered energy, they provide an incentive towards trapping and recovering more waste energy. A plant refrigeration system is another classic sink for recovered waste energy. In this case, the waste heat can be used to operate an absorption refrigeration component. Doing this will make it easy to minimize the load of the currently used system. Up to this end, common sinks of recovered waste energy provide an important incentive towards recovering energy and channelling it effectively.

To make profitable use of recovered low-grade heat, it is important to examine recovery technologies. This research proposes the best criterion for achieving this is determining whether there is a suitable sink. There should be an appropriate sink for effective heat exchange. The heat exchanger technology is perhaps one of the leading systems that makes effective use of waste heat (Kaushik *et al.*, 2011). This means any infrastructure that operates behind the concept of heat exchangers has the potential of being a sink. Specifically, machines that share similar technology as a typical heat exchanger can utilize recovered waste heat. The concepts presented in the research of waste heat recovery remain instrumental in understanding how effectively collected waste energy can be brought to use. Theoretical models championed by the research remain critical in showing how sources and sinks of recovered heat are related. This relationship provides the basic concept of using recovered waste heat in commercial, economic and technical platforms. The research puts forward machines where harvested waste energy has been applied: thermoelectric units, liquid heat exchangers and refrigeration systems (Law *et al.*, 2013). The research concludes by pointing that increased use of waste heat will help improve the entire efficiency of technological plants – especially those capable of using fairly low-temperature energies.

5.2.3 Identifying Potential Sources of Waste Heat Energy

Industries, both manufacturing and processing, can offer reliable sources of waste heat energy (Atkins *et al.*, 2010). Low-grade heat, however, although available in such contemporary industrial platforms, requires a highly technical approach in harvesting. Ammar, in a section of her research to identify significant sources of energy, observes that process industry in the UK poses a significant source. In 2006, the Carbon Trust estimated the potential of thermal energy in United Kingdom as 18TW h. The McKenna source pursued a similar research linking this energy to between 10 – 20 TW h. In both research studies, a number of industries were pointed as significant sources (Carbon Trust

2011). These sectors include; cement, glass, food and drinks, chemical, ceramics and aluminium. The diverse range of industries in the United Kingdom market offers classic entry points for heat recovery.

Up to this end, it is clear that harvesting low-grade heat goes a long way in identifying potential sources. Doing this also involves linking the availability of energy to harvesting technologies. The collective potential of above sectors, including others such as steel, paper, pulp, lime and gypsum, can offer a great potential in low-grade heat waste recovery. Ammar's research into low grade thermal energy sources thus remains instrumental and forms a valuable guide for experts on what channels to tap into for successful collection. A close look at the research reveals that recovering low-grade heat can be done in myriad of ways. However, these approaches are extremely technical and require expert modifications. Ammar's research offers the architecture of a thermal exchanger noting that the in-built structures do not fully add towards effective heat collection. The research also casts a strong eye to the direct Rankine hybrid cycle. A critical analysis of this source of thermal energy shows the possibility of collecting low-grade thermal heat.

From the direct Rankine hybrid cycle, the research uncovers the need to revise a number of components. These include; the steam turbine, the generator, the cryogenic pump and the heat exchanger. These components remain instrumental in ensuring low-grade heat can be harvested and channelled effectively to suitable sinks. The first research (by Ammar) creates deep insight as to how low-grade heat can be captured and used for designated purposes. Machines used in industries should be examined, analysed, evaluated and cross-checked to ensure they meet the rising need of waste energy recovery. These machines emit insurmountable volumes of thermal energy anytime they are in use (Reddy 2011). The amount of rejected energy rises with time and task. Of special concern to recovery is to ensure machines are able to conform to collection technologies. For instance, the condenser, the generator, steam turbine, pumps and heat exchangers should be designed to allow collection of low-temperature heat. Through technical know-how, industry innovation and research can be achieved.

5.2.4 Application of Recovered Heat Energy

Effective and timely application of recovered heat is another section discussed in the research. Imperial College observes that the application of recovered heat will depend on the nature of sinks and how these sinks are prepared to deal with the volumes of energy from sources. The term "sink" typically refers to a range of structures where recovered heat is used. These sinks include; appliances, on-site tools, low-energy machinery and related applications. The nature of these sinks can affect the application of recovered heat depending on the volume of energy needed for above

infrastructures to operate (Imperial College London 2014). More specifically, the operation of an iron box as a sink of recovered heat will be determined by the voltage of energy the iron uses. Hence, it is important to design sinks in a way that can tap recovered waste energy and bring it to significant use.

Another important component for the research was to examine the opportunity provided in using recovered heat. From a critical analysis of the research, the United Kingdom industry consumed approximately 20% of the total energy in the country's economy. The industry generates 32% of the country's related carbon dioxide emissions with the manufacturing industry leading for energy efficiency. The Digest Source for UK Energy Statistics observes that 73% of the total industrial heat demand is used exclusively for heating purposes. 22% of this energy is for high-temperature purposes and nearly half is for low-heat energy purposes. From the above statistics therefore, the United Kingdom represents a massive hub of thermal energy. The industrial sector dominates the country's energy consumption at 73%. This suggests that a great deal of waste energy could be harnessed from the country's industrial sector.

Both high and low temperature activities can be modified to ensure energy output is recovered and used for third party activities; domestic and commercial purposes. The research proposes that heat intensive industries may consider integrating recovery technologies inside machines. For instance, part of the amount of heat converted in the manufacture of cement should find a way through specialised external sources. Specifically, not all energy consumed by manufacturing sources is used, part of it gets lost in the atmosphere and part finds its way through unconventional sources. Recovering waste heat goes a long way towards identifying heat escape points and determining how these points can be sealed by specialized sources. These sources are the waste heat recovery models the research refers to. To this end, there is high potential for recovering and re-using industrial energy. Surplus thermal energy can be used to seal a number of gaps – including running domestic and commercial appliances.

From the research, re-use of industrial waste heat is a favourable concept that can be used in solving the universal heat crisis. The United Kingdom industry represents a great deal of thermal energy that is not channelled to any significant use. Yet, this sector represents the highest consumer of energy. To address this, machines, tools and technologies leveraged for industrial activities can be modified to ensure waste energy is recovered. This approach requires technical know-how, innovation and cutting-edge industrial technology. It is recommended that government policies should support this requirement through waste energy recovery incentives. The literature has identified a number of supporting research concepts including: thermal heat modelling, drivers for waste heat recovery, development of techno-economic models, heat recovery technologies and energy-application bases.

Only such a joined up strategy will enable the required critical awakening in the recovery of waste energy.

5.3 Energy Recovery System for Electric Motor Drive System

Nowadays, particular attention is being paid to whether energy can be recovered from manufacturing equipment and tools. This is especially true for those which function in a way that is repetitive and where rapid accelerating and decelerating operations are required.

An analysis of energy recovery systems serving injection moulding machinery by Takahashi *et al.* (2010) indicates that the current system, in which the regenerated energy produced from the motor drive system is mostly consumed by resistors connected to the Direct Current (DC) bus line of the inverter, is not efficient in terms of energy saving. An energy recovery system with Electric Double-Layer Capacitor (EDLC) for motor drive systems is analysed using computer aided simulation.

Energy losses in the electric motor drive system during decelerating and accelerating operation of an injection moulding machine are identified (Takahashi *et al.*, 2010). The energy losses are generated in each part when the energy from the motor is stored into EDLC, similarly the losses are generated when energy is drawn out of the storage system to power the motor, with the shortfall of the demand energy to be supplied from the utility grid (Figure 5.4).

Simulation results show that a total of 5300J of regenerated energy is available, however due to energy losses in each part of the operation; the actual recoverable energy is 4130J and was charged into EDLC. As in the accelerating operation, energy stored in the EDLC and from utility supply contributes to the final demand energy.

Comparisons between machine with and without energy recovery system were also carried out and a 49% energy saving was achieved by adding an energy recovery system with EDLC (see Figure 5.5).

5.4 Energy Harvesting from Vibration

Energy harvesting, also known as energy scavenging, is the process by which energy is collected from external sources in the surrounding environment, and stored for small, wireless autonomous devices, such as those used in wearable electronics and wireless sensor devices.

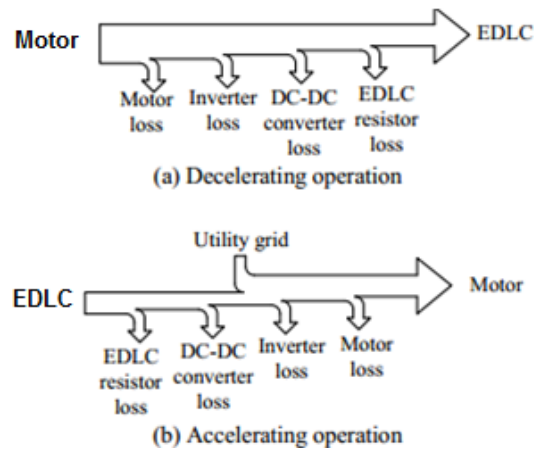


Figure 5. 4 System energy flow of decelerating and accelerating operation, adapted from Takahashi et al. (2010)

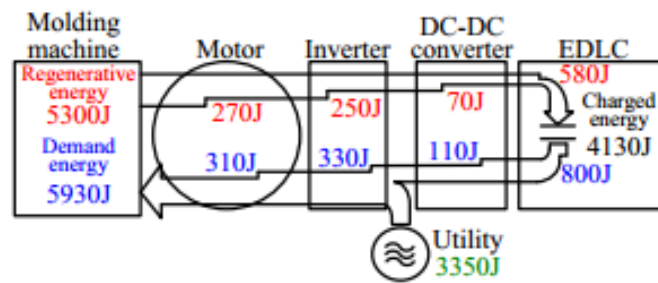


Figure 5. 5 Losses generated at each part and the energy flow per cycle, adapted from Takahashi et al. (2010)

Energy harvesting technologies have attracted much interest across the commercial and industrial sectors especially those systems which scavenge energy from ambient vibrations, wind, heat or light and enable smart sensors to functional indefinitely. Consequently many academic and commercial groups have been involved in the development of vibration powered energy harvesting technology.

Beeby *et al.* (2006) at the University of Southampton reviewed the state-of-the-art vibration energy harvesting for wireless, self-powered microsystems and three principal transduction mechanisms that are associated in order to extract energy from the systems. These transduction mechanisms are: piezoelectric, electromagnetic and electrostatic.

Despite the potential opportunity for energy harvesting, the applications of these technologies are very limited and their complexity often leads to implementation constraints. Most importantly, no significant improvement to the energy efficiency has been achieved to date.

5.5 Chapter Summary

Energy security is a topic near and dear to many nations. The conflicting nature of non-renewable energy sources presents a stark challenge to governments. Because of the growing need for industrialisation, governments are finding it important to use conserve non-renewable sources of

energy more efficiently. Renewable sources of energy such as solar energy, wind energy, water energy (in form of hydropower) and related sources are considered promising but unfortunately, the output of renewable sources does not fully live up to the expectations of high-input industries. This means that wind power or solar energy cannot be sustainably used in a paper milling industry. Thus, both sources of energy, renewable and non-renewable, need to be revisited to ensure the waste heat recovery and reutilisation is able to operate in a streamlined fashion in industry. Re-using energy is perhaps the best alternative to energy crisis (Atkins *et al.*, 2010). Re-using energy goes a long way towards identifying the operation and model of industrial machines. As it appears, the existing technology can only harvest low-grade waste energy because of its low-temperature density. Currently, waste heat recovery requires a significant effort towards a sustainable future.

This offers a reason that this review section subscribed to a range of scholarly and scientific sources to expand the scope of its analysis. Recovering and re-using high and low-grade heat remains one of the greatest efforts towards a sustainable future. The review has examined currently existing waste heat recovery studies. This review also takes a critical look at three studies describing the theories and models advocated by each of them. This section expands the search scope and describes the relationship that exists between the sources and sinks of waste energy. In doing so, it pulls together knowledge and creates insight into currently existing waste energy recovery approaches and sets the scene for the main research into how systematic recovery of waste heat energy is achieved.

Chapter 6 **Research Methodology**

6.1 Introduction

This chapter provides an overview of the research methodology used within this thesis. It begins with an overview of common research methodologies, identifying the main characteristics of each and proceeds to provide an interpretation of the preceding literature review together with the corresponding refinement in the research hypothesis based on the knowledge gap established. It then describes the research approach taken to bridge this capability gap, which consists of the description of a four stage framework for the identification and evaluation of waste heat energy recovery. The chapter concludes by introducing a software tool to aid waste heat energy recovery decision support within a manufacturing environment. A schematic of the research activities is provided at the end of the chapter.

6.2 A Brief Overview of Research Methodology

According to the Oxford Dictionary, research is defined as “the systematic investigation into and study of materials and sources in order to establish facts and research new conclusions.” It is usually associated with technical terms such as experimentation, testing, analysis and fact-finding. According to Creswell *et al.* (2003) it is the process of making assertions and then refining or abandoning some of them for other statements more strongly justified. There are numerous different research methods being used for management, natural and social sciences and engineering which include the scientific method, theoretical and analytical method, empirical method, survey method, action method, and so forth. Clearly each method requires a different approach, but for any given work regardless of the method chosen, the results and conclusions should be the same.

Research methods are conventionally divided into quantitative, qualitative and mixed each with different approaches, tools and techniques. Quantitative methods are dominantly concerned with rigorous experimental measurement in order to determine the truth or falsehood of particular pre-defined hypothesis. Whereas qualitative method is a type of scientific research that consists of an investigation that: seeks answers to a question, systematically uses a predefine set of procedures to answer the question, collects evidence, produces findings that were not determined in advance and produces findings that are applicable beyond the immediate boundaries of the study. Qualitative research is especially effective in obtaining culturally specific information about the values, opinions, behaviours and social contexts of particular population. The three most common qualitative methods are participant observation, in-depth interviews, and focus groups. Each method is

particularly suited for obtaining a specific type of data. The mixed method involves the researcher making knowledge assertions on pragmatic grounds and employs strategies of inquiry that involve collecting data either simultaneously or sequentially to best understand the research problems (Creswell 2003). The research methodology adopted by this thesis is closely related to the mixed method research, which is further described in the next section.

6.3 Research Methodology Adopted in this Thesis

The proposed research methodology consists of four stages:

1. Review of research background, making hypothesis and definition of scope
2. Framework and software tool development
3. Testing and validation of research concept and case studies
4. Discussion and research conclusions

The methodology adopted is in line with those commonly used within typical engineering research (John W. Creswell, 2003). Figure 6.1 provides an overview of the research approach, highlighting how various elements of the research are grouped within the four stages.

6.3.1 Review of Research Background, Research Questions and Define Scope

The initial research assertion “How do we identify the quantity, quality and availability of waste heat energy from a manufacturing process, and determine the most appropriate technology for recovery?” was defined based on the author’s prior knowledge and a number of industrial visits one of which was to a chemical etching facility and the other to a large automotive engine casting plant. The knowledge was then further developed by conducting an extensive review of the literature, regarding the energy management systems within manufacturing, state-of-the-art technologies used for waste energy recovery and current research carried out in this field. During the establishment of the research background for the thesis, via literature survey and industrial visits, it became apparent that just like the proactive and reactive approaches that are adopted for materials recycling, there was also an opportunity for energy to be considered via the reactive approach to explore energy recovery, options including tools and technologies that are capable of harnessing waste energy and reutilising this within a manufacturing environment. The research assertion was then refined to acknowledge that waste energy recovery is an area of broad aspects, including waste mechanical, light, sound, and chemical energy which are generally more difficult to harvest and of insignificant value compared to waste heat which is easier to recover and is of more benefit to the manufacturers. There are numerous waste heat recovery technologies on the market, however because of the lack

of knowledge and informed decision making, industrial waste heat is often not recovered in a systematic and therefore optimised way.

6.3.2 Research Activities and Framework Development

The final establishment of the aim, objective and scope of the research led the work into the second stage (i.e. Research activities and framework development). Based on the definition of research assertion and questions, the research is focused on the development of a framework for waste heat energy recovery, by which different scenarios of waste heat sources, sinks and recovery technologies can be defined, assessed and compared. From the research objectives, the evaluation methodology adopted in the framework is required to evaluate quantity and quality of waste heat energy source in a manufacturing facility with quantitative and qualitative descriptors such as temperature, pressure, contaminant, temporal availability etc., so as to compare the waste heat sources with suitable uses within a factory. Subject to the information obtained from the comparison between waste heat sources and potential uses, the framework also allows for identification of appropriate methods and technologies to harness waste heat provided by the knowledge of technology database from extensive literature survey and waste heat energy survey. This provides a structured approach, identifying advantages and disadvantages of each method and technology, and visually compares many different solutions to give decision making guidance for complex problems. Interpretation of obtained information and calculation is also required to process data and make informed decisions for industries to quickly react. Thus a software tool is implemented to aid the framework in an accessible way. In addition, information provided by a cost and benefit analysis also enables evaluation of economic and environmental impact for the chosen solution in order to provide an optimised decision.

6.3.3 Testing and Validation of Research Concept and Case Studies

After the framework was structured, the software tool required validation by case studies. The objective of carrying out this additional step was to test the software with practical issues by gathering real data and its ability produce consistent results. In order to verify the performance of the framework and software tool, two different cases examples were carried out. In this thesis one example is in the low temperature manufacturing industry while another example focuses on a high temperature processes. The purpose of having such arrangement of case studies is to: 1) validate the functionality of the framework and software tool when applied to the two extreme ends of the spectrum, and 2) to compare recoverability, economic benefit and reutilisation method of each case. The use of case studies to validate the framework and software tool allows findings to be analysed and further improvement of the framework, potential iteration process to be incorporated within

the decision making system. A systematic approach was developed to conduct both of the case studies with data from both provided and collected via onsite sources.

6.3.4 Discussion and Research Conclusions

The completion of the case studies marks the start of the final stage of the research which discusses all research results documented in the thesis in order to draw overall conclusions. The purpose of the discussion is to explain the results and their potential implications and limitations. It also scrutinises the results obtained and discusses the possible influence of methodological biases and errors on data validity. The discussion also addresses general limitations and weakness of the study and comments on these. The conclusions section summarises the answers to the research questions and assertions raised in Chapter 2, which then leads to the generation of concluding statements based on the findings.

6.4 Chapter Summary

This chapter has identified the different types of research utilised in the thesis, based on the requirement to address the research aim and objectives identified in Chapter 2. The research methodology adopted in the thesis has been presented by following the aforementioned general overview. The four stages of research methodology have been illustrated schematically, showing the stepwise development of this thesis. The research supported by the first stage of the methodology is reported in the earlier part of the thesis, in Chapters 1-5. Similarly, stages two and three of the research methodology are documented in Chapters 7-9 and Chapters 10-11 respectively, and finally Chapters 12 and 13 cover the fourth stage of the research methodology. Although the methodology presented in Figure 6.1 suggests a linear progression through the four stages defined in this section, it is acknowledged that research has an iterative nature, such that specific aspects may require revisiting and refinement in light of new findings, as the research progresses.

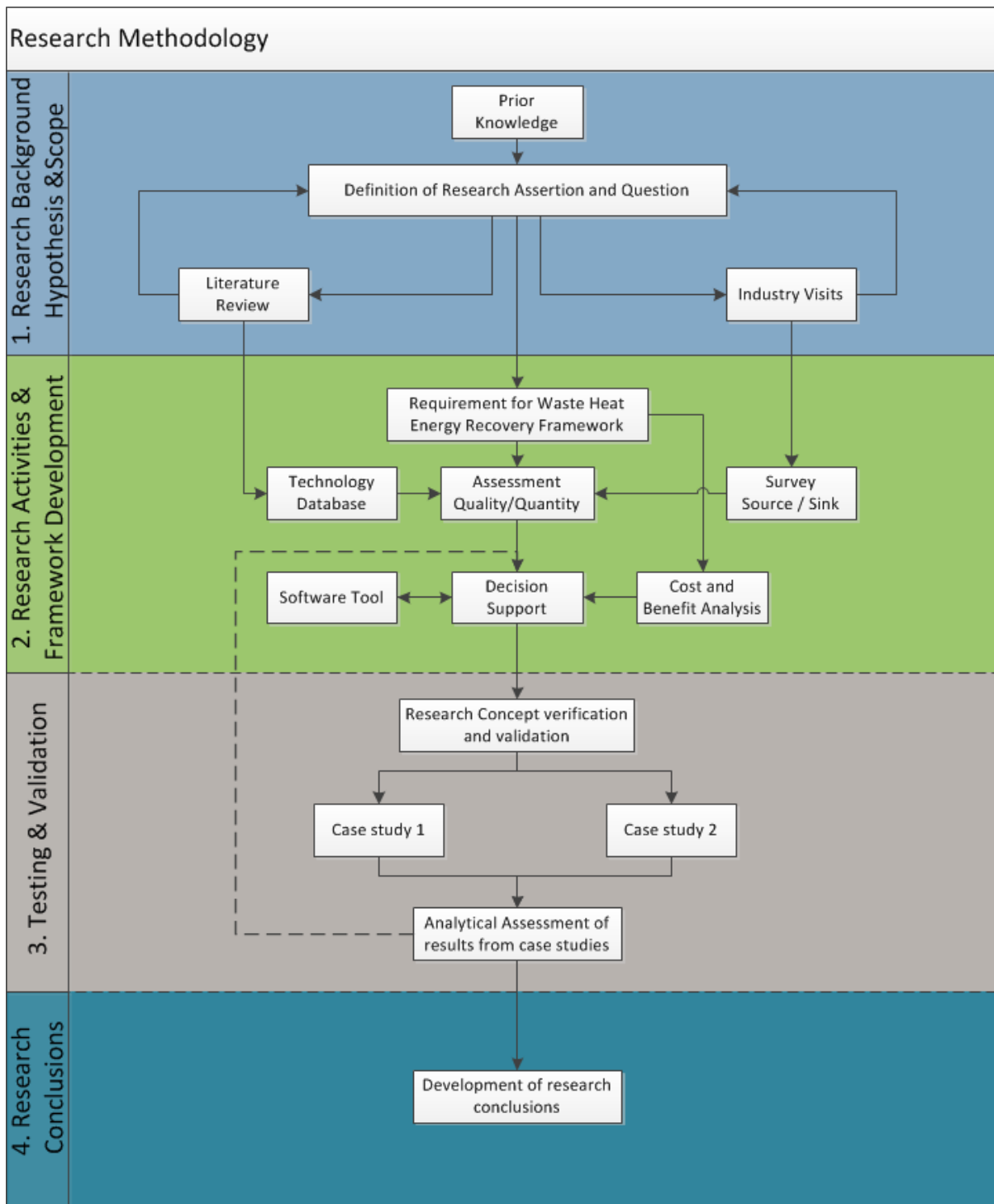


Figure 6. 1 Outline of research methodology

Chapter 7 Waste Heat Recovery Framework

7.1 Introduction

This chapter introduces a framework that has been generated by this research to aid manufacturers in making decisions regarding the most suitable solution to recover waste heat from their activities. The framework describes a methodology to identify sources of waste heat throughout a manufacturing plant, production processes and product levels, and provides an overview of waste heat hotspots within the production system. This analysis is used to highlight opportunities for heat recovery, by capturing available waste heat with suitable recovery technologies and reuse, recycle or energy storage options in order to improve overall energy efficiency.

7.2 An Overview of the Framework

Energy intensive manufacturing processes that utilise kilns, dryers, boilers and mills for example, release flue gases and wastewater streams. As mentioned in the literature survey in the previous chapters, there is a potential for such waste heat energy to be recovered and utilised for different purposes. In the past, energy emissions from these manufacturing processes have often been an underused resource since focus has been paid to proactively minimising energy consumption in manufacturing. Most of this heat is produced by the combustion of fossil fuels, and 30% of this heat is never utilised (Dupont & Sapora, 2009). The literature review of this research highlighted that there is often a substantial amount of unutilised heat energy available for recovery, and the framework presented in this chapter has been developed to provide a systematic approach to maximise the recovery potential.

The structure of the framework Chapters is laid out in such way that the gathered and generated information is fed into a database where information is processed and passed on and compared with the technology database to provide suitable options for waste heat recovery. As shown in Figure 7.1, the Framework consists of four essential steps beginning with collection of data, processing using quantitatively and qualitatively defined terms and equations, comparison of key parameters from the analysis with a database of available technologies and utilisation of a decision making algorithm provide a number of options for waste heat recovery. Finally a cost and benefit analysis is made to allow recommendations for the respective manufacturers.

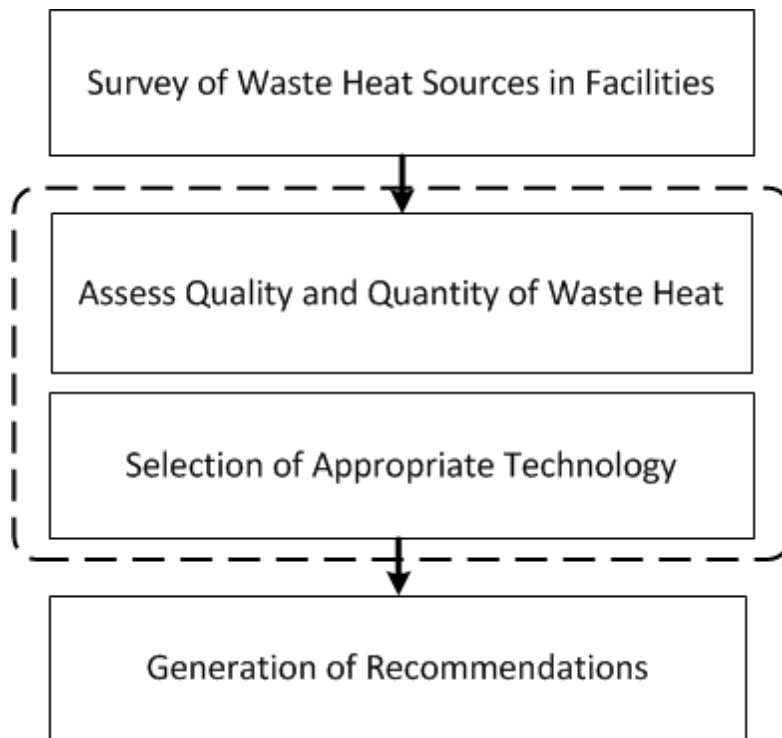


Figure 7. 1 Overview of the four stage waste heat recovery framework

The four Waste Heat Recovery Framework steps are:

- Step1: Waste Heat Survey
- Step2 (Part I): Assessment of Waste Heat Quantity and Quality
- Step2 (Part II): Selection of Appropriate Technology
- Step3: Generate Recommendations for Waste Heat Recovery

An overview for each of the four framework steps is presented in the following sections.

7.3 Step 1 – Waste Heat Survey

Undertaking a waste heat survey is the first step in the Waste Heat Recovery Framework (WHRF). As outlined in Section 7.1, step 1 describes the identification of sources of waste heat within a manufacturing environment from the Plant, Process and Product perspectives. Plant, Process and Product (3P) perspective have previously been used to show energy consumption in a manufacturing environment (Rahimifard et al., 2010) to give a clear indication of where energy consumption hotspots are in manufacturing process chains and to calculate a range of energy efficiency ratios. This chapter also highlights the three approaches to data generation required to carry out a complete waste heat survey as illustrated in Figure 7.2. These approaches are: database collection, empirical measurement and theoretical calculation.

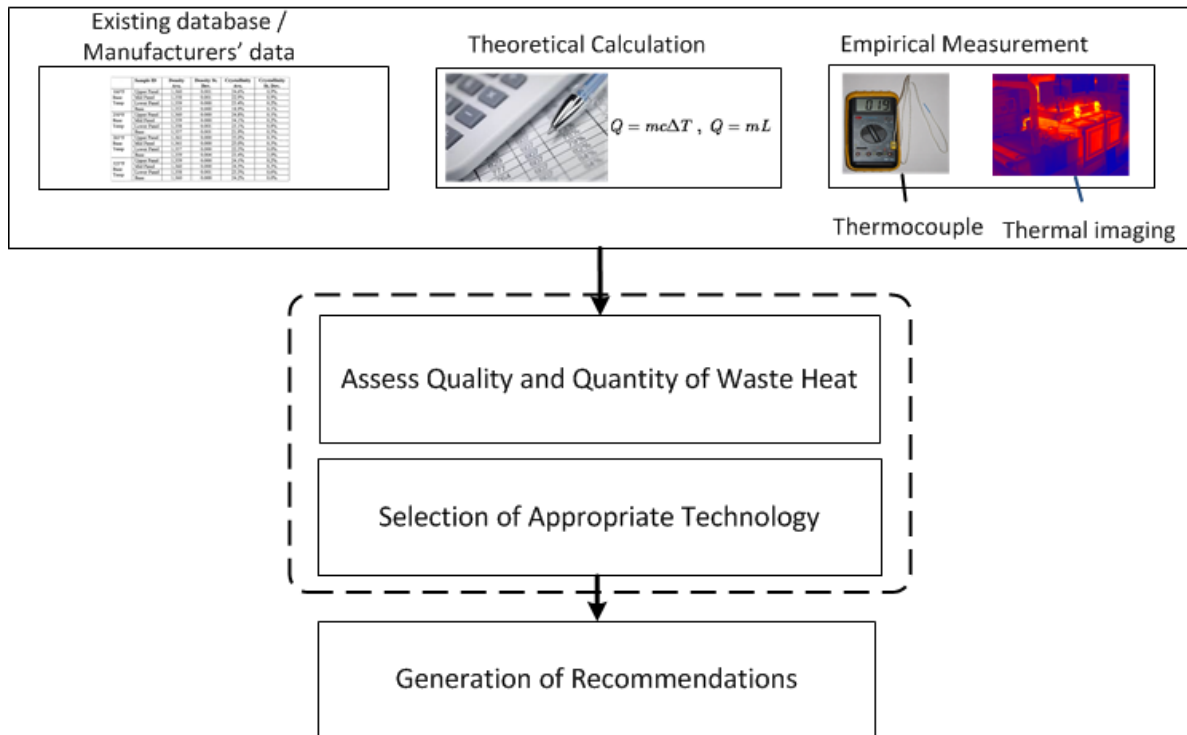


Figure 7. 2 First stage of the framework consists of using existing database, theoretical calculation and empirical measurement

The most preferable way of collecting accurate waste heat data is through empirical measurement which utilises existing energy or facility safety audits that manufacturers may already have. For special cases when data is insufficient, actual experimental measurement is required e.g. utilising thermocouple, infrared etc. Moreover, data collection can also be achieved via supplier data sheets or from previous study of process equipment. Theoretical calculation is based on assumptions made to best represent the real situation and can be useful when database or empirical measurement is not suitable, however it can also be time consuming and potentially introduce errors. These methods can be used to evaluate and visualise the amount of waste heat energy in a manufacturing facility.

7.4 Step 2 (Part I) – Assessment of Waste Heat Quantity and Quality

As outlined in Section 7.1, this step follows the first step of identifying sources of waste heat in a manufacturing environment to ensure that each source of waste heat is quantified and qualified in a structured way that can be evaluated and analysed by the relevant parts of the framework. A survey of waste heat generated within a plant is able to reveal some potential opportunities from generic and sector-specific manufacturing processes, and the method used in this thesis assigns a number of quantitative and qualitative descriptors to each of these opportunities in order to assess their recoverability in the context of the plant using available heat recovery techniques.

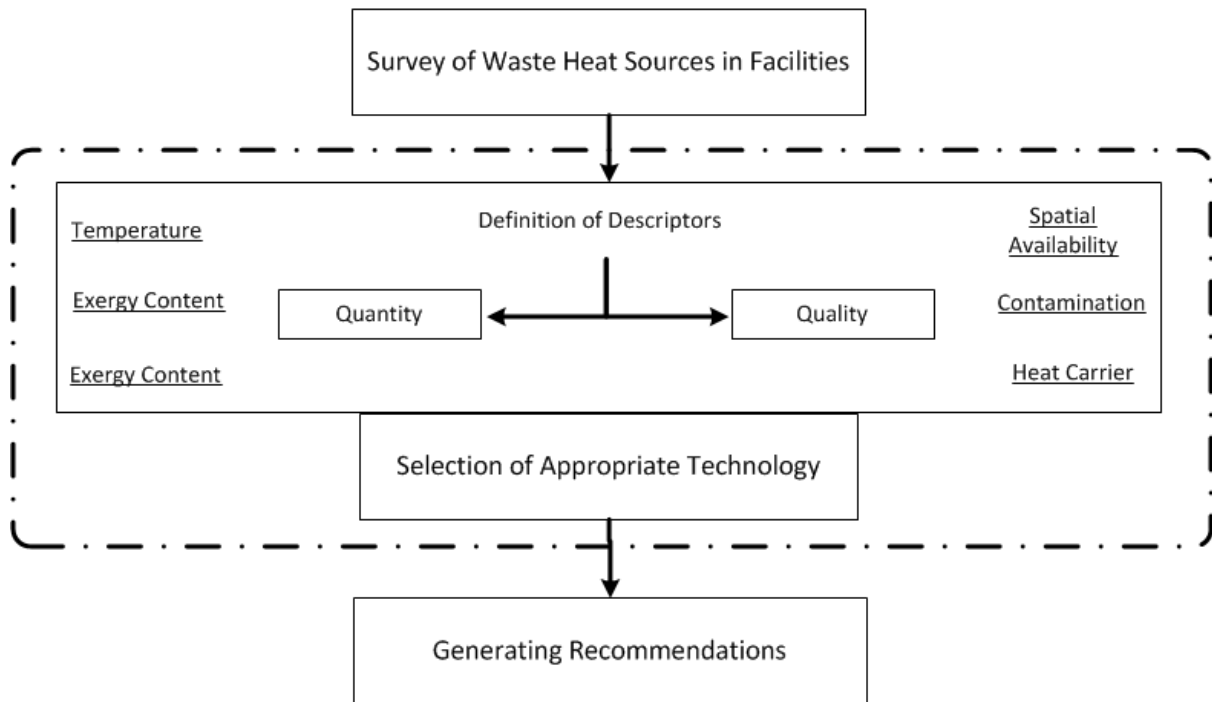


Figure 7. 3 Second stage of the framework consists of definition and assessment of quantity and quality descriptors and post interrogation

In order to quantitatively evaluate waste heat sources in a manufacturing environment, some important parameters must be defined to provide necessary data to carry out calculations using mathematical modelling techniques. In this framework the quantitative descriptors include temperature (or temperature difference between source and sink), available energy (or exergy) content, temporal availability of the waste heat sources, and how concentrated they are. Meanwhile, qualitative evaluation is more subjective than quantitative evaluation and uses very different methods of collecting information, the parameters include the carrying medium of waste heat sources, spatial availability in the nearby area to install heat recovery equipment and whether there is risk of contamination to this equipment. The qualitative and quantitative descriptors of the available waste heat energy can be used to compare potential heat recovery solutions with the available sources.

7.5 Step 2 (part II) – Selection of Appropriate Technology

This section introduces the technologies available for waste heat recovery in a manufacturing environment and their advantages and disadvantages relating to the quantitative and qualitative descriptors which are defined in detail in Chapter 9.

There are many different methods and technologies for recovering waste energy in a manufacturing environment, such as kinetic energy from movement of the machine parts, chemical energy from reactions, thermal energy as a result of combustion and a number of other well established

engineering cycles which enable heat energy recovery. In this framework, only waste heat is considered for recovery, and so only those technologies and solutions that pertain to heat energy recovery are considered.

Despite the variation in technology, they all have the same aim, which is to collect and reuse or recycle waste energy arising from any process that would otherwise be lost. The process might be inherent to a factory building, such as space heating, ventilation for example, or could be something carried out as part of manufacturing activity, such as the use of ovens, furnaces etc. Waste heat energy recovery can help to reduce the overall energy consumption of the process itself, or provide a useful energy source for other purposes.

The structure of this part of the framework is laid out in three steps as shown in Figure 7.4. The first step to technology selection is achieved by defining the selection criteria which consists of four fundamental properties of the heat recovery technology. These selection criteria are cost of implementation, type of waste heat carrier, whether there is risk of contamination, size of the equipment and minimum and maximum operating temperatures.

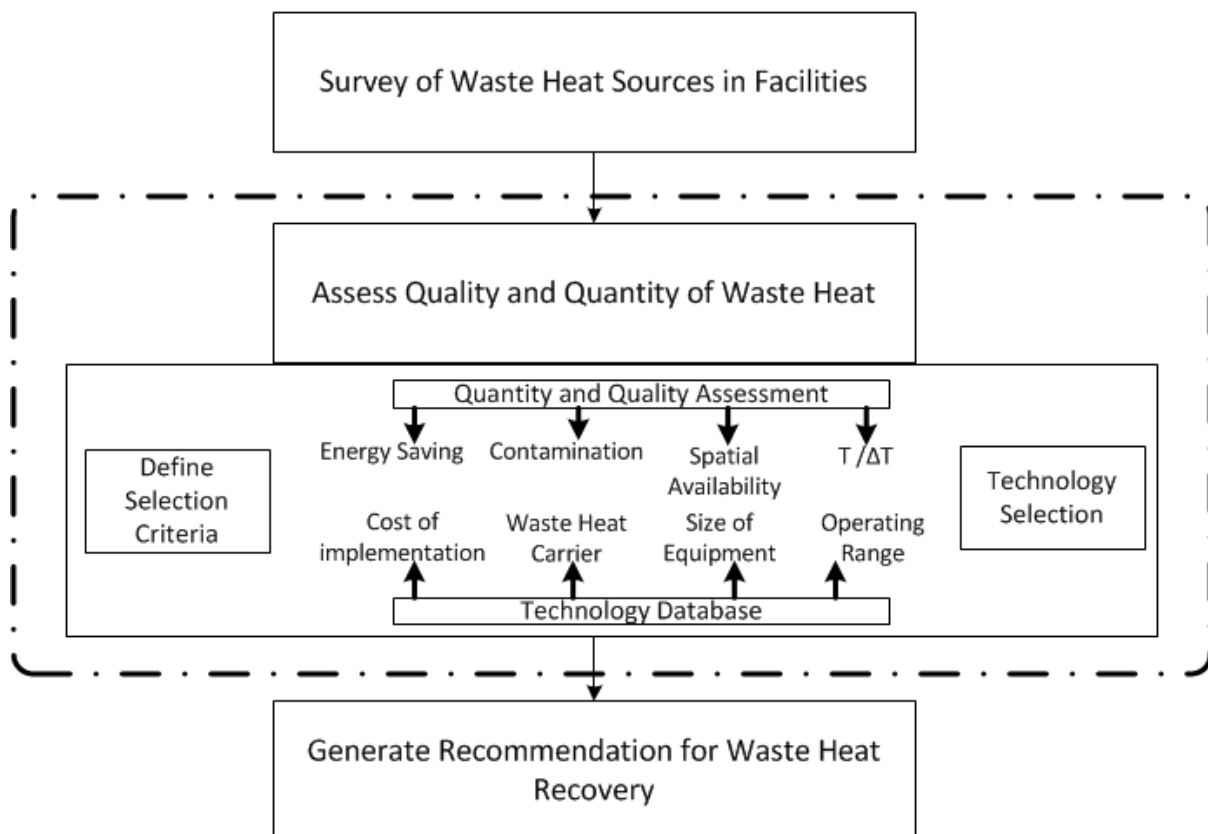


Figure 7. 4 Third stage of the framework consists of defining selection criteria, comparing parameters from Q&Q assessment and technology and finally decision making

The second step of the technology selection stage is to compare selection criteria established in step one with the output from the assessment of the descriptors of waste heat energy described in the previous section. The purpose of this stage is to use results from the waste heat quantitative and qualitative assessment to narrow down the range/ number of technology options from a database of existing heat recovery research and technologies (as described in the literature survey carried out in Chapter 4).

The final step of the technology selection process is to provide a number of different technology options which based on the comparison of criteria described above, considering a number of available waste heat energy. The output results of this step are carried forward into the next stage of the framework, which utilises environmental, economic and social analysis methods to compare between the selected options to influence a final decision.

7.6 Step 3 – Generate Recommendation for Waste Heat Recovery

The last step of the framework describes the process of making a final recommendation for manufacturers to identify an appropriate technology to recover waste heat energy (see Figure 7.5). In order to enable manufacturers to choose the most suitable technology to harness various waste heat energy in their facilities, from those identified from the technology selection process of the framework, the framework needs to undertake a cost and benefit analysis, followed by an environmental impact analysis to compare between these different options in order to generate a final recommendation.

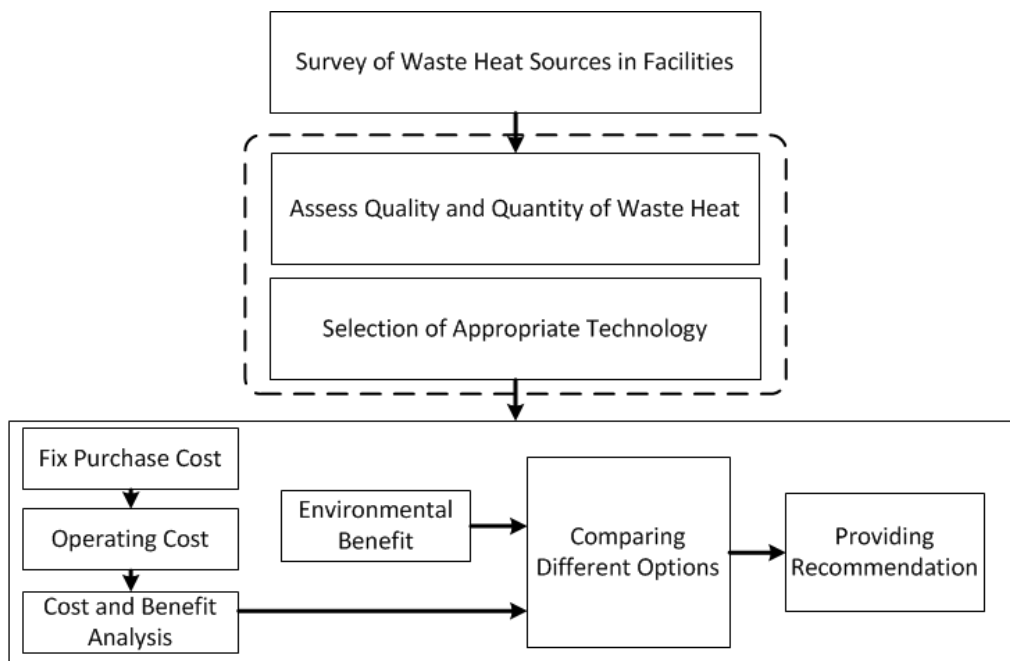


Figure 7. 5 Final stage of the framework consists of generation of recommendations

7.7 Chapter Summary

This chapter has introduced the waste heat recovery framework which is based on four essential steps its structure shown in Figure 7.6. The data collection can be further divided by undertaking empirical measurements or utilising existing databases from the manufacturers or, alternatively, by using estimated data to carry out theoretical calculation to provide an approximate heat energy evaluation. The collected data is a mixture of numerical and descriptive attributes and therefore requires interpretation using various descriptors, which are quantitative and qualitative. It is then possible for manufacturers to self-assess the quality and quantity of waste heat sources in their facility using parameters such as potential energy saving, chemical or particle content carried by the heat transfer medium, physical space and temperature difference between waste heat and that which is useful. Once the self-assessment of waste heat sources is carried out, the information can be fed into a technology selection process which also, in respect of quantitative and qualitative assessment, provides various selection criteria in order to classify suitable heat recovery technologies. This process enables comparison between different waste heat sources against available technology databases. To further analyse the viability of these chosen technologies, analyses of environmental, economic and social impact can be carried out to generate a final recommendation.

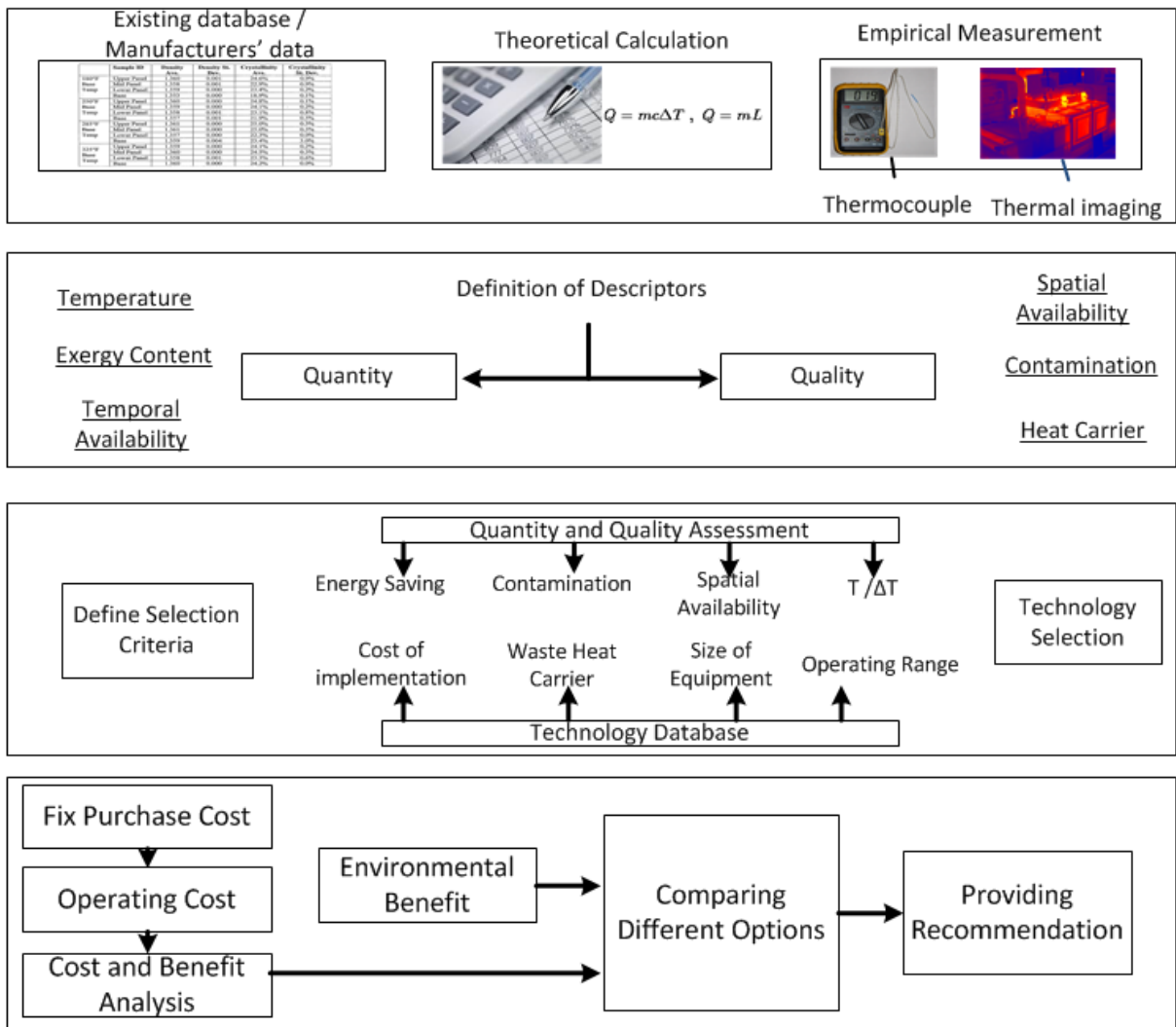


Figure 7. 6 Detailed structure of Waste Heat Recovery Framework

Chapter 8 Survey of Waste Heat Sources in Facility

8.1 Introduction

This chapter explains the first step of the waste heat recovery framework that has been developed to allow manufacturers to gain an understanding of where unutilised heat sources occur in a manufacturing plant. This survey identifies various “hot-spots” of heat occurring in the facility, providing an overview of potential areas for heat recovery and associated investment to improve overall energy efficiency. There are three methods of waste heat energy data collection proposed in this framework which are empirical, existing database and theoretical calculation.

The initial part of the chapter describes the Plant, Process and Product (3P) perspective which categorises the different levels in which heat energy is available within a manufacturing plant. In order to identify waste heat sources, the later section of the chapter details a structured approach to undertake a survey of waste heat sources within a manufacturing environment.

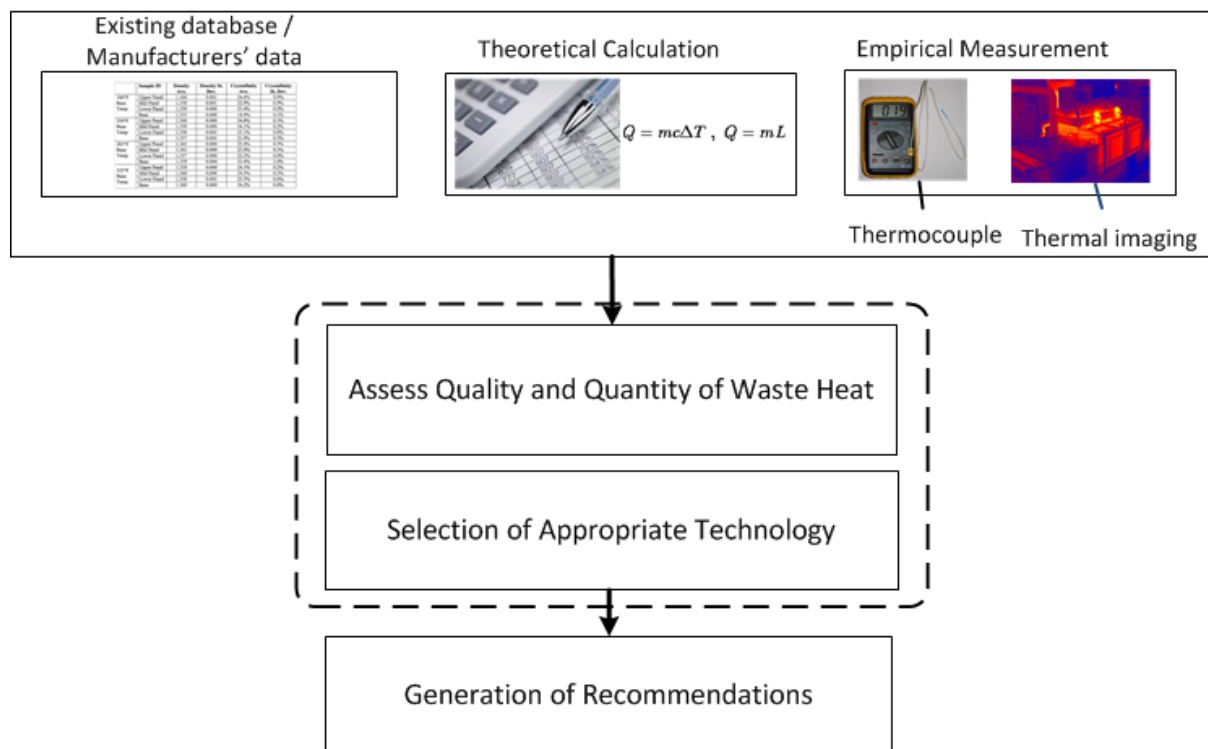


Figure 8. 1 Waste Heat Recovery Framework - Waste Heat Survey

8.2 Plant, Process and Product Perspective

The 3P perspective has previously been used to show energy consumption in a manufacturing environment via framework to model Embodied Product Energy (Rahimifard et al., 2010), which

gives a clear indication of where energy consumption “hotspots” exist within manufacturing process chains, and is used to gauge whether energy is used efficiently. Similar to the 3P perspective, the International Standards Organisation (ISO) has developed a model composed of a six-level hierarchical structure (Figure 8.2), including enterprise, facility, machine cell, machine and turret. The enterprise level is responsible for the achievement of the mission of the enterprise and clearly its planning horizon is measured in the long term. The facility or plant level is responsible for the implementation of the enterprise functions and the reporting of status information to the enterprise level. It includes functions such as manufacturing engineering, information management, production management and scheduling and production engineering. At the machine cell level, the responsibilities are provision and allocation of resources and the coordination of production on the shop floor. The cell level is responsible for the sequencing of jobs through the various stations. Its functions include resource analysis and assignment, making decisions on job routings, dispatching jobs to individual machines and the monitoring of task and machine status. The turret level is responsible for the direction and coordination of relatively small integrated workstations (Bauer & Browne, 1994). When considering the theoretical degree of detail at the turret level and diverse range of activities at the enterprise level, which may present significant problems with the availability of energy data, these two manufacturing levels would likely prove problematic. Therefore, in this research, only the facility, machine cell and process level are considered, highlighted by red circles in Figure 8.2.

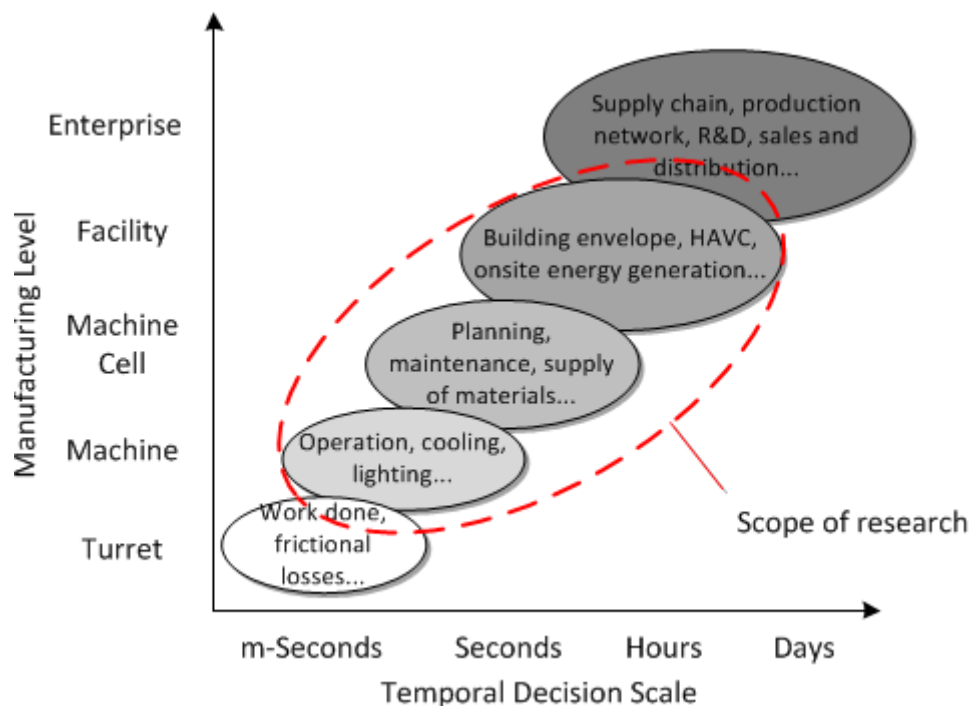


Figure 8. 2 Energy considerations at the various manufacturing levels and the defined scope of this research

In this research the 3P perspective is used to identify where waste heat is available for recovery in a manufacturing environment. This is because not only are the energy survey requirements rather different for these three perspectives but also the quantity and quality of energy available is significantly different and so will be the requirement of technology for energy recovery. A diagram of the 3P perspective and how they interact with each other has been created shown in Figure 8.3. In general, the applicability for waste heat recovery is to reuse the energy for the same activity or to cascade its use to an activity at a higher manufacturing level. In order to develop a detailed breakdown of waste heat sources within a production facility, there is a need to systematically identify waste heat hot spots and this leads to a complete survey of the facility.

8.2.1 Plant

From a 'plant' level perspective, heat energy is required by the infrastructure and other high level services that are responsible for maintaining the required production conditions/environment. Examples of 'plant' level heat usage are lighting, space heating, air-conditioning and ventilation. Heat is lost from a broad range of activities in a manufacturing facility, and this is contributed by building heating, cooling, and ventilation sections of the facility.

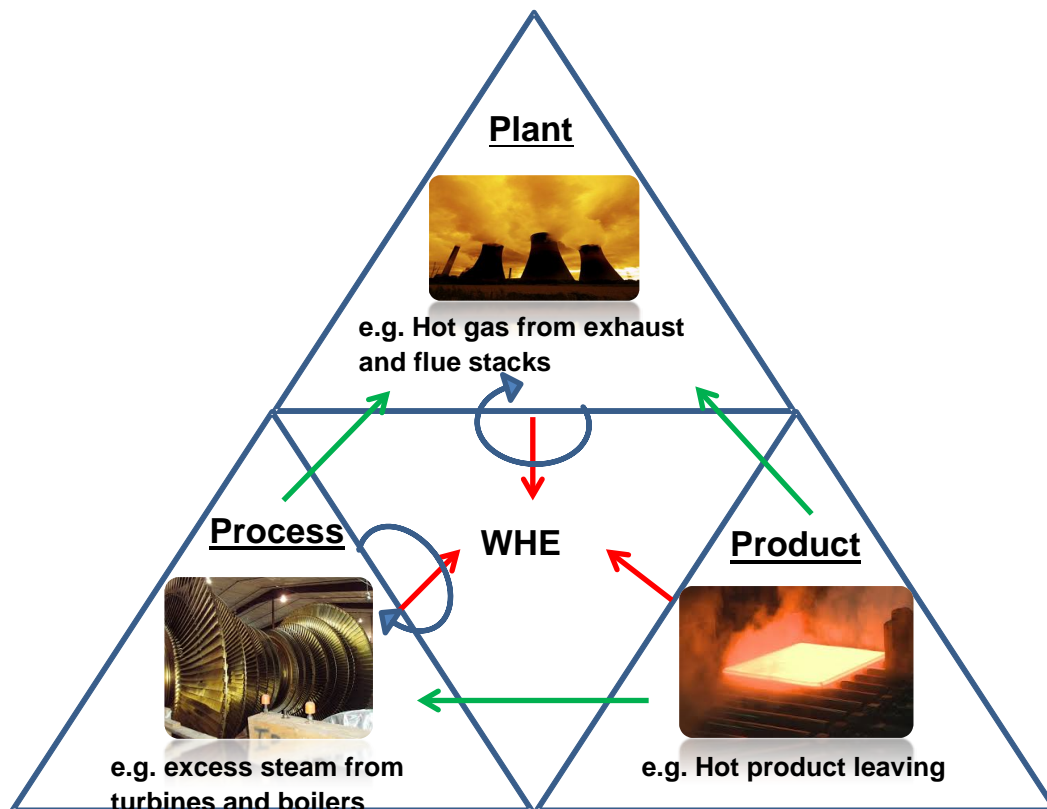


Figure 8. 3 Red arrows represent waste heat being generated; green arrows indicate recovered waste heat energy and blue arrows show potential for reuse within the same activity

Examples of such activities include boilers which provide space heating or hot water, ventilation/air conditioning systems without any means of recirculation or heat recovery, water chiller or other cooling plant rejecting heat to outside, and temperature control in high spaces. Demand for these activities may vary significantly depending on the weather and season of the year. For example, boilers are required to work throughout winter to provide space heating and hot water to the building but space heating may not be necessary during hot summer days. Ventilation/air conditioning system may be required to be fully operational throughout the year to maintain a suitable working environment.

At the plant level, much of the heat loss improvements are encompassed as part of a generic Energy Management System (EMS) which would typically involve energy audits and monitoring. However the investment required for recovering unutilised heat at this level could be very significant, for example the major cost of restructuring of the heat systems to the factory.

8.2.2 Process

In a manufacturing facility all energy used by a process, that does not reside in the products as it leaves the process is ultimately lost to the environment. Some of the energy is useful, e.g. heat from coolant pumps, and some less useful, e.g. lighting an unmanned process. From this perspective, the existing research typically has investigated areas for energy improvement which relates either to the improvement of operational procedures or machine design. This improvement in operational procedures could include minimising idle time in a process through better production planning or improving the process through more effective sensing and control. The improvement in machine design could include elimination/reduction of non-essential activities (e.g. coolant, lubricant). These improvements are of particular interest to manufacturers especially where energy savings make economic sense. However such investments are only capable of reducing energy demand so far before they become financially prohibitive. Therefore a reactive approach to recovery of waste heat energy that could potentially be more cost effective should be considered.

A study done by the U.S. Department of Energy reported that a significant percentage (20-50%) of industrial energy inputs is lost as waste heat in the process stage, totalling anywhere from 2 to 4 TWh (Johnson *et al.*, 2008). This highlights that there is a significant amount of waste heat can be recovered, and also a need for energy transparency across a production facility so that energy hotspots can be identified.

8.2.3 Product

The integration of energy considerations at the plant and process perspective into a 'product' perspective would give manufacturers effective indication of which activities and processes are energy intensive and/or potential waste heat hotspots. Seow & Rahimifard (2011) used the 'product' perspective to systematically identify the total energy required to manufacture a product, also referred to as the Embodied Product Energy (Rahimifard *et al.*, 2010). The study undertook an in-depth analysis of energy requirements based on product design features, manufacturing parameters and operational procedures. The study aimed at enabling engineers and designers to identify the energy hotspots during production and facilitate process design optimisation, production and process planning improvements as well as product design enhancements.

In this research, waste heat energy at 'product' level is defined as the heat contained in the final products when it leaves its treatment process. It is present in the form of heat energy in products coming out of the process, and they may still carry a significant amount of residual heat from their treatment, for example, in metal casting or oven baking process. This heat is unwanted and dispersed using means of cooling, e.g., water or air. Some products may be required to, or will naturally cool at particular rate depending on desired final perspectives, etc., different specific heat capacities.

As discussed in Chapter 4 of this thesis, heat at the product level of manufacturing has not been paid much attention and is often wasted despite being potentially recoverable. Although the waste heat temperature of the products, especially with metal casting products, can be reasonably high, the waste stream continuity is not constant and there are issues with other waste heat quality criteria which will be discussed in later sections.

8.3 Waste Heat Survey

There is relatively little publically available data on the waste heat resource associated with industrial processes in the UK. In its call for evidence on heat in 2008, the Department for Business, Enterprise and Regulatory Reform (BERR) provided an estimate of 40TWh per year (BERR, 2008), but a more detailed bottom up study by McKenna & Norman (2010), which captured an estimated 90% of the energy intensive process industries, put the value at between 10 and 20TWh. It is assumed that the true value is in the 10-40 TWh range.

When considering the potential benefit of waste heat recovery within a facility, it is essential to have a good understanding of what and where the most lucrative sources of waste heat are. The first stage of doing this requires a high-level categorisation of available waste heat energy, before a more

detailed survey is conducted. As outlined in Chapter 7, this chapter details the Plant, Process and Product (3P) approach developed to identify sources of waste heat within a manufacturing environment. It is clearly identified that, a waste heat survey is required as part of the energy audit process to allow information to be collected and analysed. This signifies the first step towards waste heat recovery as to understand where waste heat is generated within the 3P perspectives. In addition, a more in-depth energy survey is needed to systematically review how heat energy is wasted within the 3P levels. It includes a physical inspection of buildings and equipment, which can range from a simple visual inspection to a fully instrumented study.

There are three types of survey, desktop based, theoretical calculation and empirical measurement. The most preferable way of collecting waste heat data is empirical measurement which utilises data that manufacturers may already have access to from existing energy or facility safety audits. And for special cases when data is insufficient, actual empirical measurement is required e.g. utilising energy meters, thermocouples, and infrared cameras. Moreover, data collection can also be achieved by consultation of databases from supplier data sheets or from previous studies of process equipment. Theoretical calculations are based on assumptions made to best represent the real situation and can be useful when database or empirical measurement is not suitable, however it can also be time consuming and potentially introduce errors. These methods can be used to evaluate and visualise the amount of waste heat energy in a manufacturing facility.

It is important to have a structured approach to waste heat survey to make the most of the opportunity. In order to achieve this, a structured approach of this waste heat survey is shown in Figure 8.4 below and detailed in the following section.

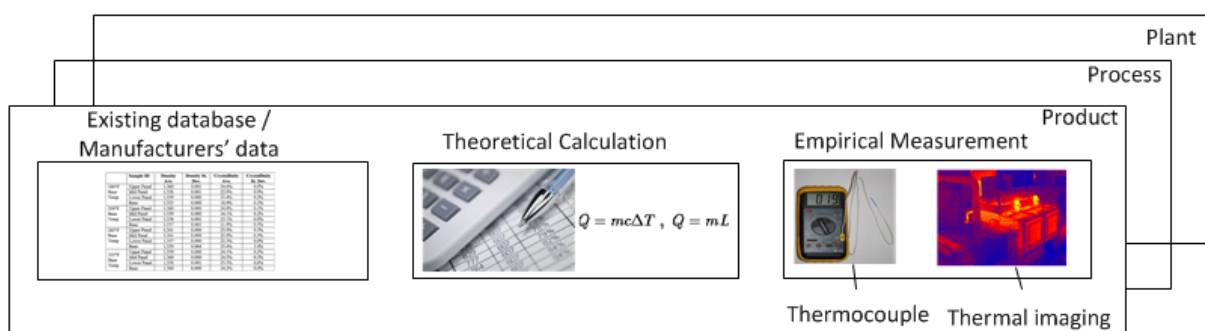


Figure 8.4 Methods of waste heat survey

8.3.1 Empirical Measurement

The survey consists of a systematic study of the source of waste heat in the plant, process and product levels of manufacturing and opportunities for its use. In this study a low grade heat demanding process is termed a sink. The empirical measurement is the most preferred method of

conducting such a survey as it collects real-time data regarding energy consumption and heat generation in a manufacturing environment which best represents the actual situation.

Information should be gathered that can lead to a complete heat/energy balance of the equipment or the system that produces it. This method can often be insufficient, in which case measurement of essential parameters are carried out. Generally speaking, the characterisation of the quantity, quality, and temporal availability of the waste heat energy requires that volumetric flow rate, temperature, and flow intervals be measured.

In order to carry out the aforementioned measurements, case specific instruments are usually required, such as a thermocouple, data logger, flow meter, infrared camera etc. Thermocouples are widely used in science and industry and their applications include temperature measurement of kilns, gas turbine exhaust, diesel engines, and other industrial processes (Figure 8.5a). A flow meter is a device that measures mass or volumetric flow rate of a fluid (e.g. gaseous or liquid) travelling through a tube (see Figure 8.5b) and typically, flow measurements can be expressed in the units of kilograms per second (kg/s) or m^3/s for mass and volumetric flows respectively. Infrared camera is a device that forms an image using infrared radiation and generally speaking the higher an object's temperature is, the larger the wavelength of infrared light is emitted as black-body radiation (see Figure 8.5c). Therefore with careful calibration it is possible to apply infrared camera to difficult situations where thermocouple measurement cannot be implemented or no lighting is available.

8.3.2 Use of Existing Database

This is a less preferable method of conducting waste heat survey as it is risky to base waste heat source availability used for decisions concerning expensive waste heat recovery systems on nonspecific, generic data. However, when measurements are not possible, it may become necessary to rely on the best approximations available.



Figure 8. 5 a: Thermocouple data logger; b: Flow analyser; c: Infrared camera

The approximations must be made taking full advantage of all relevant data at hand which could include equipment datasheets, installation, operating and maintenance records, production records and fuel and utility invoices. Alternatively, the use of published or available data from various literature sources should be considered. There are an increasing number of energy inventory databases such as ‘Unit Process Life Cycle Inventory’, UPLCI (2010) and ‘Cooperative Effort on Process Emissions in Manufacturing’ CO₂PE initiative (Figure 8.6), which is led by Duflou *et al.* (2012) at the University of Leuven to cluster forces in different continents, involving machine builders as well as academics, to analyse existing and emerging manufacturing processes for their ecological impact in terms of direct and indirect energy consumption, resource consumption and process emissions (Kellens *et al.*, 2011).

The advantages of utilising a database system include reduced updating errors and increased consistency, greater data integrity, improved data access to users and reduced data entry and storage effort. However, the disadvantages are also instinctive, they include higher risk of data security, total dependence on a third party to update the database, data format might requiring normalisation before usage.

8.3.3 Theoretical Calculation

Another method of ascertaining waste heat energy data is via a theoretical approach to calculate the energy used by the production processes and heat energy loss.

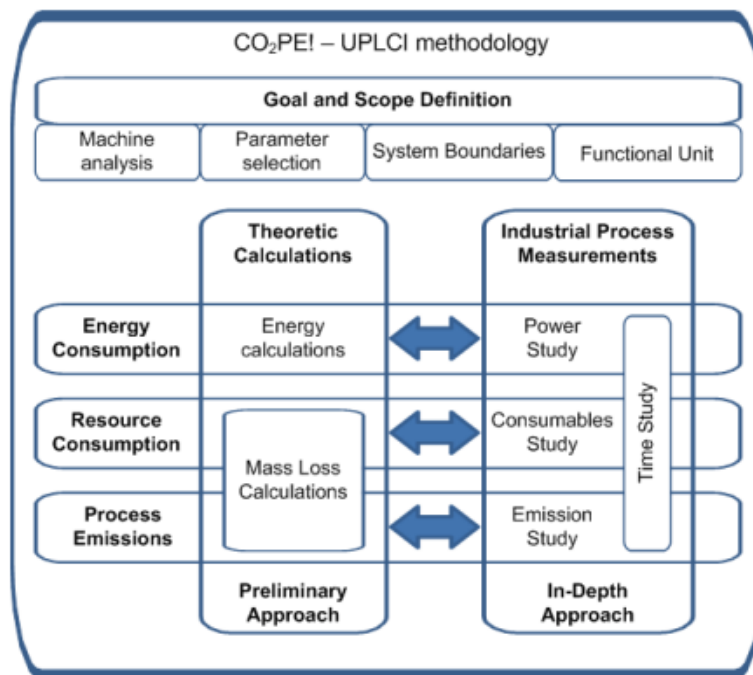


Figure 8. 6 CO₂P initiative (cooperative effort on process emissions in manufacturing) (Kellens *et al.*, 2011)

Mathematical equations can be used to calculate the energy required to, for example, melt a specific material and heat energy loss to the environment when the heat processed material is allowed to cool down, see Equation 8.1 (Ashby, 2008):

$$\sum Q = \sum m_n c_n (T_m - T) + \sum m_n L_n \quad [\text{Equation 8.1}]$$

Where,

Q : Heat captured in material (J)

m : Mass (kg)

C : Specific heat capacity (kJ/kgK)

T_m : Melting temperature (K)

T : Temperature of metal before melting (K)

L : Latent heat of melting (kJ/kg)

The mathematical model can be applied to a number of different manufacturing processes including metal casting and heat treatment processes, processing of metal powders, ceramics, glasses and superconductors, processing of polymers, bulk deformation processes. The energy equations are an approximation of the basic heat energy requirement or heat dissipated to the environment, and should only be used where the energy data cannot be obtained through empirical studies and are not available within published literature.

8.4 Chapter Summary

As the first step of the framework, this chapter has presented a number of methods to conduct a waste heat survey required to understand where heat energy is wasted in the plant, process and product levels of manufacturing. The methods adopted in this research consists of undertaking empirical measurement with the aid of a number of measuring techniques i.e. thermocouple, flow meter or infrared camera, the use of existing database or published data and carrying out theoretical calculations to obtain waste heat energy data for further analysis in the framework.

Data collected from this step can be fed into a manufacturing facility database which enables quantitative and qualitative assessments to clearly define the characteristics of the waste heat sources found in the respective facility. The definition and implementation of these assessments will be discussed in Chapter 9.

Chapter 9 Assessment of Waste Heat Quantity and Quality

9.1 Introduction

This chapter describes the method used in this thesis that assigns a number of quantitative and qualitative descriptors to each of the identified waste heat source opportunities in order to assess their recoverability in the context of the plant and using available heat recovery techniques. In order to quantitatively evaluate waste heat sources in a manufacturing environment, some important parameters must be defined to provide necessary data to carry out calculations using mathematical modelling techniques. In this framework the quantitative descriptors include temperature (or temperature difference between source and sink), available energy (or exergy) content, temporal availability and concentration of the waste heat sources. Meanwhile, qualitative evaluation is more subjective than quantitative evaluation and uses very different methods of collecting information. The parameters include the carrying medium of waste heat sources, spatial availability in the nearby area to install heat recovery equipment and whether there is risk of contamination to this equipment. This structured assessment is essential in order to evaluate waste heat energy against suitable technologies and potential uses in recovery, as will be described in Chapter 10.

As discussed in the previous Chapter, waste heat sources can be found in the Plant, Process and Product levels of a manufacturing environment. In this Chapter, they are further classified into two main categories, the general purpose and sector-specific waste heat. In order to clearly define various waste heat sources, quantitative and qualitative assessment method is used to assign some descriptors to the characteristics of the waste heat sources. Section 9.3 details the quantitative evaluation which included the parameters that can be measured or calculated numerically while Section 9.4 details the qualitative evaluation which must be defined by means of descriptions. Section 9.5 summaries the highlights of the qualitative and quantitative descriptors for waste heat sources and heat sinks. Figure 9.1 illustrates the distribution of quantitative and qualitative evolution according to the type of information.

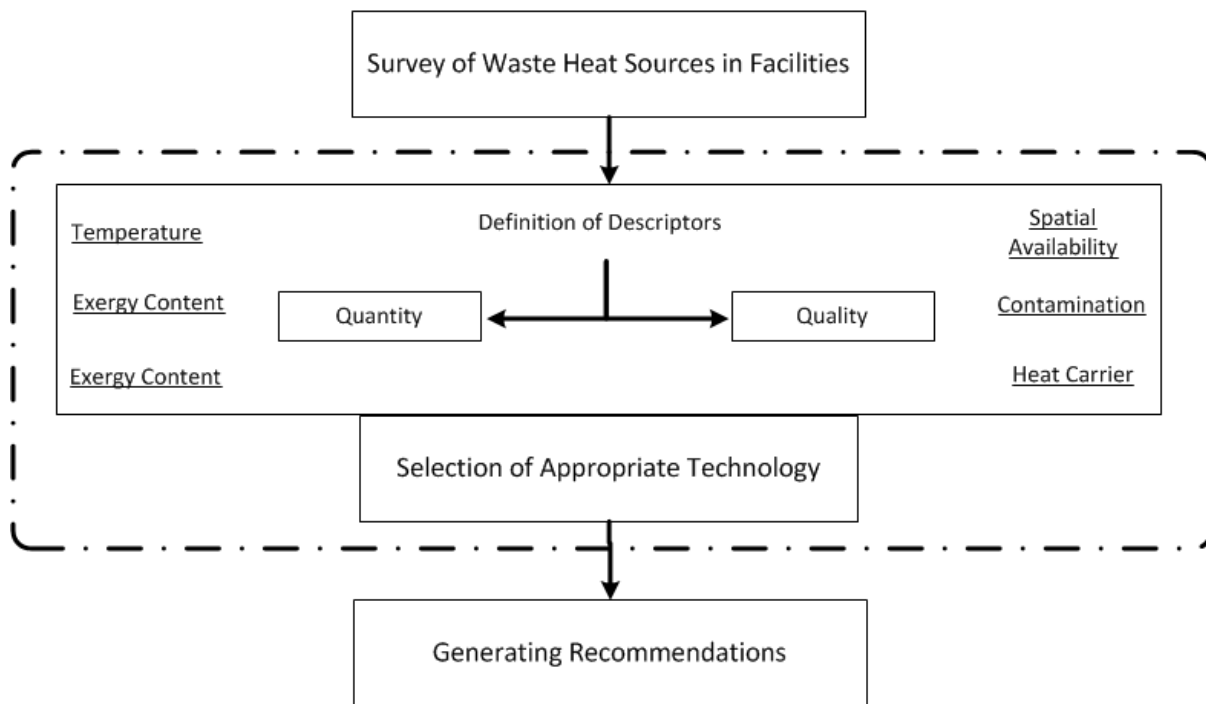


Figure 9. 1 Waste heat recovery framework, assessment of quantity and quality is highlighted

9.2 Quantitative Evaluation

Quantitative observations are made using scientific tools and measurements. In order to quantitatively evaluate waste heat source in a manufacturing environment, some important parameters must be monitored to generate necessary data to carry out calculations using mathematical modelling techniques. These descriptors include Temperature, Available Heat Energy, Exergy Content and Temporal Availability which are described in more details in the following sections.

9.2.1 Temporal Availability

The temporal availability is one of the six descriptors that have been defined to quantify and qualify the waste heat source and sink properties. In order to decide how appropriate a heat sink is compared to specific heat sources, comparisons of both availability and demand must be carried out based on the same time scale. A flowchart has been generated to demonstrate the principle of such modelling activity and how a qualitative descriptor is computed into quantifiable measures. For the purpose of this demonstration, a simulated dataset has been randomly generated, however in a real case scenario, users are required to input data with the most accurate data resolution (Figure 9.2).

In order to model the resemblances between waste heat availability and sink, there are two core functions that need to be defined based on the same time scale:

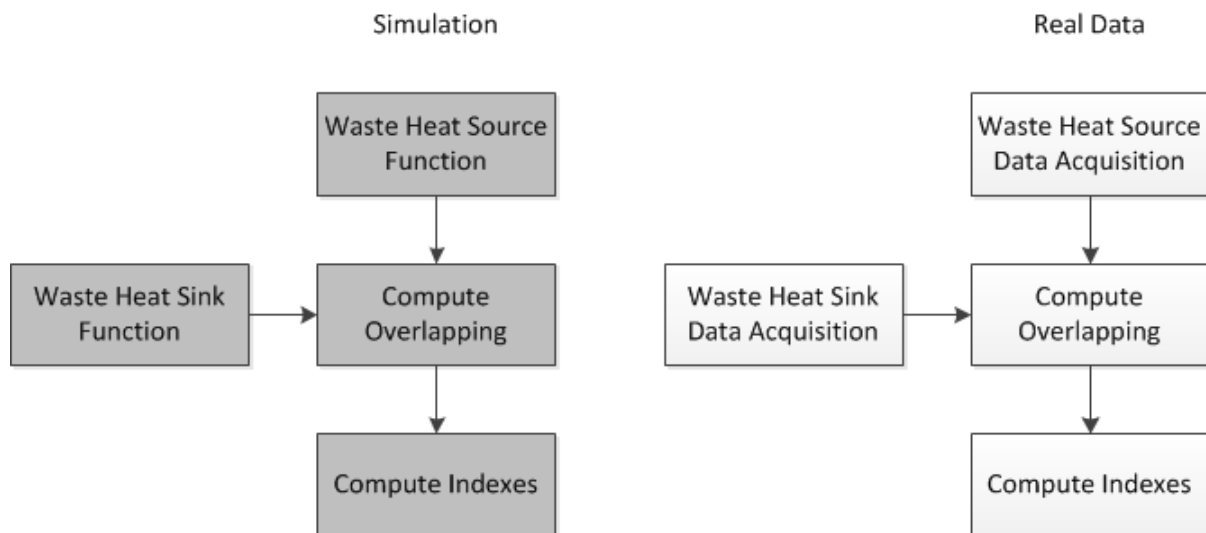


Figure 9. 2 Overview for Modelling Temporal Availability

- Waste heat availability function
- Waste heat sink function

Waste heat availability function represents the flow profile of a particular waste heat source during a length of time at an appropriate unit of measurement, such as power (kW). This data requires user input obtained empirically from the actual production data metered onsite or theoretically from waste heat power calculation. Waste heat sink function characterises the potential demand for energy input such as combustion air preheating for another process or space heating within the factory floor and offices, especially in the context of waste heat recovery of excess heat generated from specific manufacturing processes such as furnaces and ovens etc. This function should also be based on user input as a reflection of what potential uses are for waste heat generated onsite.

In addition to the aforementioned two core functions, in order to compute resemblances between the two functions, a common time based scale must also be defined. The timescale is used to define the time allowed for, or taken by a process, or sequence of events, to take place. Usually in a manufacturing environment the timescale for processes can be in a range of between minutes to weeks. In this case, both waste heat availability and waste heat sink function need to be evaluated computationally.

Having defined the appropriate waste heat availability and waste heat sink functions on a common timescale, there are periods when waste heat availability and waste heat sink is aligned, i.e. waste heat availability meets, or partially meets, the demand of a waste heat sink; and there are also moments when there is no intersections. Complex patterns of waste heat availability and sink functions can be difficult to compare. To be able to quantify and evaluate the aligned and mismatched periods within the comparison, Recovery Index (RI), Waste Index (WI) and Utilisation

Index (UI) are required to assess the recoverability of the waste heat source depending on a chosen waste heat sink.

9.2.1.1 Definition for the three indexes

The indexes used to computationally evaluate the aforementioned waste heat and sink functions are described below:

i. Overlap function

Overlap is the area under the common intersection between waste heat source and waste heat sink function. In an example demonstration below (Figure 9.3), the blue line represents waste heat availability and the red line is denoted for waste heat sink, hence the aligned common area for both functions in the figure is shaded green.

The overlap function has been operated by the MATLAB mathematical modelling software tool. There are two conditions associated with the functionality of overlap, (1) at any moment when the sink function is lesser than the availability function, overlap is equal to the sink function; (2) at any moment when sink function is greater than or same as the availability function, then overlap is equal to the availability function (Equation 9.1).

$$\text{Overlap Function } O(t) = \begin{cases} O(t) = \text{sink}(t) & \text{sink}(t) < \text{availability}(t) \\ O(t) = \text{availability}(t) & \text{sink}(t) \geq \text{availability}(t) \end{cases} \quad \text{[Equation 9.1]}$$

ii. Recovery Index (RI)

RI is defined as the ratio of aligned period over available period, which indicates the theoretical amount of waste heat energy that can be recovered based on the current sink and appropriate recovery technology.

The comparison of the aligned area between waste heat source n and waste heat sink A functions, $RI_{process(nA)}$ is defined as overlap divided by availability. The value of this ratio is always between 0 and 1, as shown in Equation 9.2. A higher value of $RI_{process(nA)}$ (i.e. values closer to 1) is indicative of larger percentage of synchronisation, and therefore signifies a more suitable waste heat recoverability in terms of time.

Conversely, a lower value of $RI_{source(nA)}$ (i.e. values closer to 0) denotes an inefficient match of waste heat source and sink, which then requires further consideration for a different source and sink matchup, improvements and possible investment for waste heat energy storage system.

$$0 < RI_{source(nA)} = \frac{\text{overlap}(nA)}{\text{availability}(n)} < 1 \quad \text{[Equation 9.2]}$$

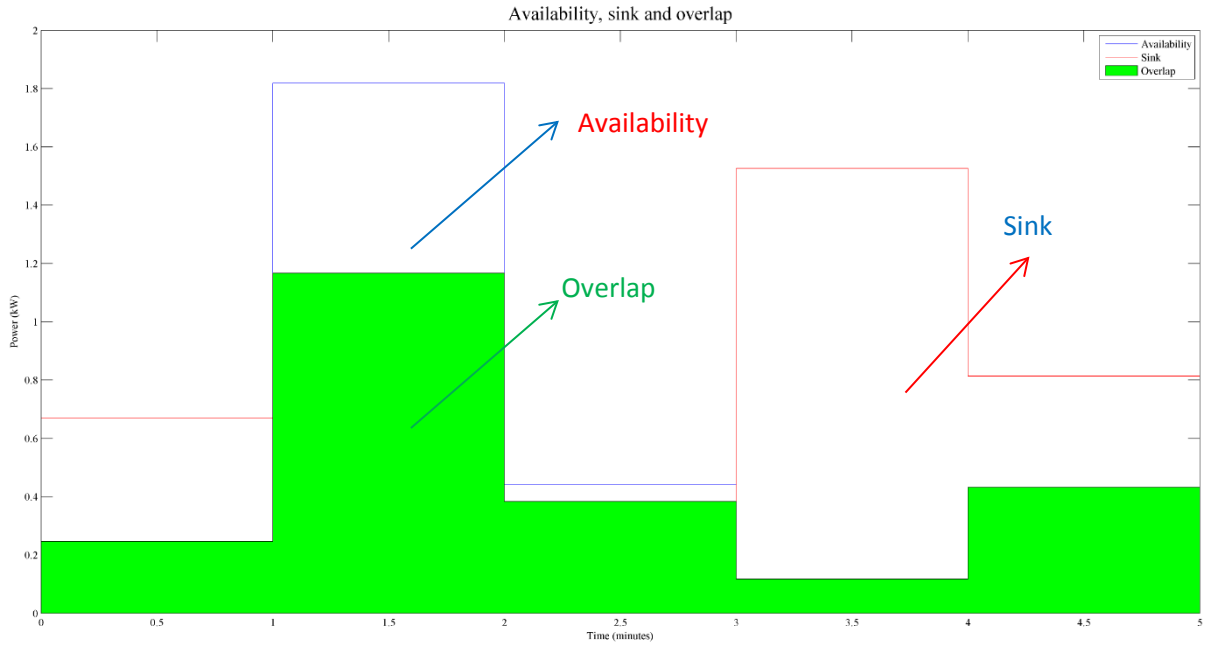


Figure 9.3 Availability, sink function and overlap

Where,

$RI_{source(nA)}$ is the RI for waste heat source n when comparing with waste heat sink A

$Overlap_{(nA)}$ is the temporal alignment of waste heat source n when comparing with waste heat sink A

$Availability(nA)$ is the temporal availability of waste heat source n

iii. Waste Index (WI)

Similarly, the WI compares the unaligned area between waste heat source n and waste heat sink A, $WI_{source(nA)}$ is defined as 1 minus overlap divided by total availability (Equation 9.3). This is the ratio of misalignment over the specified period between waste heat source n and waste heat sink A, which shows the proportion of remaining amount of available heat energy that cannot be utilised because of the unavailability of suitable waste heat sink (Figure 9.3).

$$0 < WI_{source(nA)} = 1 - \frac{overlap_{(nA)}}{availability_n} < 1 \quad \text{[Equation 9.3]}$$

Where,

$WI_{source(nA)}$ is the WI for waste heat source n when comparing with waste heat sink A

$Overlap_{(nA)}$ is the temporal alignment of waste heat source n when comparing with waste heat sink A

Availability(nA) is the temporal availability of waste heat source n

iv. Utilisation Index (UI)

Unlike the RI and WI explained above, UI ($UI_{sink(nA)}$) is defined as overlap divided by sink, representing ratio of waste heat sink utilised. This value of this ratio is always between 0 and 1, as shown in Equation 9.4. A higher value of $UI_{sink(nA)}$ (i.e. values closer to 1) is suggestive of larger proportion of demand being met and therefore signifies a good choice for the sink. Therefore from economical point of view, larger percentage of savings can be made. Conversely, a lower value of $UI_{sink(nA)}$ (i.e. values closer to 0) indicates an inefficient match of waste heat source and sink. It is also to be noted that, a good UI does not always represent a good comparison (i.e. waste heat sink capacity is small, even though the UI is 1, larger amounts of waste heat availability could be unutilised).

$$0 < UI_{sink(nA)} = \frac{overlap(nA)}{sink(A)} < 1 \quad \text{[Equation 9.4]}$$

Where,

$UI_{source(nA)}$ is the UI for waste heat source n when comparing with waste heat sink A

$Overlap(nA)$ is the temporal alignment of waste heat source n when comparing with waste heat sink A

$sink(A)$ is the temporal availability of waste heat sink A

9.2.1.2 *Modelling with Synthesised Data:*

For purpose of modelling and demonstration, data required in this exercise by the waste heat availability and sink function is synthesised.

Initial assumptions made:

Timescales (x axis) – The initial step of the modelling is to define a suitable timescale for both the waste heat availability and sink functions. It is user defined parameter based on the length of the period that is of particular interest, such as hourly, daily and weekly (only usual working days from Monday to Friday are modelled). This mechanism is also reflected by displaying an ‘options log’ (see Figure 9.4), which provides respective options to compute. In this example, all of the three options are modelled.

Functional unit (y axis) – this is assumed to be power (kW).

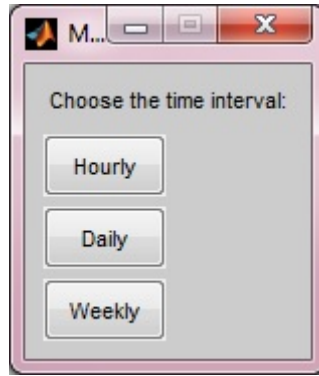


Figure 9. 4 Model selection dialogue

Waste heat availability function – is modelled randomly as the source of waste heat energy generated over a period of time in a manufacturing environment and is represented with blue line in Figure 9.5a.

Waste heat sink function – is modelled randomly as the potential waste heat sink existing over a period of time in a manufacturing environment and is represented with red line in Figure 9.5b.

Overlap – is the area where waste heat availability and sink aligns and is represented with green line in Figure 9.5c.

The results from modelling temporal availability of a given waste heat source and sink can be easily shown and analysed.

In addition to the graphical demonstration of the waste heat source and sink matchup, this model is able to output a dialogue message (see Figure 9. 6), displaying the three indexes that are of interest. In this example, the RI and WI for the chosen waste heat source and sink is 0.573 and 0.427 respectively. These are suggestive that, over a one hour period, 57.3% of the available waste heat source can be potentially recovered and, the remaining 42.7% will be inevitably lost due to temporal limitation and capacity restraint of this particular sink. The UI of this setup is 0.574, which is indicative that almost 60% of the sink (i.e. Heat requirement for space heating) can be met. The UI of this setup is 0.574, which is indicative that almost 60% of the sink (i.e. Heat requirement for space heating) can be met.

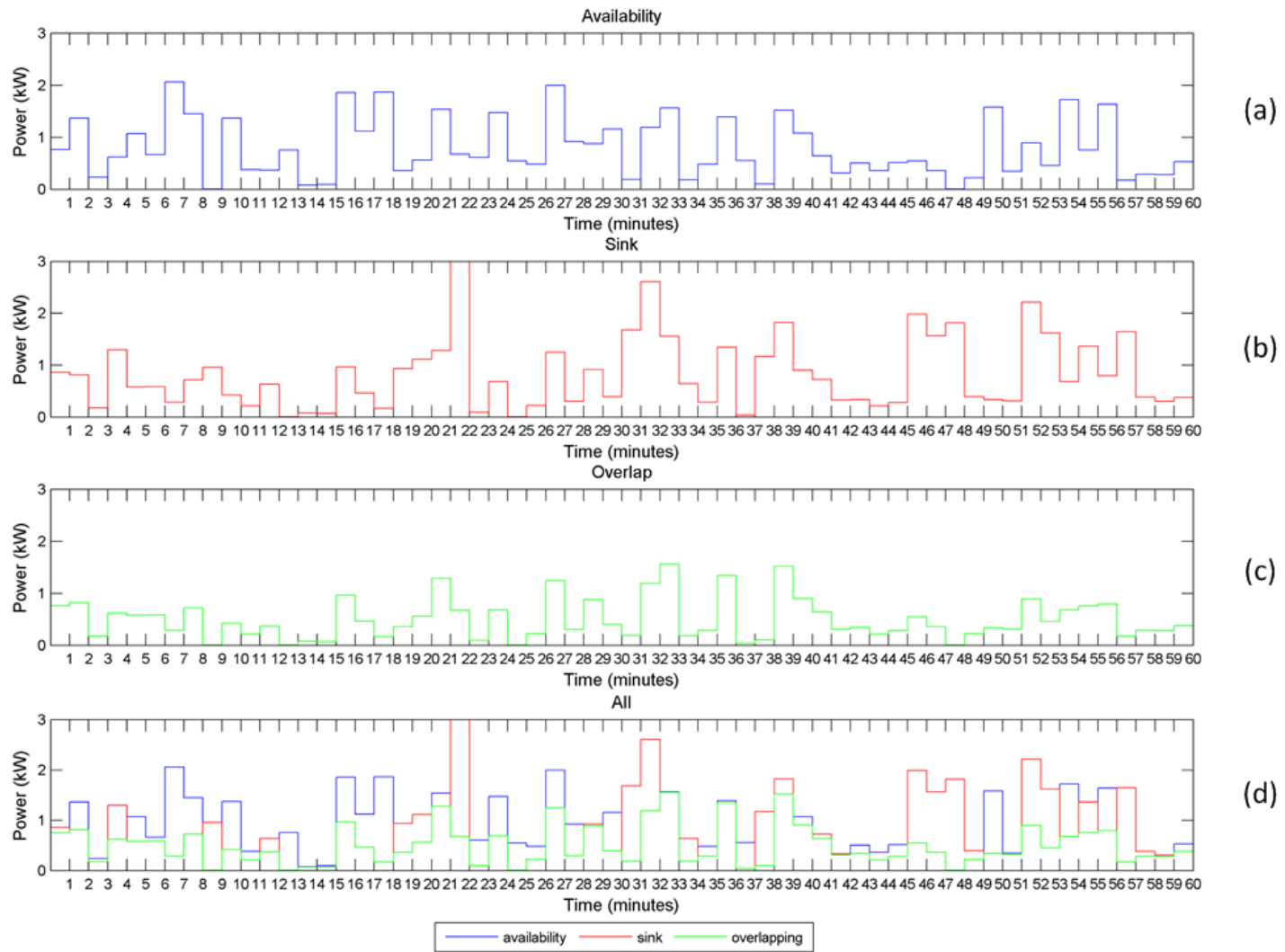


Figure 9. 5 (a) Availability function, (b) Sink function, (c) Overlap of both functions, (d) Overlap of all three plots

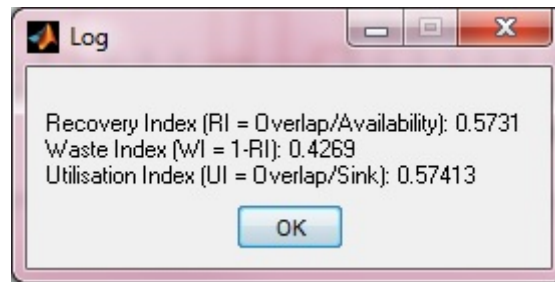


Figure 9. 6 Dialogue message automatically generated showing RI, WI and UI

From an economic point of view, more than half of the fuel consumption to provide heat requirement in a manufacturing environment can be displaced, hence large amounts of savings in energy cost can be made.

9.2.2 Temperature

In order to understand the supply of waste heat and the characteristics of sinks, the report also generated some statistics to differentiate heat sources and heat sinks into distinguished temperature bands and the medium in which heat is available (sources) or required (sinks). The waste heat source bands are:

- Ambient (20°C) – 250 °C is classed as low temperature band,
- 250 – 500 °C is classed as medium temperature band, and
- >500 °C is classed as high temperature band.

The heat sink bands are:

- Ambient (20°C) – 150 °C is classed as low temperature band,
- 150 – 250 °C is classed as medium temperature band, and
- >250 °C is classed as high temperature band.

Temperature measurement is a central task of data acquisition and processing for the assessment of waste heat quantity and quality. Temperature as one of the descriptors has to be properly defined, including in which temperature sampling resolution is of significant importance.

As introduced in chapter 8, one of the methods to acquire data is through empirical measurement, in which temperature data can be obtained from many different sources. These include the use of an infrared camera to identify temperature profile of many different components in a manufacturing environment e.g. shop floor, manufacturing machines and processes etc. or the use of a single point temperature sensors to log temperature variation over a period of time which can include: thermocouples, Resistance Temperature Devices (RTDs), and thermistors and infrared thermometers. The selection of measurement devices need to consider the following factors:

temperatures resolution, sample rate, temperature ranges and medium of the measuring subject where it is explained in the next section.

Temperature resolution refers to the precision of a measurement with respect to temperature. During the process of acquiring temperature data of a particular process in question, it is essential to define an appropriate temperature resolution, such that the stream of data includes every detail of the temperature variation within the period of data acquisition without unnecessary data being recorded. An industrial example is represented in Figure 9.7 below which demonstrates the importance of having a suitably defined temperature resolution.

Figure 9.7 is the plot for a heat up profile of a tank of water from 120 °C to just below 350 °C. As can be seen from the figure, although the average increase in temperature is constant, the change in temperature within a particular period can be significant. It can be noticed from the figure that some temperature spikes occur within the heat up profiles. In this example, the temperature data was collected at 1 minute interval which provides a good resolution because the incremental change in temperature is averaged at 1.13 °C per minute which ties with the accuracy of the measuring device used. If the same measurement was taken at a lower resolution, it may result in the temperature spike variations to be missed during the data acquisition, resulting in the plot and data interpretation being misleading.

In fact, the temperature resolution is very much associated with the sampling rate. It is widely used in the field of digital signal processing, the sampling theorem is a fundamental bridge between continuous time signals and discrete-time signals.

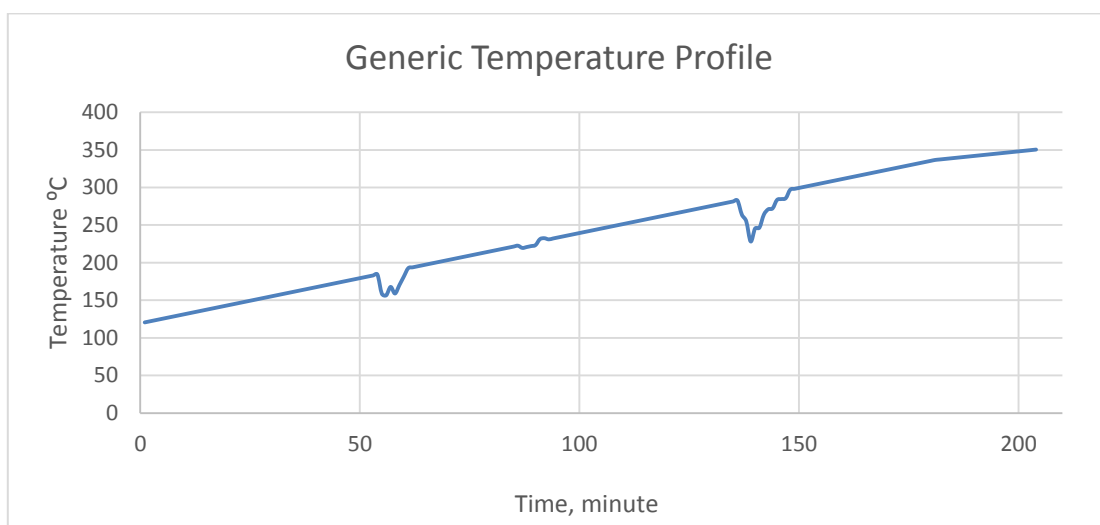


Figure 9. 7 Generic temperature profile for heating up a tank of water

The Nyquist-Shannon sampling theorem introduces the concept of a sample rate that is sufficient for perfect fidelity for the class of functions that are bandlimited to a given bandwidth, such that no actual information is lost in the sampling process. The sampling frequency or sampling rate, f_s , is the average number of samples obtained in one second, thus $f_s = 1/T$. It is exemplified below in Figure 9.8 that the actual temperature data (highlighted in blue) requires sampling rate of 0.067 (1 sample every 15 seconds) to obtain a complete set of information in order to accurately plot the temperature profile. Conversely, if lower sampling rate (low data resolution) is applied, e.g. at sampling rate of 0.022 (1 sample every 45 seconds) the obtained information is insufficient to gain a complete understanding of the temperature profile and thus misleading.

In general, the sample rate or data resolution depends primarily upon the temperature band the data acquisition is carried out within, Figure 9.9. When monitoring temperature signals, the first thing to decide is how fast the signal is changing. For faster signals (rapid change in temperature), this is determined from the maximum frequency component in the signal. For frequency components the Nyquist theorem demands that the signal be sampled at least twice in each cycle, otherwise the amplitude of this frequency component will distort the signal at lower frequencies. To get an accurate picture of the temperature profile, it is required that a sampling rate of 10 to 20 times the highest frequency.

Besides the resolution of the temperature data, methods of determining temperature and accuracy of the temperature measurement is of great importance. To meet this wide array of needs there are a large number of sensors and devices to handle the demand. Sampling temperature of waste heat source and sink must be carried out in a rigorous manner.

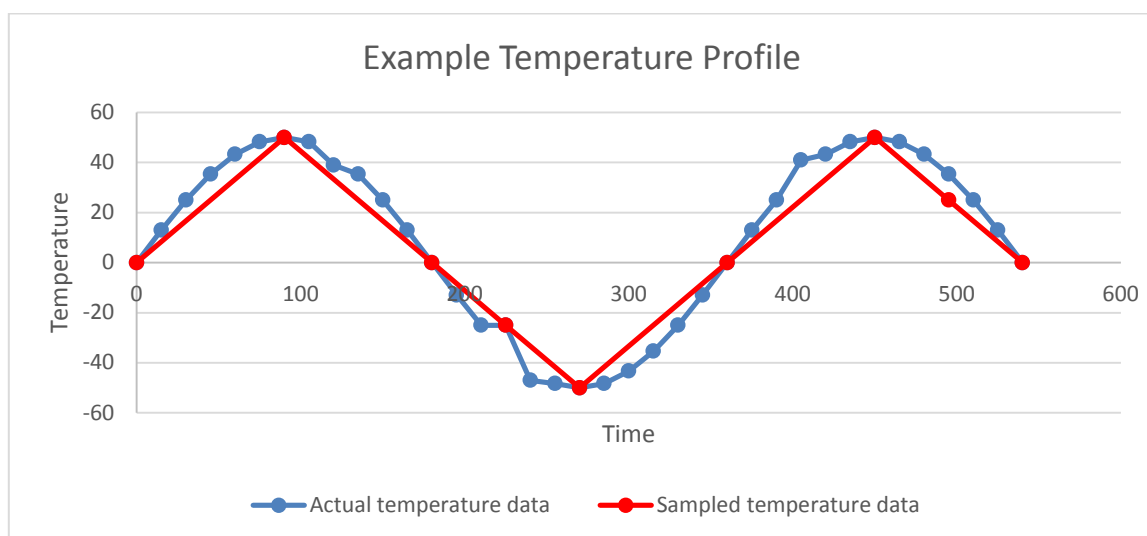


Figure 9. 8 A comparison of Temperature data resolution

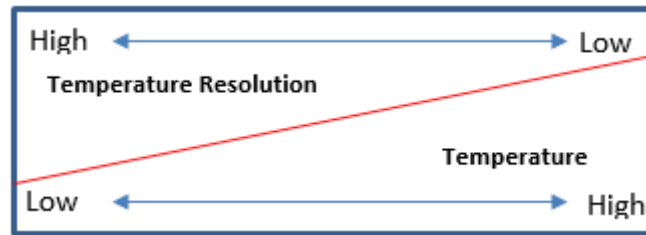


Figure 9.9 Relationship between temperature resolution and temperature

This can range from the simple monitoring of the ejected water temperature of an industrial process, or as complex as the temperature of a weld in a laser welding application. More complicated measurements such as the temperature of flue gas generated from a blast furnace for an engine casting factory. Much more common are the temperatures of fluids in processes or process support applications, or the temperature of solid objects such as cast engine blocks, metal plates and shafts in a piece of machinery.

Despite the variation in temperature measurement methods, knowledge of making the right measurement or using the most appropriate device is very significant to the overall results acquired. For example, an experiment trying to observe the temperature increase of equal volumes of water being heated separately using two piece of temperature sensors, one is an expensive and accurate sensor (with 0.01°C accuracy), whilst another having a low-cost thermocouple connected (0.5 °C accuracy). Although the result of the expensive sensor give much accurate temperature data the thermocouple solution is more cost effective and is accurate-enough for the requirements.

Having considered what is going to be measured, the next step is to decide which type of sensor to use. There are three sensors commonly used in research and industry: the thermocouple, the Resistance Temperature Detector (RTD or resistance thermometer); and the thermistor, which are compared in Table 9.1.

Thermocouples are not precision sensors with typical errors of 2 °C. However thermocouples have a wide temperature range (-200 to 2000 °C) and are often needed simply because alternative devices do not operate at the desired temperature. There are a number of standard types of thermocouples which are used (Table 9.2) because they possess predictable output voltages and large temperature gradients.

Another widely used type of temperature measuring device is the resistance temperature detector (RTD) – the most stable and accurate yet most expensive and fragile of the three sensor types discussed in this section. The most common type of RTD is the platinum resistance thermometer (PRT), the practical operating range of which is -250 to 850 °C.

Table 9. 1 commonly used temperature sensors and their comparison, adapted from: (Cigoy, 2007)

	Thermocouple	RTD (Pt100)	Thermistor
Operating Range	-200 °C to 2000 °C	-250 to 850 °C	-100 to 300 °C
Accuracy	Low 1 °C common	Very High 0.03 °C	High 0.1°C
Thermal response	Fast	Slow	Medium
Cost	Low	High	Low to moderate
Noise problems	High	Medium	Low
Long term stability	Low	High	Medium
Cost of measuring instrument	Medium	High	Low

Thermistors were regarded as inaccurate sensors in the past when thermistors had 5% tolerances at best. However, modern thermistors are not far behind RTDs, in fact thermistors with 0.1 °C accuracy are now widely available and at very reasonable costs. They have a fast response time and a greater output per °C than RTDs. Due to thermistors' high sensitivity they are ideal devices for detecting small changes in temperature – especially when it is the change and not the absolute value that is important. High precision temperature measurement is possible through the use of well-specified and suitably calibrated sensors and instrumentation. However, the accuracy of these measurements will be meaningless unless the equipment and sensors are used correctly.

9.2.3 Exergy Content

Exergy has an important role to play in increasing efficiencies of energy systems and technologies not only because of its unique ability to clearly identify efficiency improvements and reductions in thermodynamic losses, but also because it better identifies environmental benefits and economics of energy technologies than that of the term energy can provide.

Nevertheless, the full value of exergy is not achieved because many researchers regard that exergy is applicable only to systems or studies involving extensive thermodynamics, in areas like mechanical, chemical and electrical engineering, thus it is neglected or underutilised in other research areas.

Table 9. 2 Types of thermocouple available on the market, adapted from Cigoy, (2007)

Thermocouple type	Overall range (°C)	Typical accuracy (°C)	Comments
Type B (Platinum / Rhodium)	100 to 1800	5 °C (at 1000°C)	Suited for high temperature measurements. Unusually, type B thermocouples give the same output at 0 °C and 42 °C. This makes them useless below 50 °C.
Type E (Chromel / Constantan)	-200 to 900	1.7 °C	Type E has a high output (68 $\mu\text{V}/^\circ\text{C}$) which makes it well suited to low temperature (cryogenic) use. Another property is that it is non-magnetic.
Type J (Iron / Constantan)	-40 to 760	2.2 °C	Limited range makes type J less popular than type K. J types should not be used above 760°C as an abrupt magnetic transformation will cause permanent decalibration.
Type K (Chromel / Alumel)	-200 to 1300	2.2 °C	Type K is the 'general purpose' thermocouple. It is low cost and popular. Sensitivity is approximately 41 $\mu\text{V}/^\circ\text{C}$. Use type K unless you have a good reason not to.
Type N (Nicrosil / Nisil)	-200 to 1300	2.2 °C	High stability and resistance to high temperature oxidation makes type N suitable for high temperature measurements without the cost of platinum (B,R,S) types. Designed to be an 'improved' type K, it is becoming increasingly popular.
Type R (Platinum / Rhodium)	-50 to 1760	1.5 °C	Suited for high temperature measurements up to 1600 °C. Low sensitivity (10 $\mu\text{V}/^\circ\text{C}$) and high cost makes them unsuitable for general purpose use.
Type S (Platinum / Rhodium)	-50 to 1760	1.5 °C	Suited for high temperature measurements up to 1600 °C. Low sensitivity (10 $\mu\text{V}/^\circ\text{C}$) and high cost makes them unsuitable for general purpose use. Due to its high stability type S is used as the standard of calibration for the melting point of gold (1064.43 °C).
Type T (Copper / Constantan)	-200 to 400	1 °C	Best accuracy of common thermocouples, often used for food monitoring and environmental applications.

This section goes on to describe exergy, exergy methods, and their applicability to the waste heat recovery research established in this thesis. Examples are also used to illustrate the use of exergy as a tool to understand and improve energy efficiency.

Exergy analysis is a methodology that utilises the principle of conservation of energy (which is embodied in the first law of thermodynamics) together with non-conservation of entropy principle (which is embodied in the second law of thermodynamics) for the analysis, design and improvement of energy and other systems (Szargut *et al.*, 1987). It is identified that the exergy method is useful for improving the energy efficiency by clearly quantifying the locations, types and magnitudes of waste and losses.

A unique characteristic of exergy analysis is that the reference environment must be readily specified before analysis if carried out, which is normally done by providing the temperature, pressure and chemical composition of the reference environment. Therefore, the results of exergy analyses are relative to the specified reference condition which in most cases is modelled after the actual local environment.

The exergy of a portion of matter is equal to the maximum useful work obtainable when taken from its given state to the thermodynamic equilibrium with the environment, without intervention rather than its own and the one of the environment (Kotas, 1985). Such a final state of equilibrium is known as dead state. From another point of view, the exergy can be considered as a measure of the existing disequilibrium between the considered matter and the environment. To be able to carry out exergy calculations, it is necessary to define a reasonable idealized model for the environment, which is taken as reference, since the exergy will always depend on the system's and environment's states. It is also essential to the diverse possibilities of reaching the dead state of equilibrium with the environment, following the restrictions imposed on the different analysed systems. The exergy of heat flow can be calculated with the methods shown in this section.

9.2.3.1 Exergy of Heat Source

The exergy content of a heat flow Q at a temperature T is given as:

$$E_q = \left(1 - \frac{T_0}{T}\right) Q \quad \text{[Equation 9.5]}$$

Where,

E_q = Exergy of heat flow

T_0 = Environmental temperature

T = Temperature of heat flow

Q = Amount of heat energy to cause temperature difference by ΔT

This indicates that for the same heat flow, the exergy content is lower when the temperature T is near T_0 .

Considering cooling water from a compressed air system as a particular waste heat stream, for example, the temperature of the discharged cooling water is at 60 °C and is supplied to the space heating system in a nearby workshop at 20 °C. This particular waste heat stream was identified to discharge cooling water at a constant rate of 0.012 m^3/min .

According to the equation defined in the previous section for waste heat carriers, $Q = mc\Delta T$ heat energy content per hour of the waste heat source can be calculated, assuming that the water density is 983 kg/m^3 and specific heat capacity of 4.185 $KJ/kg K$.

Mass of the cooling water in an hour, $m = \rho V = 983 \times 0.012 \times 60 = 707.76 \text{ kg}$;

Theoretical heat energy content per unit hour, $Q = mc\Delta T = 707.76 \times 4.185 \times 40 = 118.5 \times 10^3 \text{ kJ}$;

By applying equation 9.5, the Exergy value for the waste heat source, $E_q = \left(1 - \frac{T_0}{T}\right) Q = 118.5 \times 10^3 \times \left(1 - \frac{293}{333}\right) = 14.23 \times 10^3 \text{ kJ}$

It can be seen that since T_0 is fixed by the environment, the amount of exergy available is limited by the Carnot Efficiency which is influenced by the temperature of waste heat supplied. As the supplied heat is at relatively low temperature band, the exergy available for the heat transfer is therefore significantly lower than total energy supplied.

9.2.3.2 Exergy Based Technology Analysis

Based on the exergy value determined from the waste heat source stream, and combination of a number of other descriptors, it is possible to determine the type of technology to utilise. Considering a heat exchanger as an example heat recovery technology, it is used to pass energy from hot fluid to cold. The energy is passed in the form of heat which, due to the temperature difference between both fluids, will flow from one to the other spontaneously. These energy transfer carry exergy, so that the hot fluid passes exergy to the cold fluid which absorbs it, and then out into where it can be utilised efficiently. During the movements of the fluids across the tubes of the exchanger, part of the exergy will be consumed by fluid friction.

The energetic loss or exergy destruction in a heat exchanger can therefore be generalised as follows:

- The hot fluid releases exergy to the cold fluid, but some is destroyed in this process due to the temperature difference between the fluids;
- The heat transfer between the exchanger and its surroundings also entails an exergy transfer.

9.3 Qualitative Evaluation

Qualitative evaluation is more subjective than quantitative evaluation and uses very different methods of collecting information. It is defined as a method that usually emphasises descriptions rather than quantification in the collection and analysis of data. In this respect, this section will not be translating works into numbers to be analysed mathematically. Instead, it analyses the aspect of waste heat recovery in an exploratory way and measures what it assumes to be a static reality, in hopes of developing universal laws.

9.3.1 Waste Heat Carrier

As noted in the previous sections, typical waste heat can come from a wide range of sources such as exhaust gases from refining furnaces, iron and steel furnaces, glass melting furnace, gas turbines, reciprocating engines and water heating boilers; waste steam from a steam boiler; and cooling water from compressors. In order to utilise waste heat energy, the heat may be transferred in many cases to a different heat carrier. This is necessary because often the medium from the original process is contaminated or not suitable for use with particular recovery technologies. Waste heat carrier is the general term defined as the medium that waste heat resides in and is able to move from one place to another through heat transfer mechanisms. A waste heat carrier does not produce energy, it simply contains energy imbued by another system. Although waste heat carriers are not so important compared to waste heat itself, because of its physical, chemical and thermodynamic properties, they may have significant impact on waste heat recovery. A waste heat carrier can be in the form of liquid, gas or solid. Dictated by the physical nature of liquid and gas, waste heat carriers in these forms have great flexibility and mobility, meaning that the flow and heat transfer rates are greater than that of solid waste heat carrier, enabling wider range of reutilisation applications.

9.3.1.1 Waste Heat Carrier – Liquid Form

Waste heat carrier in the form of liquid usually includes water and thermal oil. An example for waste heat carrier in liquid form is a coolant liquid. It is a fluid which flows through or around a device to prevent it from overheating, transferring the heat produced by the device to other devices that use or dissipate it. An ideal coolant has high thermal capacity, low viscosity, is low-cost, non-toxic, and chemically inert, neither causing nor promoting corrosion of the cooling system. The most common coolant is water, its high heat capacity and availability with low cost makes it a suitable waste heat carrier. It is usually used with additives, like corrosion inhibitors and antifreeze. Thermal oils are

used for applications where water is unsuitable. Typically oils have higher boiling points than water and can be raised to considerable higher temperature (above 100 degrees Celsius) without introducing high pressures within the container or loop system in question.

There are a number of considerations that can determine the properties of waste heat carrier in liquid form, as outlined in following sections.

- Specific heat capacity of liquid
- Volumetric flow rate of the liquid and its viscosity
- Density of liquid
- Difference in temperature with respect to the environment reference

i. Specific Heat Capacity of Waste Heat Carrier

Specific heat is the amount of heat required to raise the temperature of a certain mass by 1 °C. The amount of waste heat Q can be calculated with the equation:

$$Q = C_p \cdot m \cdot \Delta T \quad \text{[Equation 9.6]}$$

Where m is the mass of the heat carrying medium, C_p the heat capacity of the medium and ΔT the temperature difference between the waste heat and ambient temperature (e.g. room temperature). In order to determine the amount of waste heat available, the specific heat capacity of the heat transfer medium must be identified. The specific heat capacity of some common waste heat media is readily available from published data, however, other ways to access this information includes datasheets, operation and maintenance manuals, or by carrying out experimentation.

ii. Waste Heat Carrier Fluid Flow Rate and Viscosity

Flow rate, V is defined as the volume of fluid which passes per unit time, e.g. volume/time. For example, if it takes 5 seconds for cooling water from a manufacturing process discharge to fill up a 1L capacity tank, the flow rate from the process is (1L/5s) or (0.2 L/s). Flow rate may depend on several factors:

- The type of fluid that is flowing (low viscosity or “thin” fluids flow faster than high viscosity or “thick” fluids)
- The force pushing or pressure on the fluid (stronger forces produce fast flow rates)
- The size of the pipe or opening the fluid is flowing through (larger openings allow for fast flow)
- The type of surface over which the fluid is flowing (smooth surfaces allow for faster flow)

For the purpose of determining the total amount of waste heat energy available during a specific time frame, the carrier flow rate data can be used to calculate the total volume of flow

corresponding to that time. This result is an essential part to determine the mass flow of the amount of liquid, thus total energy content within the flow.

iii. Density of Waste Heat Carrier Liquid

The density of a waste heat carrier liquid plays an important role in determining the total energy contained in an identified waste heat carrier. It is denoted by the symbol ρ and is defined as mass per unit volume, (e.g. *kg/L*). As in the previous section, the amount of waste heat Q contained in a waste heat carrier is proportional to, m , the mass of the waste heat carrier.

The mass of the waste heat carrier can be calculated using equation:

$$m = \rho \cdot V \quad \text{[Equation 9.7]}$$

Where ρ the density, m is the mass, and V is the volume.

iv. Temperature Differential between Waste Heat Carrier and Waste Heat Sink

As mentioned in the previous section, in order to calculate the amount of waste heat Q , the temperature differential between the heat carrier and waste heat sink, ΔT , is required. The methodology of measuring temperature and calculating ΔT can be found in the defining temperature section. Additionally, there is the amount of heat coming from phase transformations (latent heat), during the condensation of a flue gas or the solidifying of a liquid among others. However, attention must be paid when condensing flue gases, particularly regarding corrosion. In order to use “conventional”, and therefore, cheaper heat recovery materials, it is often recommended to keep the flue gases above the dew point. Thus, the higher the mass flow rate and the usable temperature difference, the greater the waste heat amount. (Equation 9.6)

9.3.1.2 Waste Heat Carrier – Gaseous Form

One of the common types of waste heat carrier is the exhaust gas from combustion processes. It is considered as a by-product and carries a certain amount of thermal energy depending on its temperature and flow rate. Other types of gaseous waste heat carrier include air, which uses either convective airflow (passive cooling), or a forced circulation using fans. Hydrogen is often used as a high-performance gaseous coolant. Its thermal conductivity is higher than all other gaseous with high specific heat capacity, low density and therefore low viscosity. Steam can also be used where high specific heat capacity is required in gaseous form and the corrosive properties of hot water are accounted for.

The process of determining amount of heat energy contained in liquid form can also be applied for that carried in gaseous form. Where specific heat capacity, C_p , mass, m , and temperature differential between carrier and heat sink, ΔT are required in order to calculate the energy content.

9.3.1.3 Waste Heat Carrier – Solid Form

In some applications, solid materials are also considered as a type of waste heat carrier. For example blast furnace is one of the largest energy consumers in an iron and steel manufacturing plant. The operating temperature of this particular process is usually above 1000 °C, depending on the requirements, with over 500 °C of exhaust gas emission, which is within the high temperature band of the waste heat source classification.

Unlike other types of waste heat carrier, solid material such as moulded steel beams leaving their processes does not flow freely, they are produced and moving through a conveyer system with unit of throughput, e.g. No. of steel beams per minute. As solid waste heat carriers are considered as a discrete flow of heat energy, it can be difficult to quantify the amount of waste heat energy contained for each individual product, i.e. discrete shape, size and material etc. Hence, it may require another type of medium, for example liquid or gaseous as an intermediate heat energy carrier to extract waste heat energy out of the discrete solid product. However this process is highly subjective to the type of process and product being manufactured.

Another influencing factor to heat energy recovery from solid waste heat carrier is the geometry associated with the object in question. The Surface-Area-to-Volume ratio (SA: V) is a typical example, it is defined as the amount of surface area per unit volume of an object. For a given shape, SA: V is inversely proportional to size. A cube 1 m on a side has a ratio of 6 m^{-1} , half that of a cube 0.5 m on a side (see Figure 9.10).

The larger the SA:V ratio, the faster the object is likely to cool down (through conduction, convection and radiation). Some products need to be cooled at a specific rate to ensure correct material properties (e.g. structural steel) which may limit heat recovery. In general, it is still possible to apply equation 9.6 but with a number of conditions as described above.

9.3.2 Contaminant

Waste heat recovery technologies such as heat exchangers usually provide a long service life with little maintenance other than a routine inspection and cleaning. Fouling and corrosion are the main causes of degraded performance or failure.

A very expensive failure may occur when a leak develops, allowing the cooling water to mix with the hydraulic fluid, contaminating both the hydraulic system and the cooling water system. Other heat exchanger failures can be caused by silting, scaling or other forms of obstructing the cooling water passageways. These types of failures are not as disastrous as corrosion failures, but can occur over time.

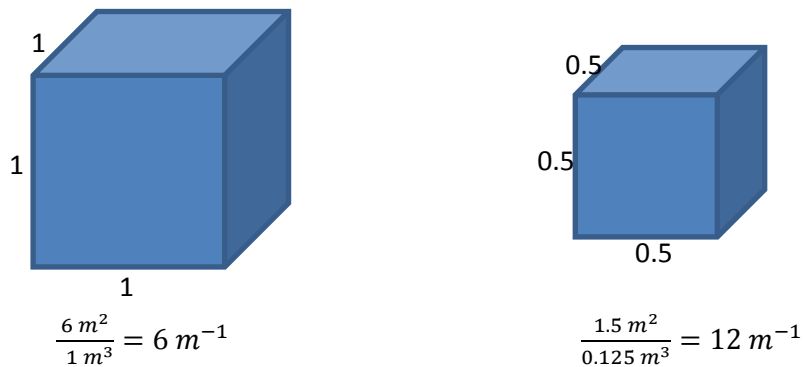


Figure 9.10 Demonstration of SA:V

9.3.2.1 Fouling and Corrosion

Fouling is the accumulation of deposits that decrease the thermal transfer of a surface and increase the system's flow resistance. The result is that due to reduced heat transfer coefficients, the cooling water volumetric flow rate has to increase to keep the system at the same temperature.

Corrosion is the degradation of a metal due to chemical reactions with the working environment. Shell and tube hydraulic fluid-to-water heat exchangers are usually constructed with copper or copper alloy tubes. Copper and its alloys are normally resistive to corrosion, but the corrosion rate will vary depending on the concentration of one or more corrosive elements present in the hot hydraulic fluid or cooling water (MTS Systems Corporation, 2005). A normal corrosion rate is 5–25 μm per year. Over a period of time, this slow dissolving of the metal will result in component failure:

- Corrosion products may settle in the heat exchanger tubing, causing the fluid flow to be blocked.
- Corrosion can eventually cause leaks between the water and hydraulic fluid supplies.
 - Water contamination in the hydraulic fluid can seriously shorten the life of the hydraulic components of hydraulic power units (HPU) and test system.
 - Hydraulic fluid in the water can result in a costly clean-up supervised by the local environmental protection agency.

The type of contamination occurs is dependent on the extent of the corrosion and the pressure in the hydraulic fluid and water supplies. Since fluid tends to flow from a high pressure area to one of low pressure, the lower pressure fluid will become contaminated. Eventually, however, both the water and the supplies may be contaminated as more leakage occurs (MTS Systems Corporation, 2005).

9.3.2.2 Contaminants and Guidelines for Technology

In general, the use of cooling towers may be the cause of corrosion failure in heat exchangers. These towers use fan propelled ambient air to evaporate a portion of the cooling water and thus cool the remaining water. This action transfers whatever air pollution exists into the cooling water. Also, since the towers are open to the environment, they are prone to collecting animal and vegetable matter which is damaging to heat exchangers.

Contaminants must be controlled to the levels listed in the following table. Ideally, the pH level should be maintained in the 7.5 to 9.0 pH range for most applications. Chlorine should be used to limit the growth of microbiological organisms that are generated by protein decay. The following table lists the acceptable levels of common compounds allowed in the cooling water supply.

In general, parameters of normal water based waste heat carrier determining the overall corrosion stability of a heat recovery technology are: temperature, pH, carbonate hardness (alkalinity), total hardness as well as chloride, sulphate and nitrate concentration; conductivity is often used as sum parameter for the total ion (salt) content.

Table 9. 3 water chemistry for heat exchanger, adapted from MTS Systems Corporation (2005)

Compounds found in water	Allowable quantity (parts per million)
Ammonia	none
Bacteria	must be bacteriologically safe
calcium	<800 ppm
Chlorides	<5 ppm
Dissolved solids	>50 but <500ppm; limit to 150 ppm if abrasive solids present
Iron	3ppm
Nitrates	<10 ppm
Nitrogen compounds	none
Oxidising salts or acids	none
pH level	7.5 - 9.0
Silica as SiO ₂	<150 ppm to limit silica scale
Sulfides	<1 ppm
Sulfur dioxide	<50 ppm

A description of the most important water parameters and their specifications are listed below:

Temperature: in general, an increase in temperature will increase the corrosion rate of most metals. For copper in heated water, the likelihood of pitting is higher at temperatures above 60°C. Also the risk of stress corrosion cracking of stainless steel will increase at temperatures above 60°C, and pitting and crack corrosion in stainless steel is also temperature dependent (BSI, 2005).

pH: General corrosion of copper mainly depends on pH and the risk of corrosion is lowest if pH is kept above 7.5 and below 9.0 (BSI, 2005).

Alkalinity: If the content of hydrogen carbonate (HCO_3^-) in the water is very low, i.e. below 60 mg/l, corrosion products of copper may dissolve and be released into the system. It is also recommendable not to exceed a HCO_3^- concentration of 300 mg/l (VDI, 2009).

Conductivity: A high conductivity in the tap water means that the water has a high concentration of ionic substances. In general, an increase in conductivity of tap water will increase the corrosion rate of most metals. A maximum conductivity of 500 $\mu\text{S}/\text{cm}$ is in general a desirable value.

Hardness: Copper is susceptible to corrosion in soft water; the $[\text{Ca}^{2+}, \text{Mg}^{2+}] / [\text{HCO}_3^-]$ ratio must therefore be greater than 0.5.

Sulphate: High concentrations of sulphate will increase the risk of pitting in copper. A maximum sulphate concentration of 100 mg/l is recommended, but corrosion can also take place at lower concentrations if the $[\text{HCO}_3^-] / [\text{SO}_4^{2-}]$ ratio is below 1.

Nitrate: Nitrate ions have an influence similar to that of sulphate, and a maximum nitrate concentration of 100 mg/l is recommendable.

To monitor and regulate fluid quality from sources of waste heat, respective sensors should be installed.

There is a need to link the restrictions when selecting recovery technologies:

- Size of pipes
- Materials in contact
- Throughput or flow rate

9.3.3 Spatial Availability

There is a large range of waste heat recovery equipment with different capacity and spatial requirement. In general, it is vital for manufacturers to assess the spatial availability around the interested waste heat source and provide sufficient free space around the target area. This facilitates access to the waste heat source to install heat recovery equipment, as well as to provide the space necessary for service tasks during its term of operation.

9.3.3.1 Accessibility of Waste Heat Source

- Geometry of the process

- Size, complexity, how deeply embedded is source/ sink
- Locality of the waste heat outlet/passage relative to the process
 - Height, underground, in water course, from service vents

Another concern is the ease of access to the waste heat source. The geometry of the process such as size, complexity, and how deeply embedded may influence the access of waste heat sources and installation of any additional heat recovery equipment. For example, a process may release certain amount of heat from chemical reactions taking place. However, due to safety reasons the process machine, as shown in Figure 9.11, is completely sealed during operation which makes it inaccessible to waste heat recovery.

Alternatively, the pipework that carries the chemical fluid and the pumps which drive the fluid around also contain a significant amount of heat, they are mostly exposed to the environment, which makes them easier to access and recover heat from. The image on the right hand side of Figure 9.11 demonstrates an infrared image of the process, showing in the circles where the areas of heat loss are located.

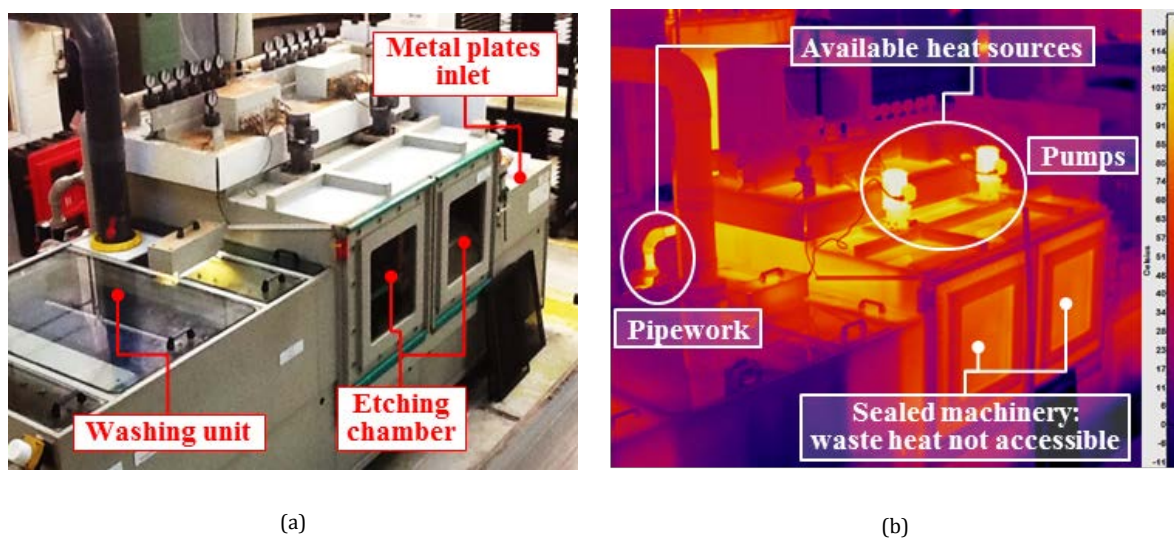


Figure 9. 11 Identification of waste heat hotspots in a chemical etching production line (a) using an infrared camera (b)

9.3.3.2 Ability to Install Heat Recovery Technology

When considering the technology options to recover waste heat energy from potential sources, the ability to install heat recovery technology must also be taken into account. Heat recovery technologies come with different types and sizes, which can limit their applicability by the allowable space of the factory floor. An example, Alfa Laval steel plate heat exchanger with a liquid flow

capacity of $36 \text{ m}^3/\text{h}$ requires at least $1200 \cdot 320 \cdot 930\text{mm}$ amount of space, in addition to the main device, there is the auxiliary equipment, such as pipes, pumps and motors, etc.

9.3.3.3 *Locality of the Waste Heat Source and Sink*

There is another influencing factor which can have an important bearing on the utilisation of waste heat energy, the locality of the waste heat source and sink. This is where the consideration of the elimination of non-viable options at an early stage can provide a corresponding saving in time and investment.

- Geographic distance between heat source and sink and barriers in between:
 - Onsite reuse; both source and sink are on the same site not necessarily the same process or facility,
 - Over the fence; delivery from a source to a sink at another industrial facility,
 - Heat to power; the assumption is made that all power produced can be fed to the grid, at no additional cost, i.e. every site has a suitable grid connection, and
 - District heat production; considers the production of district heat and delivery to the fence of the industrial facility.

The shorter the distance between source and sink, the more viable a heat recovery operation is likely to be. The cost of an intermediate heat transfer system and heat losses from pipes and ducts are the key concerns and can adversely affect the viability of a waste heat recovery plan. The best option is to reuse the heat from source directly onsite without transformation to a different form and/or transport over long distances. For example, feed water and combustion air can be preheated using boiler exhaust gases, blowdown, and condensate. However, barriers such as having to link heat source and sink exist when they are in different buildings, or separated by a number of other workshops in the same building.

9.4 Chapter Summary

As discussed in the previous Chapter, waste heat sources can be found in the Plant, Process and Product levels of a manufacturing environment and in this Chapter, they are further classified into two main categories, general purpose and sector-specific waste heat. In order to clearly define various waste heat sources, quantitative and qualitative assessment methods are used to assign some descriptors to the characteristics of the waste heat sources.

Section 9.3 details the quantitative evaluation which included the modelling of temporal availability, temperature and exergy content for waste heat source and sink. Modelling of temporal availability is

carried out in order to decide how appropriate a heat sink is compared to specific heat sources, comparisons of both availability and demand must be carried out based on the same time scale. Temperature as one of the descriptors governs how useful the waste heat sources are in a manufacturing facility and in addition, temperature measurement is central to the task of data acquisition and processing for the assessment of waste heat quantity and quality. In this section, temperature band and sampling resolution are defined. Available energy of waste heat sources are represented as exergy content which defines not only the quantity but also quality of energy in a heat energy recovery system. In addition, exergy calculation of heat flow from waste heat source and sink along with an example calculation is demonstrated.

Section 9.4 details the qualitative evaluation which may be defined by descriptions or assessment criteria. These qualitative evaluations included waste heat carrier, contaminant and spatial availability. Waste heat carrier is the general term used to define the medium that waste heat resides in and is able to move from one place to another through heat transfer mechanisms and is further categorised into liquid, gaseous and solid forms. Calculations for energy and exergy content with respect to each form are additionally described. Contaminant as one of the qualitative terms describes and provides assessment criteria for waste heat streams which may contain corrosive substances or deposition which may cause corrosion and/or clogging in heat recovery equipment. The assessment includes the chemical properties of waste liquid or gas, pH value, temperature and conductivity, etc. Spatial availability describes the space requirement for heat recovery equipment in relation to the available spaces in a facility, e.g. specific height and width requirement of the machinery. In general, it is vital for manufacturers to assess the spatial availability conveniently around the interested waste heat source and provide sufficient free space around the target area. This facilitates access to the waste heat source to install heat recovery equipment as well as to provide necessary service tasks during its term of operation.

Chapter 10 Development of Decision Support Tool

10.1 Introduction

This chapter discusses the logic, decision pathways and design configurations of the Waste Heat Recovery (WHR) Decision Support Tool. Justification of the methods employed and schematics of the system logic are presented as appropriate throughout the chapter.

Having established a framework for the understanding of available WHE, it is important to demonstrate appropriate data flow and identify structure to allow use of the framework to analyse real world applications. In order to implement the framework in a professional manner, it is highly useful to have a software tool to undertake data input, rapid analysis, storage of data, series of computation, scenario design, informed decision making and report generation. Therefore, a decision support software tool has been developed and a detailed working procedure is presented in the following sections.

There are three scenarios where using a software tool that implements the WHR framework could be beneficial;

- Recovery of waste heat energy within an existing manufacturing plant;
- Implementing waste heat recovery within a reconfigurable manufacturing system;
- Consideration of waste heat recovery in the process design stage of a manufacturing system;

However for the purposes of this research, the software tool has been designed primarily to implement WHR within existing manufacturing plants.

Much of the energy required for industrial processes is ultimately emitted to the environment in the form of heat. This is particularly true within existing manufacturing plants where recovery of such “wasted” energy is limited due to poorly designed manufacturing systems, inefficient machinery, and out-of-date management procedures. An example of this might be a food processing plant that carries out a frying process in the morning and drying in the afternoon, where the factory floor is centrally heated using a gas boiler. By implementing heat recovery, it is possible that flue gas emitted from the frying process can be used via a heat exchanger to preheat air at the inlet of the drying process, in addition to preheating the feed water for the gas boiler or directly heating the factory floor. In this scenario, the software tool is able to provide an environmental manager of a manufacturing plant with tailored heat recovery technology recommendations for both mass and batch production. However, since the heat recovery technologies are to be implemented on a

production line, spatial restrictions, risks of contamination and health and safety issues are likely to arise as discussed in the literature chapter.

The software tool described in this chapter is also suitable for use within a Reconfigurable Manufacturing System (RMS). A RMS is designed at the outset for rapid change in its structure and location, as well as its hardware components. This flexibility is required in order to quickly reconfigure its production capacity and functionality within a manufacturing plant in rapid response to market and system changes. For each configuration the quantity and quality of waste heat energy will be different. For example, an ice cream manufacturer may reduce or expand production of a particular ice cream product depending on the market demand, and this causes the manufacturer to increase the size of or relocate hardware components, extend the hours of production, etc. The decision support software is able to provide a selection of technologies that are flexible and adaptable to reconfigurations. For RMS situations, the software tool needs to be applied periodically in order to track system performance and make informed decisions accordingly.

Another scenario in which this software is useful is at the design stage, where processes are to be planned and implemented in order to meet specifications. The software tool enables waste heat energy recovery to be considered as part of holistic design process, through matching of potential waste heat sources and sinks, and designation of floor space to host waste heat recovery technology. However, at the process design stage, much of the data on temperatures, pressures, flowrates, contamination, etc., of the potential heat sources is not available and must be predicted based on expert knowledge. The dynamic nature of the software tool allows for iterative use with defined parameters to obtain the most suitable waste heat recovery recommendation to serve as a guideline for process designers.

The analysis techniques used in the software tool are based on techniques identified in the literature review undertaken in Chapters 4 and 5, while the methods for formulating the software structure are discussed in Chapter 8 and 9. This chapter presents a detailed description of the software developed to implement the WHR framework, as well as a stepwise instruction for potential users.

Section 10.2 outlines the design requirements of the tool while Sections 10.3 and 10.4 discuss the user data input and data analysis modules. Section 10.4 is divided into two parts, namely the waste heat source and sink selector, and the heat recovery technology selector respectively. Section 10.5 presents the results generation and report preparation module of the programme, which then leads to the final summary of the chapter presented in Section 10.6.

10.2 Overview of the WHR Software Tool

It has been briefly alluded to in section 10.1 that this decision support software tool can be used by a number of different user groups, including environmental managers planning to implement a waste heat recovery project within existing manufacturing facilities, or periodically reviewing a reconfigurable manufacturing plant for energy efficiency, and process designers planning to install waste heat recovery technology alongside production processes. The following sections detail the scope and the information flow path of the software tool for different user groups.

10.2.1 Scope of Software Tool

The WHR framework had originally been intended to enable recommendations covering a wide range of waste heat recovery technologies, including heat exchangers, thermoelectric generators, thermal engineering cycles, and heat pumps. However, a few problems arise in attempting to construct a technology database that describes technologies in sufficient depth. For example, thermoelectric generators are attractive because they convert heat energy directly into electricity which is convenient. However the technology is still at an early stage, where the efficiency to cost ratio is lower than a justifiable threshold. In addition, populating a comprehensive technology database has proven to be difficult as a number of waste heat recovery technologies are customised by their supplier to be better suited for the specific task, which means capability data on that technology is either not publically available, or a complex design procedure must be undertaken with real data provided by the technology manufacturer, which vary from brand to brand. For these and other reasons, the software tool is limited to providing heat exchanger selection only. Users are able to make use of a detailed heat transfer evaluation generated alongside the technology recommendation to undertake a more in-depth heat exchanger design to better suit the process under consideration.

Although the software tool has been programmed in MATLAB, users are required only to use a Microsoft Excel interface for input of data and viewing of results. This arrangement combines efficiency and user friendliness as MATLAB is software designed for carrying out mathematical operations that work on arrays or matrices, while Excel is designed for data management and is more accessible. The MATLAB engine of the software tool can be exported as a standalone application file to be used by any computer operating system.

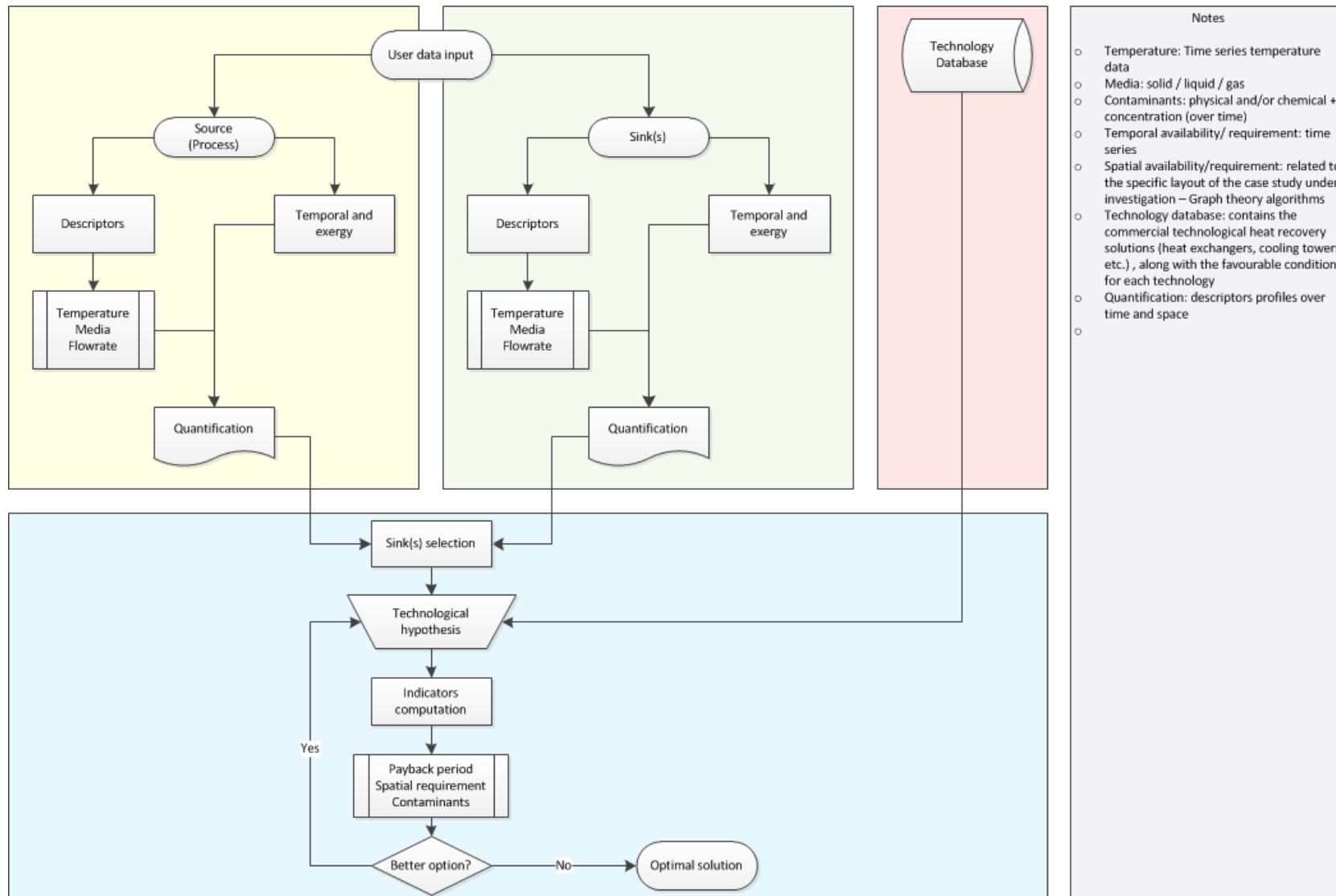


Figure 10. 1 Overview of information flow path of the WHR software tool.

10.2.2 Information Flow Path of the Software Tool

Figure 10.1 shows an overview of stages of operation in the WHR Decision Support Tool. The system is comprised of three major modules; data entry, data analysis and computation, technology database, and results generation.

The user data entry module is responsible for collection of essential data in the format required by the software system. This includes requesting users to define where waste heat is generated (waste heat sources) and where is the demand for heat energy input is (waste heat sinks) in their facility, the time period when these sources and sinks are active i.e. the time window, and how often they are monitored, i.e. the temporal resolution. Depending on the nature of the processes of interest and the production schedule, the time window may differ from one case to another. Therefore it must be defined whether hourly, daily or weekly data is to be analysed. And of course, depending on how much fluctuation there is in the recorded data, the required time resolution to achieve accurate and detailed representation of the process varies. For example, a process with a rapid and large variation in its operational temperature and pressure may require a higher resolution compared with another process that operates at constant temperature and pressure.

The data analysis and computation module is responsible for manipulation of input raw data into pre-defined descriptors. Whilst temporal availability and exergy analysis are used to identify the best waste heat source and sink matches both in terms of periods of availability and quantity of exergy, other descriptors such as temperature range, stream media and flowrate are required for selection of the appropriate technology in order to harness waste heat energy from the source, with or without transfer of such heat energy via a different medium to be utilised by a sink. Depending on the amount of data input by the user, the system carries out a large amount of computation, analysing each of the possible waste heat sources, sinks and technology combinations. However not all combinations are technically or financially viable. The system intelligently excludes some of the results on the grounds of inappropriate timing, exergy quantity and quality, and poor heat recovery performance associated with a given technology choice.

As important as the data input and computation module, the results generation module is where the recommendation support process is undertaken. Out of the feasible source and sink combinations, a technology selection is undertaken on the basis of payback period, spatial requirement and ability to cope with contaminants. Lastly the module is responsible for presenting the results and recommendations in the form of a report back to users.

10.3 User Data Entry Module

Although the software tool engine is programmed in MATLAB, the user data input module of the software tool is created with the user-friendly Microsoft Excel engine. This also improves access as Excel is the most commonly used data management programme. The objective of this section is to provide an instructive guide to the means of inputting data and describe the series of computations carried out in MATLAB based on the data provided.

In order for MATLAB engine to recognise the data entry and associated time a number of key parameters must be defined by the user. These parameters include defining an appropriate time profile and number of waste heat sources and sinks utilised by the waste heat recovery framework. Having established the time constraint and number of sources and sinks, the engine is able to automatically generate an input template for data entry.

As discussed in Section 9.3, matching heat sources and heat sinks is an essential part of the feasibility study, which involves assessing:

- The quantity of heat available against that required by a sink;
- The temperature of the heat available and that required;
- The time profiles at which the heat is available and required;

This matching is key to successful and economically feasible heat recovery. For example, the average daily hot water demand may appear similar in quantity to the heat recovered, but it may actually be required in a number of large peaks rather than as a constant demand throughout the period of interest, making it more difficult to recover the heat usefully. Figure 10.2 illustrates the matching process.

Figure 10.2a demonstrate that recovered waste heat energy alone is insufficient to meet the demand for the period that the demand is required, indicating that all the heat available is used during production hours but also requires additional heat sources to meet demand. Figure 10.2b shows that the recovered heat meets the entire demand and surplus heat energy yielded can potentially be recovered for additional heat demand from other process or facility.

Thus, in order to implement the matching process, definitions of the time profile and possible number of heat sources and sinks must be identified, and subsequent data entered in the template generated. Figure 10.3 displays the interfaces for source and sink data input module. Time window is defined as the time period when waste heat sources and sinks are active, which can denominate hourly, daily or weekly depending on the actual production campaign.

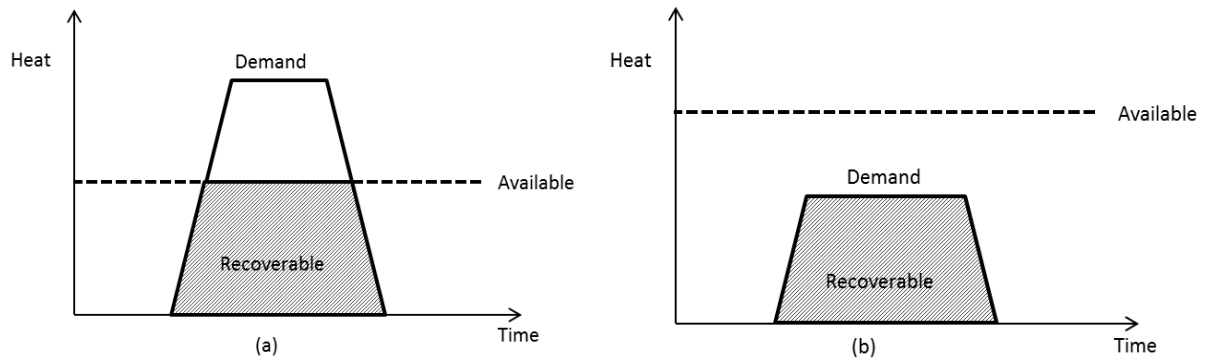


Figure 10. 2 matching availability and demand on the same time profile

While time resolution is defined as how often process specific data is recorded in units seconds, minutes or hours. The Nyquist-Shannon sampling theorem can be used to identify a sampling rate sufficient to describe a given rate of variation of a quantity of interest. And lastly, the user is asked to define the number of waste heat sources and sinks. A larger number of sources and sinks will result in more complex source and sink matching.

A corresponding template is then generated based on the user entry. For example, if a user identified two existing waste heat sources and three waste heat sinks available in their manufacturing facility and the production time window is one day, with an hourly sampling interval, Figure 10.4 and 10.5 illustrates the blank templates generated automatically by pressing the “generate input template” button. Within the template, the number of rows displayed in the table represent individual data samples and is determined by the time window and resolution, e.g. if daily production is investigated with hourly data resolution, 24 blank rows are included in the template for users to enter sampling data at each hour.

Users are expected to firstly specify the stream medium of identified sources and sinks from a predefined database using a dropdown list, as shown in Figure 10.4 and 10.5. The stream media database is setup to aid users with limited knowledge of the physical properties of waste heat carriers, such as density and specific heat capacity. Instead, the software has been developed to have a built-in database, covering physical property data for every pre-defined stream medium.



Figure 10. 3 Overview of source and sink data input windows

Source1				Source2			
Stream medium		Air		Stream medium		Air	
Th_in	Th_out			in	Th_out	T_amb	Flow rate
		Air					
		Medium pressure gas					
		High pressure gas					
		Water					
		Low viscosity liquid					
		Medium viscosity liquid					
		High viscosity liquid					
		Boiling water					

Figure 10. 4 waste heat source template generated based on user entry

Sink1			Sink2				Sink3			
Stream medium		Water	Stream medium		Water		Stream medium		Water	
Tc_in	Tc_out		in	Tc_out	T_amb	Flow rate	Tc_in	Tc_out	T_amb	Flow rate
		Water								
		Low viscosity liquid								
		Medium viscosity liquid								
		High viscosity liquid								
		Boiling water								
		Boiling organic liquid								
		Acqueous inorganic liquid								
		30% Triethylene Glycol/W								

Figure 10. 5 waste heat sink template generated based on user entry

It is possible for the users to expand the database on demand by manually inputting additional stream media types and the respective physical properties. Following the definition of stream medium, users are also required to enter data into several other columns such as the inlet and outlet temperatures of source and sink streams, represented as $T_{h,in}$, $T_{h,out}$, $T_{c,in}$ and $T_{c,out}$ respectively. In addition, the ambient or process surrounding temperature, T_{amb} as well as the volumetric flow rate V , is required in order to evaluate exergy availability and demand.

Having a controlled template is important in ensuring effective data entry and project management, and smooth operation of the main software engine. A well designed template saves time for users when entering data and helps avoid unnecessary input errors. For this reason the dynamic template approach is taken which generates just enough cells, based on the definition of time window and resolution, for the data required and keeps all fields of entry consistent. The template assists with project management, through assisting the user with communication with different parties, from whom the information may be gathered, avoiding discontinuity of data entry and confusion. The template is able to serve as a reminder of whether sufficient data has been acquired. The MATLAB engine is programmed to monitor the template pages, and is responsible for converting Excel data into MATLAB format for further computation.

10.4 Data Analysis and Computation

As introduced in section 10.2, the software tool consists of two core subroutines, one of which is the Waste Heat Sink Selector and the other named the Heat Recovery Technology Selector. The purpose of the waste heat sink selector is to allow initial selection of the most suitable uses for the recovered waste heat energy to be completed prior to the selection among feasible technology types. As discussed in the description of the waste heat recovery framework in Chapters 8 and 9, it is essential for the users of the software tool to provide key raw data regarding the waste heat sources and potential sinks characteristics, such as inlet and outlet temperatures of the hot and cold streams, flow rates, and time profiles. The combination of temporal modelling and exergy calculation can be done based on data provided by users which enables further analysis of each individual source and sink matching. Section 10.4.1 details the source and sink selection module of the software engine while Section 10.4.2 discusses the working procedure for technology selection.

10.4.1 Source and Sink Selection

Upon the user filling in the template and saving the Excel spreadsheet, the MATLAB engines automatically imports the saved source and sink data to a temporary database for further processing. A methodical approach is used to undertake source and sink selection. The procedure for evaluating the best source and sink matchup using exergy and temporal availability analysis is as follows:

1. A list of possible source and sink combinations is produced;
2. For each combination, the exergy availability from the source(s) and exergy demand from the sink(s) are evaluated;
3. The exergy availability and demand based on window and resolution defined by users is plotted, the overlap between those quantities is identified and the Recovery, Waste and Utilisation Indexes are evaluated;
4. The computation is repeated for the rest of the possible combinations, the results presented in a tabular format and a possible ranking carried out;

The MATLAB engine initiates by identifying a list of the possible waste heat source and sink combinations from the data provided. The number of combinations is solely dependent on the numbers of sources and sinks input. For example if the user identified three waste heat sources and four sinks in a facility and entered data for all of them, the software tool would provide a list of 105 different combinations (a section of the list is shown in Figure 10.6. Exergy and temporal assessment would be carried out for each listed options.

sourcecolumn	sinkcolumn
'Source 1'	'Sink 1'
'Source 1'	'Sink 2'
'Source 1'	'Sink 1 + Sink 2'
'Source 2'	'Sink 1'
'Source 2'	'Sink 2'
'Source 2'	'Sink 1 + Sink 2'
'Source 1 + Source 2'	'Sink 1'
'Source 1 + Source 2'	'Sink 2'
'Source 1 + Source 2'	'Sink 1 + Sink 2'

Figure 10. 6 Exemplified source and sink combination for a three sources and four sinks scenario

As aforementioned in Section 9.2.3, exergy is defined as the maximum useful work obtainable when a system is taken from its given state to thermodynamic equilibrium with the environment, without external intervention (Kotas, 1985). The exergy calculation uses the user supplied amount of heat flow, ambient temperature, and temperature difference between hot and cold streams, while the integrated database within MATLAB is accessed to supply the required physical properties (i.e. density, specific heat capacity) for the selected stream media type. An example calculation of exergy content for a compressed air exhaust is shown in Section 9.2.3.1. The source and sink selection module automatically executes the exergy computation for every valid datum, e.g. for data from a day's production recorded on an hourly basis, the exergy value at each hour is computed. Hence figures for exergy power (kW) at a given time (t) can be plotted, (see Figure 10.7). The plot displays the power associated with the waste heat source over 24 hours as a blue stepped graph whereas that of the waste heat sink is displayed in red. The green sections are where the blue and red curves intersect, and the area under the green curve is the area of the overlap. In Section 9.2.1.1 the Recovery Index (RI) is defined as the ratio of aligned period over available period, which indicates the theoretical fractional amount of waste heat exergy that can be recovered (Equation 9.1). The Waste Index (WI) is the ratio of misalignment over the specified period between waste heat source and sink, which describes the amount of available heat which cannot be utilised because there is no corresponding contemporaneous demand (Equation 9.2). The Utilisation Index (UI) is defined as the overlap area divided by the sink power demand, representing the percentage of heat demand that can be met (Equation 9.3).

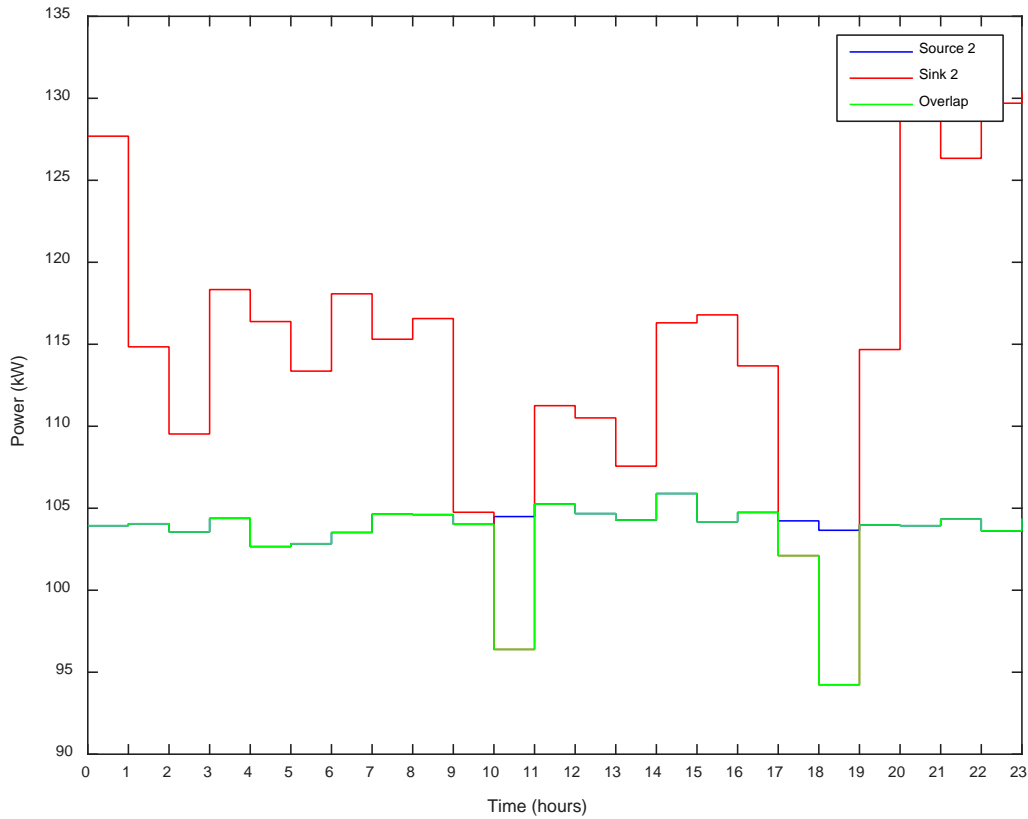


Figure 10. 7 Exergy and temporal availability plot for source No.2 and sink No.2

Having completed a computation of indexes for the entire list of waste heat source and sink combinations, the results are tabulated. Table 10.1 presents a sample of the outcomes for the example in Figure 10.6.

Table 10. 1 Results of exergy and temporal availability computation showing RI, WI and UI

	Sources	Sinks	RI	WI	UI
1	Source 1	Sink 1	0.5864	0.4136	1
2	Source 1	Sink 1 + Sink 2	0.8797	0.1203	1
3	Source 1	Sink 1 + Sink 3	0.9842	0.0158	0.959
4	Source 1	Sink 1 + Sink 4	0.6532	0.3468	1
5	Source 1	Sink 2 + Sink 3	0.733	0.267	1
6	Source 1	Sink 3 + Sink 4	0.5066	0.4934	1
7	Source 1	Sink 1 + Sink 2 + Sink 3	1	0	0.7579
8	Source 1	Sink 1 + Sink 2 + Sink 4	0.9419	0.0581	0.9952
9	Source 1	Sink 1 + Sink 3 + Sink 4	0.9957	0.0043	0.9109
10	Source 1	Sink 2 + Sink 3 + Sink 4	0.7998	0.2002	1
11	Source 1	Sink 1 + Sink 2 + Sink 3 + Sink 4	1	0	0.7214
12	Source 2	Sink 1 + Sink 3	0.5131	0.4869	1
13	Source 2	Sink 1 + Sink 2 + Sink 3	0.6597	0.3403	1
14	Source 2	Sink 1 + Sink 3 + Sink 4	0.5465	0.4535	1
15	Source 2	Sink 1 + Sink 2 + Sink 3 + Sink 4	0.6931	0.3069	1
16	Source 3	Sink 1 + Sink 2 + Sink 3	0.5864	0.4136	1
17	Source 3	Sink 1 + Sink 2 + Sink 3 + Sink 4	0.6161	0.3839	1

It is obvious that some of the listed combinations are not likely to warrant further analysis, such as combination No. 12 which has a RI of 0.513 meaning that only 51% of the energy available for capture could be recovered compared to combination No. 2 which has a RI of 0.879. Combinations with low RI are filtered out by an automated feature of the software tool engine. Users are given an opportunity to set a threshold RI value¹. Combinations with RI below the threshold are removed. Figure 10.8 shows the schematic of the decision path for this feature.

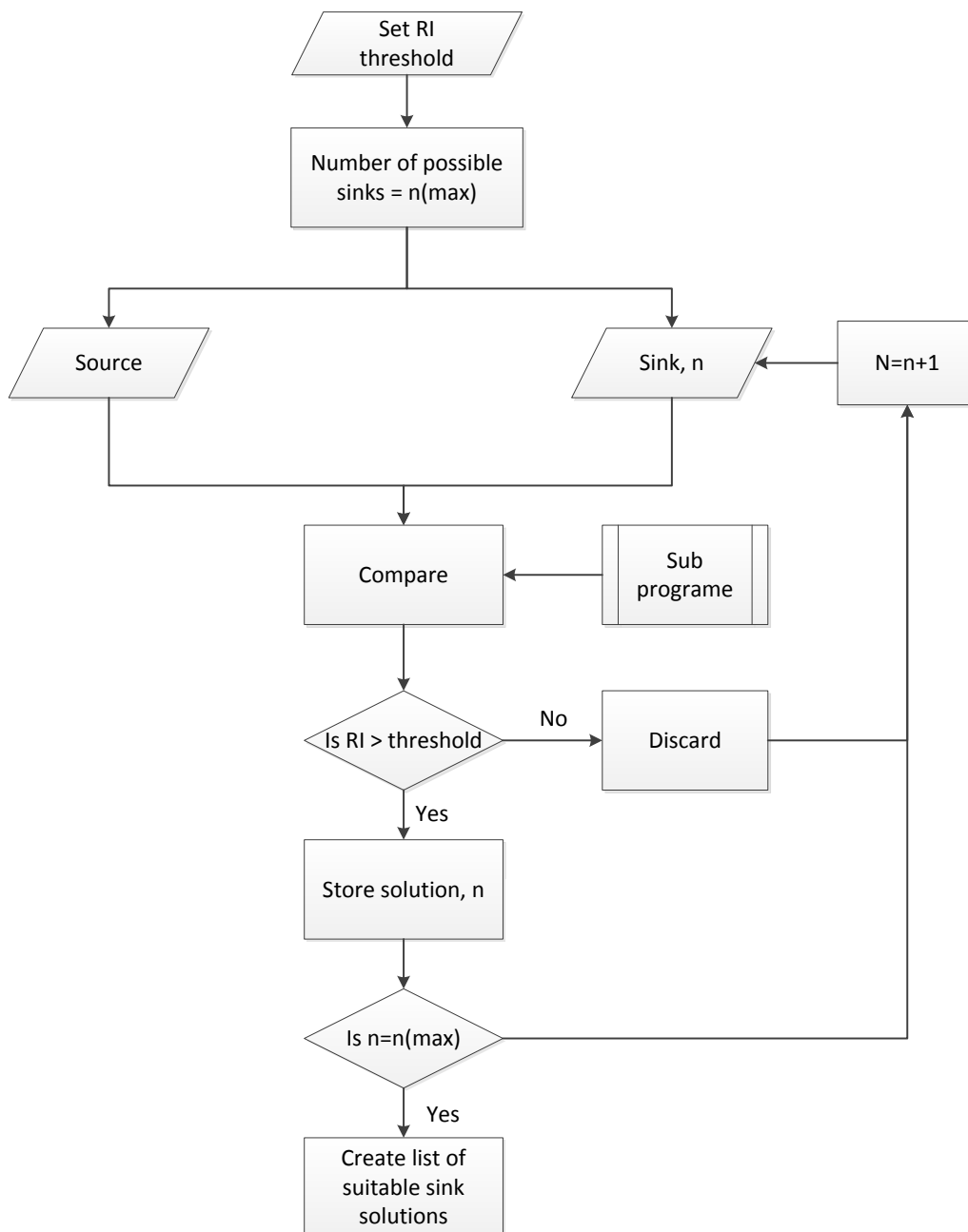


Figure 10. 8 Decision path for automatic source and sink combination filtering, similar iterative loop for n sources

¹ Note that since an extensive number of WHR surveys have not yet been undertaken, it is not possible to accurately set a threshold value, but in this research the threshold has been set at 0.7 to demonstrate the system function.

10.4.2 Heat Exchanger Technology Selection

Heat exchangers have become common components in many scenarios for sustainable development in many industrial disciplines. There are a wide range of heat exchanger designs and, depending on specific requirements, various types of heat exchanger are available to meet a range of physical conditions, including pressure, temperature, corrosion resistance, heat transfer mechanism, and size. It is therefore the designer who selects among feasible heat exchanger types, with the final decision often largely influenced by cost.

Traditionally, the total cost of a heat exchanger, C_{tot} is subdivided into costs of capital, C_{cap} comprised of the initial purchase and installation, and the operating expenses for energy and supplies, C_E , and the operating expenses C_S for maintenance, repair, technical staff and replacement of heat transfer fluids:

$$C_{tot} = C_{Cap} + C_E + C_S \quad \text{[Equation 10.1]}$$

This method requires a great deal of information the gathering of which is a very complex process, e.g. for the cost of capital, C_{cap} , the acquisition values of the heat exchanger, pump, compressors, and other auxiliary components to convey the fluids through both channels of the exchanger are required. Energy costs and other operating expenses are dependent on individual cases, but they are generally assumed to be roughly proportional to the annual operating time and equipment costs. In the development of this waste heat recovery software tool, the heat exchanger costing method outlined above is not implemented both because of the complexity of the economic evaluation methods required and also some considerations, such as the requirement for auxiliary equipment, maintenance and servicing falling out of the scope of the software tool.

Consequently an alternative method to consider cost in the selection of a suitable heat exchanger technology is required. The method used in this research has been developed and implemented by the Engineering Science Data Units (ESDU) International plc, in collaboration with heat exchanger manufacturers and under the guidance of independent committees (IHS ESDU, 1994). They published a series guides on the topic of selection and costing of heat exchangers, which allow users to firstly shortlist feasible heat exchanger types that fulfil the physical requirements, and then to estimate the cost for each of the feasible types in order to make a cost comparison.

10.4.2.1 *Selecting Feasible Designs*

For any given process, the streams between which heat is to be exchanged will have specific physical and chemical properties, such as temperature, pressure, stream media and contaminants involved, and a feasible heat exchanger is one that is able to fulfil the requirements to contain the respective

streams. In consultation with heat exchanger manufacturers, the specifications of the various heat exchangers were collected and presented by the ESDU in tabular form. Table 10.2 shows a small section of the table covering various types of heat exchangers. Although the table is only a subset of all the existing heat exchangers types, it covers the most important and widely used types. In the case that there are no feasible standard types of heat exchangers that can meet the process requirement, a heat exchanger design process must be undertaken specifically for the application.

After the selection of feasible types of heat exchangers, further decision can be made upon cost but, often, the selection is made on the basis of common practice within the particular industry. Shell-and-tube type heat exchangers have a reputation for reliability and flexibility and are the most widely used. However, other kinds of heat exchanger can be more suitable for particular applications: for very small duties, the double-pipe exchanger, which is manufactured from standard components, may be cheaper, while plate-and-frame heat exchangers are often less expensive. In addition, the physical size of a heat exchanger may be a very important deciding factor during the selection process. For a given heat transfer surface area, shell-and-tube exchangers have an order of magnitude larger volume than compared to compact heat exchangers, such as plate-fin and printed circuit exchangers. Compact heat exchangers are usually considered in cases where space is limited. Thus heat exchanger cost and geometry data are crucial in making the important selection.

10.4.2.2 Selection and Costing of Heat Exchanger – The C Value Method

The conventional way of approximating cost of heat exchangers is done in terms of the cost per unit area. If the overall heat transfer coefficient (U), heat load of the exchanger (Q), and mean temperature difference (ΔT_m), are known, then the area (A), is calculated from:

$$A = \frac{Q}{U\Delta T_m} \quad \text{[Equation 10.2]}$$

Table 10. 2 Adapted sample from ESDU tables summarising characteristics of heat exchanger types, reproduced from IHS ESDU (1994)

Heat exchanger type	Pressure(Pa)	Temperature (°C)	Normal size ranges
Scraped-surface	0 – 10	0 – 300	5 – 10m height, 0.5m diameter
Shell-and-tube	0 – 300	-25 – 600	10 to 1000 m ² (per shell-multiple shells can be used)
Spiral	0 – 18	0 – 400	Up to 200 m ²
Welded-plate	0 – 60	0 – 650	>1000 m ²

However, for various types of heat exchangers, the definition of area is often complex and this is also associated with the U value. Hewitt, Shires & Bott, (1982) first suggested the C value method, bypassing the difficulties in defining area and overall heat transfer coefficient and allowing a direct comparison between heat exchangers in terms of the heat duty carried out (Q), and the available temperature driving force (ΔT_m), which are related to the process specification. The quotient $Q/\Delta T_m$ is characteristic of the heat exchanger duty being carried out. From the point of view of the software tool, the key target is the overall cost for the particular duty, specified in terms of $Q/\Delta T_m$. The cost factor C is defined as the cost in pounds sterling per unit $Q/\Delta T_m$, and has the units $\text{£}/(\text{W}/\text{K})$. For a particular duty and configuration, values of C may be estimated and are given in addition to U values in data tables provided in the Appendix.

The procedure for evaluation of the alternative feasible types of heat exchanger using C value method is as follows:

1. Estimate the heat load, Q , from a heat balance.
2. Using F_T method (a method used to correct the mean temperature difference by a factor that accounts for the deviation from pure counter-current heat exchanger operation, F_T factor is dependent on the geometry of the heat exchanger and the inlet and outlet temperature of the hot and cold fluid streams) to estimate the mean temperature difference, ΔT_m , using standard F_T correction factor designed for worst case scenario together with the Logarithmic Mean Temperature Difference (LMTD), ΔT_{lm} .
3. Calculate the quotient $Q/\Delta T_m$ for each proposed configuration.
4. From the ESDU data tables provided for each exchanger type, read off the value of C , interpolating logarithmically between the levels of $Q/\Delta T_m$ given in the tables.
5. Calculate the cost of each configuration for the specified duty by multiplying $Q/\Delta T_m$, by C and compare the costs. It is worth noting that possible differences in installation and auxiliary equipment costs are not included within the scope of the software tool because the lack of data provided and great level of sophistication, making it difficult to estimate.
6. When all of the configurations are evaluated, ranking of favourite choices are done on the basis of cost. If one configuration is cheaper than the others, the design is automatically placed at the top of the results table and detailed calculation and estimates are then carried out. If there are several designs at around the same cost, the performance of all of the designs should be estimated in greater detail.
7. Alongside the cost approximation, possible sizing of selected heat exchangers is also undertaken.

It is to be noted that, this method is merely used for the purpose of quick order of magnitude assessment of heat exchanger costs. This procedure is usually a precursor to detailed exchanger design after technology selection is made.

The heat load, Q is readily determined from the enthalpy change of either of the hot or cold streams:

$$Q = m_h C_{p,h} (T_{h,in} - T_{h,out}) = m_c C_{p,c} (T_{c,out} - T_{c,in}) \quad \text{[Equation 10.3]}$$

Where m_h and m_c are the mass flow rates, $C_{p,h}$ and $C_{p,c}$ are the specific heat capacities of the hot and cold stream, respectively. $T_{h,in}$, $T_{h,out}$, $T_{c,in}$ and $T_{c,out}$ represent the inlet and outlet temperature of the hot and cold stream, respectively. The general temperature profiles in a counter-current flow heat exchangers are also depicted in Figure 10.9.

The procedure for determining ΔT_m using standard F_T method is as follows.

- i. Calculate parameter R from the expression: $R = \frac{(T_{h,in} - T_{h,out})}{T_{c,out} - T_{c,in}}$ and calculate the parameter P from the expression: $P = \frac{(T_{c,out} - T_{c,in})}{(T_{h,in} - T_{c,in})}$;

Read off the value of F_T from standard chart for the appropriate values of R and P . However, at the level of sophistication being used in the design selection process, it is sufficient for most purposes to assume F_T value to be 0.8, as worst case scenario.

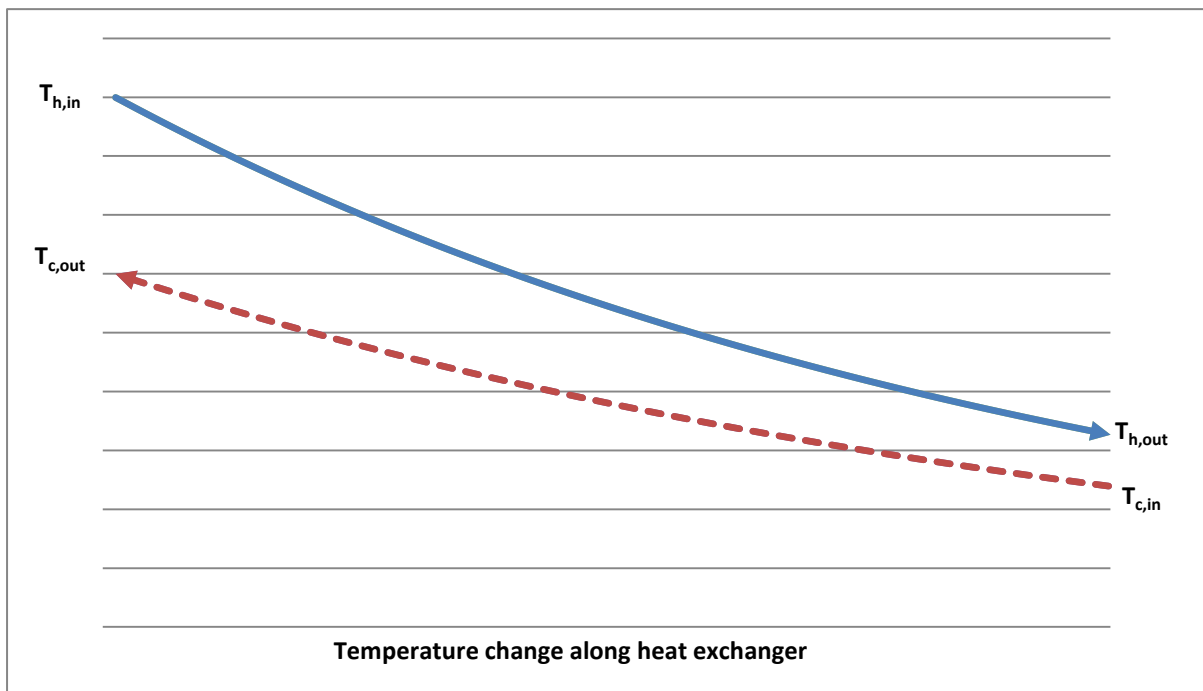


Figure 10.9 Temperature profiles in counter-current flow heat exchangers (ESDU, 1994)

ii. Calculate the LMTD, ΔT_{lm} from:

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\log_e \frac{(T_{h,in} - T_{c,out})}{(T_{h,out} - T_{c,in})}} \quad \text{[Equation 10.4]}$$

iii. Calculate mean temperature difference, ΔT_m from:

$$\Delta T_m = F_T \Delta T_{lm} \quad \text{[Equation 10.5]}$$

Having obtained the values of Q and ΔT_m from the above equations, then the quotient of $Q/\Delta T_m$ is simply calculated.

The tables of C values (exemplified by Figure 10.10) can be interpolated logarithmically, using given expression:

$$C = \exp \left\{ \log_e C_1 + \frac{\log_e(C_1/C_2) \log_e[(Q/\Delta T_m)/(Q/\Delta T_m)_1]}{\log_e((Q/\Delta T_m)_1/(Q/\Delta T_m)_2)} \right\} \quad \text{[Equation 10.6]}$$

where C_1 and C_2 are the C values of the particular hot and cold side streams pairing at $(Q/\Delta T_m)_{upper}$ and $(Q/\Delta T_m)_{lower}$, respectively.

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid								
			Low Pressure Gas (< 1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1 000	Low Pressure Gas (< 1 bar)	U (W/m ² K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	4.8	3.8	2.9	3.8	3.8	4.7	2.8	3.8	3.9
	Medium Pressure Gas (20 bar)	U (W/m ² K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	3.4	2.5	2.9	2.5	5	2.6	2.5	2.5	2.5
	High Pressure Gas (150 bar)	U (W/m ² K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
	Treated Cooling Water	U (W/m ² K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	2.8	2.5	2.9	2.5	2.5	2.5	2.5	3.9	2.5
	Low Viscosity Hydrocarbon Liquid	U (W/m ² K)	100	375	425	600	500	130	820	525	290
		C (£/(W/K))	2.7	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5
High Viscosity Hydrocarbon Liquid	U (W/m ² K)	70	140	175	160	155	85	175	155	125	
	C (£/(W/K))	4.7	2.5	2.9	2.5	2.5	3.9	2.5	2.5	2.5	
Boiling Water	U (W/m ² K)	105	470	550	875	670	140	1435	725	340	
	C (£/(W/K))	3.9	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5	
Boiling Organic Liquid	U (W/m ² K)	100	375	430	600	500	130	820	525	285	
	C (£/(W/K))	4	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5	
5 000	Low Pressure Gas (< 1 bar)	U (W/m ² K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	2.16	1.26	1.1	1.23	1.22	1.84	1.23	1.22	3.5
	Medium Pressure Gas (20 bar)	U (W/m ² K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	1.5	0.86	1	0.76	0.8	1.16	0.6	0.8	0.94
	High Pressure Gas (150 bar)	U (W/m ² K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.05	1.1	1.1	1.1	1.1	1.3	1.1	1.1	1.2
	Treated Cooling Water	U (W/m ² K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	1.4	0.75	1	0.5	0.72	1	0.4	0.72	0.9
	Low Viscosity Hydrocarbon Liquid	U (W/m ² K)	100	375	425	600	500	130	820	525	290
		C (£/(W/K))	1.45	0.8	1.05	0.8	0.9	1.1	0.5	0.9	1.2
High Viscosity Hydrocarbon Liquid	U (W/m ² K)	70	140	175	160	155	85	175	155	125	
	C (£/(W/K))	2.4	1.66	1.2	0.95	1	2.7	0.82	1.6	1.95	
Boiling Water	U (W/m ² K)	105	470	550	875	670	140	1435	725	340	
	C (£/(W/K))	1.4	0.9	1	0.5	0.6	1.1	0.4	0.73	0.9	
Boiling Organic Liquid	U (W/m ² K)	100	375	430	600	500	130	820	525	285	
	C (£/(W/K))	1.45	0.8	1.05	0.8	0.9	1.28	0.7	1	1.1	

Figure 10. 10 U & C values for double-pipe heat exchanger, adapted from Courtesy Brown Fintube Ltd (IHS ESDU, 1994)

The relative cost of one exchanger type varies from another with $(Q/\Delta T_m)$, as is exemplified by Table 10.3 taken for the case of treated cooling water on the cold-side and a low pressure gas on the hot-side.

In the comparison shown in Table 10.3 below, where values of $Q/\Delta T_m$ is assumed to be 3000 W/K, therefore the lower and upper bound levels of 1000 and 5000 are chosen. Based on the corresponding C_1 and C_2 values, using a double-pipe heat exchanger as an example, the overall C value is determined using Equation 10.6 as follows:

$$C = \exp \left\{ \log_e 2.8 + \frac{\log_e(2.8/1.4) \log_e[(3000)/(1000)]}{\log_e(1000/5000)} \right\} = 1.74 \frac{\pounds}{W/K}$$

Similarly, for the shell-and-tube, printed-circuit, and welded-plate heat exchangers are read from respective tables. Hence, the approximate cost of each exchanger type is calculated (Table 10.2) and the double-pipe exchanger is likely to be the best option for the heat transfer duty specified where its modular construction procedures are a positive cost advantage.

Though the values of U that are also tabulated are not necessary from the point of view of costing, such values are helpful from the point of view of approximating system dimensions. The heat exchanger surface area can be calculated using Equation 10.2 and the volume of the exchanger estimated if the area per unit volume is known. It is usually considered that, for shell-and-tube and double-pipe heat exchanger types, the surface area per unit volume is of the order of 50-100 m^2/m^3 , while for compact exchangers such as plate-fin and plate-frame heat exchanger types, the value is usually around 500 m^2/m^3 .

Thus, reading from Figure 10.10 the value of $U = 105 W/m^2.K$ for a double-pipe heat exchanger for the assumed value of $Q/\Delta T_m$ above, the surface area required is given as:

$$A = \frac{Q/\Delta T_m}{U} = \frac{3000}{105} = 28.57 m^2$$

Table 10. 3 Comparison of various heat exchangers cooling low pressure gas with treated cooling water (ESDU, 1992)

Heat exchanger type	C_1 & C_2 values (£/(W/K))		Overall C value £/(W/K)	Costs (£) $Q/\Delta T_m \times C$
	$Q/\Delta T_m = 1000 W/K$	$Q/\Delta T_m = 5000 W/K$		
Double-pipe	2.8	1.4	1.74	5220
Shell-and-tube	4.89	1.56	2.24	6720
Printed-circuit	12	3.6	5.28	15840
Welded-plate	5.6	2.54	3.26	9793

In addition, using guidelines for surface area per unit volume of $50 \text{ m}^2/\text{m}^3$ for double-pipe designs, volume of such heat exchanger setup is as follows:

$$V = \frac{28.57 \text{ m}^2}{50 \text{ m}^2/\text{m}^3} = 0.57 \text{ m}^3$$

The Waste Heat Recovery (WHR) software tool is able to carry out all of the above operation automatically within MATLAB and present resultant data back to users. Details of results generation and subsequent financial and environmental assessment are also undertaken in section 10.5.

10.4.3 Results Generation and Report Preparation

This section details the final step in the software tool operation, computing a number of key parameters, providing results that are easy to access and understand by users. A report mechanism of the software tool generates a summary page inclusive of acceptable solutions (above RI threshold) of source and sink and technology selection, as well as detailed individual analysis page for each solution. In addition, for those of software users without the knowledge of this thesis, a glossary of some of the terms used is provided outlining every technical term used in the report (Figure 10.11).

10.4.3.1 Results Generation

Having estimation of the system cost and dimensions for all of the possible technology options is important, but in order for users to gain a more directly relevant understanding of the results generated, data must be interpreted in terms of financial returns and environmental impact assessments. For small processes and simple heat recovery systems with a low capital cost, the software tool should provide a sufficient estimate of the economic return to justify investment. However, for large and complex manufacturing processes and where high capital cost of heat recovery technology required, a more in-depth appraisal should be carried out. A generalised economic return assessment approach is shown below, and details of any particular plant and the site must be included to make the approach more specific.

Capital costs are highly dependent on the particular site and the processes involved and it is important to take into account all the costs which might include:

- Heat exchanger;
- Pipework;
- Installation;
- Insulation;
- Control systems;
- Auxiliary pumps;

Heat Recovery Report - Guidance to use this report		
Source:	source is where waste heat energy is found within a manufacturing plant or process streams, e.g. hot air from compressed air systems	
Sink:	sink is where heat energy demand arises within a manufacturing plant or process stream, e.g. boiler feed water or combustion air preheating	
Overlap	Overlap is the area under the common intersection between waste heat source and waste heat sink function	
Temporal availability	comparisons of both availability and demand based on the same time scale	
Recovery Index:	defined as the ratio of aligned period over available period	$RI = \frac{Overlap}{Availability}$
Waste Heat Index:	compares the unaligned area between waste heat availability and demand	$WI = 1 - RI$
Utilisation Index:	defined as overlap divided by sink, representing ratio of waste heat sink utilised	$UI = \frac{Overlap}{Sink}$
Q/ΔT _m	Q/ΔT _m is characteristic of the heat exchanger duty being carried out, represent heat energy per unit temperature difference, unit: W/K	
Cost	quick order of magnitude assessment of heat exchanger costs	
Area	approximate heat exchanger surface area	
Volume	approximate heat exchanger volume based on typical heat exchanger area/volume ratio	
Payback	number of years to recover investment	
CO2 reduction	tons of carbon dioxide reduced based on the waste heat energy recovered and amount of fuel displaced	

Figure 10. 11 glossary of some of the important terms used in the software tool and report.

Payback period of installing a heat exchanger is calculated by counting the number of years it will take to recover the capital and continued running costs invested in the waste heat recovery project. It is possible to approximate the annual energy saving based on the waste heat recovery index (RI), e.g. available exergy from waste heat source multiplied by RI giving amount of exergy recovered, and depending on the time resolution defined by users at the data input stage of the software tool, the annual recoverable exergy can be calculated.

The annual recoverable exergy is the actual unit cost of the heat saved, e.g. assuming recovered heat is displacing that from a gas-fired boiler, with gas at £0.008/kWh and a boiler efficiency of 0.8, energy savings will be £0.01/kWh displaced. Taking into account the additional costs of any auxiliary equipment, such as fans or pumps, although this is usually small. An exemplified expression is shown as follows:

$$\text{Auxiliary unit running costs} = \frac{(\text{unit kW}) \cdot (\text{hour run/year}) \cdot (\text{electricity costs } \text{£/kWh})}{\text{unit efficiency ratio}}$$

Consequently a payback period of such waste heat recovery project can be approximated using:

$$\text{Payback period} = \frac{\text{heat exchanger cost} + \text{auxiliary unit running cost}}{\text{Annual cost saving}}$$

The MATLAB engine is able to carry out payback period computation for the totality of the solutions identified, providing results in terms of years to break even.

In addition to financial savings, installing a waste heat recovery technology also provides wider benefits. Saving energy can produce substantial reductions in emissions to atmosphere, particularly carbon dioxide (CO₂). The reduction in CO₂ emissions will depend upon the fuel that is displaced, e.g. burning natural gas emits 0.21 kg CO₂/kWh, if 200,000 kWh/year of waste heat energy is recovered and put into useful work such as space heating purposes, displacing heat from a gas boiler, the annual reduction in CO₂ emissions will be approximately 42 tonnes. The CO₂ saving calculation is also included in the software design and results shown in the report.

10.4.3.2 Report Generation

In order to enhance user experience, providing users with access to results generated from MATLAB computation, data must be exported back to a format which is readily accessible from majority of the computer operating systems with Microsoft Office packages. With this design objective in mind, the software tool is able to save results generated during MATLAB computation as Excel files. As well as undertaking complex source and sink matching technology selection, costing and sizing operations within MATLAB, the reporting module of the software tool automatically converts corresponding data into Excel format, (Figure 10.12). By displaying a summary page for all the possible source and sink combinations, respective technology options, and costs and sizing information, users are allowed to access each of the solutions with more detailed information from individual tabs shown in Figure 10.13.

Figure 10.14 is an example report sheet generated investigating the possible waste heat recovery project within a manufacturing facility. It is identified through exergy and temporal availability matching, source No.2 and sink No.2 is best suitable for heat recovery as can be seen in the temporal availability plot in the report sheet with an RI of 0.99 and UI of 0.90. This indicates that almost all of the waste heat can be successfully recovered with little waste while 90% of the heat demand is met by the installation of a heat exchanger.

Additionally, the report also displays the proposed heat exchanger choice, which in this case is the double-pipe, with a cost approximation of £12,000, effective heat transfer area of 82 m² and almost 2 m³ of space. The payback period calculated is about two years and five months and having this heat exchanger is able to deliver 131 tonnes of CO₂ reduction annually.

10.5 Chapter Summary

As discussed in the methodology chapter of the thesis, the purpose of a waste heat recovery framework is to help manufacturers to identify areas where waste heat is underutilised and where demand for heat energy might occur in their facility highlighting the potential for an appropriate heat exchanger technology to act as a “bridge” in order to transfer heat between source and sink. Having developed a framework is essential to provide this methodical approach to waste heat recovery however in order to implement such framework in a user-friendly and professionally in an industrial environment. Hence a software tool is developed to both help users with limited heat recovery background and to educate them how waste heat source and sink are matched and respective heat exchanger is chosen. The software tool features in simple data input, rapid analysis, storage of data, built-in database, intelligent computation, and scenario design, informative decision making and report generation.

Summary of results												
Solution #	Source(s)	Sink(s)	RI	WI	UI	Technology	Cost (£)	Area (m²)	Volume	Payback (years)	CO 2 reduction (tons)	
6	Source 1	Sink 1 + Sink 2	0.801	0.199	1.000	Double pipe	16,593	112.87	2.26	0.80	545.9225128	
8	Source 1	Sink 1 + Sink 2	0.801	0.199	1.000	Shell and tube	17,821	112.87	2.26	0.86	545.9225128	
22	Source 1 + Source 2	Sink 1 + Sink 2	0.671	0.329	1.000	Double pipe	20,329	138.29	2.77	0.98	545.9225128	
24	Source 1 + Source 2	Sink 1 + Sink 2	0.671	0.329	1.000	Shell and tube	21,646	138.29	2.77	1.04	545.9225128	
2	Source 1	Sink 1	0.589	0.411	1.000	Double pipe	16,593	112.87	2.26	1.09	400.9109454	
4	Source 1	Sink 1	0.589	0.411	1.000	Shell and tube	17,821	112.87	2.26	1.17	400.9109454	
7	Source 1	Sink 1 + Sink 2	0.801	0.199	1.000	Printed circuit	41,068	31.52	0.06	1.97	545.9225128	
23	Source 1 + Source 2	Sink 1 + Sink 2	0.671	0.329	1.000	Printed circuit	49,867	38.62	0.08	2.40	545.9225128	
14	Source 2	Sink 2	0.992	0.008	0.905	Double pipe	12,048	81.96	1.64	2.41	131.2289196	
16	Source 2	Sink 2	0.992	0.008	0.905	Shell and tube	13,118	81.96	1.64	2.62	131.2289196	
3	Source 1	Sink 1	0.589	0.411	1.000	Printed circuit	41,068	31.52	0.06	2.69	400.9109454	
10	Source 2	Sink 1	1.000	0.000	0.330	Double pipe	15,133	102.94	2.06	3.00	132.3137176	
18	Source 2	Sink 1 + Sink 2	1.000	0.000	0.242	Double pipe	15,133	102.94	2.06	3.00	132.3137176	
12	Source 2	Sink 1	1.000	0.000	0.330	Shell and tube	16,317	102.94	2.06	3.24	132.3137176	
20	Source 2	Sink 1 + Sink 2	1.000	0.000	0.242	Shell and tube	16,317	102.94	2.06	3.24	132.3137176	
15	Source 2	Sink 2	0.992	0.008	0.905	Printed circuit	30,246	22.89	0.05	6.05	131.2289196	
11	Source 2	Sink 1	1.000	0.000	0.330	Printed circuit	37,608	28.75	0.06	7.46	132.3137176	
19	Source 2	Sink 1 + Sink 2	1.000	0.000	0.242	Printed circuit	37,608	28.75	0.06	7.46	132.3137176	
1	Source 1	Sink 1	0.589	0.411	1.000	Air cooled	N/A	N/A	N/A	N/A	N/A	
5	Source 1	Sink 1 + Sink 2	0.801	0.199	1.000	Air cooled	N/A	N/A	N/A	N/A	N/A	
9	Source 2	Sink 1	1.000	0.000	0.330	Air cooled	N/A	N/A	N/A	N/A	N/A	
13	Source 2	Sink 2	0.992	0.008	0.905	Air cooled	N/A	N/A	N/A	N/A	N/A	
17	Source 2	Sink 1 + Sink 2	1.000	0.000	0.242	Air cooled	N/A	N/A	N/A	N/A	N/A	
21	Source 1 + Source 2	Sink 1 + Sink 2	0.671	0.329	1.000	Air cooled	N/A	N/A	N/A	N/A	N/A	

Figure 10. 12 Summary of waste heat recovery computation results

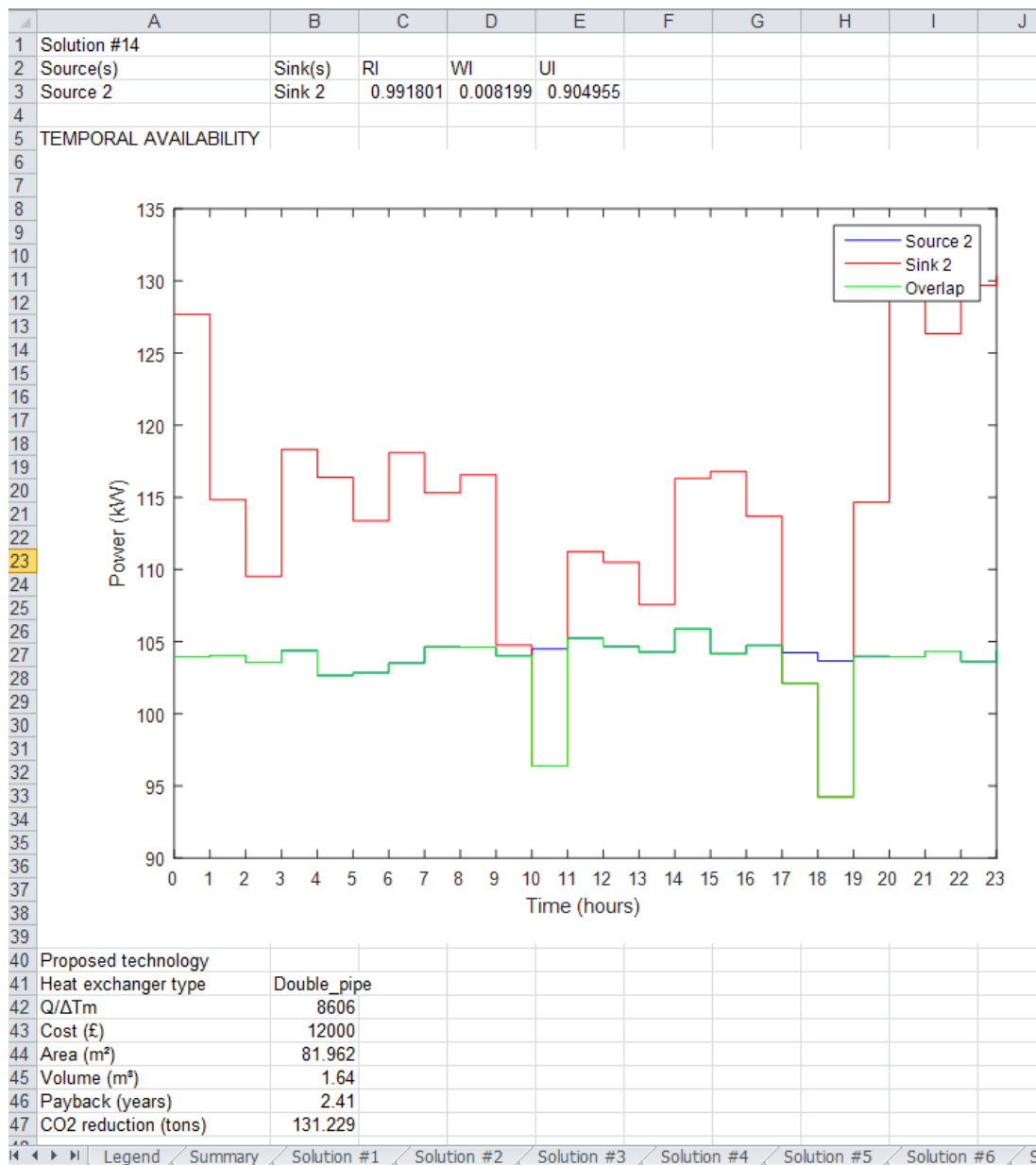


Figure 10. 13 Detailed report page for each solution

Section 10.1 introduces the design objectives and three scenarios where using this software tool can be beneficial. The three scenarios are recovery of waste heat energy within an existing manufacturing plant, implementing waste heat recovery within a reconfigurable manufacturing system and process design of a manufacturing system with waste heat recovery consideration. However, for the purpose of this research, the software tool is designed primarily to help recovery of waste heat energy within an existing manufacturing plant. Section 10.2 outlines the scope and information flow path of the software tool, explaining the practical limitations of technology choices to allow more focused decision support and detailing how information flows within the software tool. Beginning with user data input, the information is stored, analysed through series of computations, and results

generated and reported to the user. Section 10.3 details the specifics of the user data entry module of the software tool, where users are required to define a time window and resolution to analyse and number of waste heat sources and sinks in order to generate a controlled input template. This feature allows the user to input data more easily and without error, it also helps the main software engine to recognise input and carry out analysis. The user-friendly input interface is solely operated in Microsoft Excel, thus enabling the software tool to be run on majority of work stations. Section 10.4 provides a detailed working procedure for two core subroutines, one of which is the waste heat source and sink selector and another is heat recovery technology selector. The purpose of the waste heat source and sink selector is to allow initial selection of the most suitable uses for the recovered heat energy and the objective of the technology selector is to identify the most suitable heat exchanger type that is capable of transferring heat energy from waste heat source to a preferred sink with minimal cost. Having completed data analysis and computation, section 10.5 details the results generation and report preparation part of the software tool. For easy-to-access purposes, the report is generated in Excel format including a software guide page for those users without in-depth knowledge of the framework presented in this thesis, a summary page of all waste heat source and sink combinations and their respective analysis results including RI, WI, UI, approximate cost, payback period and carbon dioxide reduction, etc. Detailed information regarding individual solutions can also be accessed via a number of tabs.

Although the development of the software tool is complete and has been demonstrated through example data, validation of the software with industrial case studies is essential to prove the true applicability of the framework. Chapter 11 delivers two industrial case studies, one with relative low temperature waste heat and another at high temperature. Detailed software tool implementation and results validation is discussed in the next chapter.

Chapter 11 Case Studies

11.1 Introduction

Verifying the Waste Heat Recovery Framework (WHRF) and Waste Heat Recovery Software (WHRS) tool is necessary in order to assess the validity of the system in terms of making a positive contribution to decision making in industrial waste heat recovery (WHR) through a methodical approach. To fulfil the requirement set out in the scope of the system, the validation is completed via two industrial case studies. The case studies chosen cover two distinctive manufacturing industries with regard temperature bands:

- Case Study 1, a compressed air system at a PCB manufacturing plant (Section 11.2), is an example of a low temperature band process;
- Case Study 2, a cupola at an engine casting plant (Section 11.3), is an example of high temperature band process

The data provided for both case studies are based on original data from the respective industrial companies as well as published literature which has been used where desired information was unavailable.

11.2 Case Study 1

This case study is carried out to investigate the implementation of the decision support software for a printed circuit board (PCB) manufacturing plant in Jiangxi Province, China. The company specialises in producing high precision and high density multi-layer circuit boards, high-tech electronics products are widely used in telecommunications, computer, instrumentation, automotive, home appliances and CNC machine tools and are exported to Hong Kong, Singapore, Japan, Europe and other regions. The company's clients include Canon, Siemens, HP, Nokia, etc. One of the most energy intensive processes in the plant was identified as the air compressors, and these form the basis of the investigation in the first case study.

11.2.1 Waste Heat Survey

Having provided detailed instruction in alignment with the methodology for implementing waste heat survey as specified in section 8.3, the PCB manufacturer was able to identify waste heat hotspots and carry out empirical measurements to obtain data in preparation for

the implementation of the decision support tool. A summary of the activities involved in the survey are shown below.

1. Infrared thermography

The complexity of the manufacturing environment makes infrared camera a useful tool to pinpoint where waste heat hotspots are. Hence the factory's environmental manager implemented the technique within a large area of floor space for a period of one week covering all aspects of production schedule. Thermo-graphical images had revealed several waste heat sources in that floor space, amongst which one specific heat source had a strong and continuous temperature signal over the period of image acquisition.

2. Identifying capacity and temporal information of heat source

Further investigation by the manufacturer identified that the source of waste heat came from factory's compressed air system equipped with five Atlas Copco™ compressors (see Table 11.1) which supply equivalent to 7 bars pressure of compressed air throughout the factory to support various manufacturing operations. The system employs a smart control which switches start/stop of additional units and loading rate depending on the required air supply and pressure. On average three compressors are maintained operational throughout the year while maximum of four units are used when production requires, resulting in load rate of 70%. An energy audit revealed that the compressed air system consumes 7,020,000 kWh of electricity annually to provide about 65,000,000m³ of compressed air with system specific compression of 6.6 kW/ m³ min⁻¹. During the operation of an air compressor, 85% of the input electrical energy is converted into heat energy with less than 15% of the input actually becomes potential energy embedded in the compressed air (Atlas Copco Compressors, 2009). The heat energy generated as waste heat source is then carried away by a cooling medium (usually water or air) and ultimately wasted. There are 200 workers divided into three shifts to cover the entire working day with each shift using three compressors and one used as back-up.

3. Identifying capacity and temporal information of heat sink

The plant is currently using a boiler to supply hot water to the staff accommodation zone. For the purpose of this case study, pre-heating of water entering the boiler is considered as the only available waste heat sink. It was also provided by the manufacturer that the air compressors are simply cooled using water and the heat energy absorbed is then cooled using a cooling tower, which indicates that the heat energy is not in any way recovered by the plant. It is the manufacturer's interest to recover waste heat energy from their

compressors to be fed into their plant boiler system (to support showering facilities and plant heating). It is also specified that all compressed air units are located in a same room which is close to the boiler room.

4. Temperature data acquisition and flow rates measurements

In order to assess the quantity and quality of waste heat source and sink, inlet and outlet of hot medium and ambient temperature, as well as inlet and outlet of cold medium temperature need to be acquired using invasive techniques, such as thermometers, resistor temperature detectors and thermistors. Flow rates are measured using a range of flowmeters and flow sensors according to the types of media involved. As identified by the manufacturer that the hot and cold media are air and water respectively, correct type of flowmeters were installed and measurements taken.

Table 11. 1 Compressed air units installed in plant

Brand	Atlas Copco	Atlas Copco
Series	ZR500VSD-8.6	ZR315-51E
Volumetric Air supply /m ³ .min ⁻¹	80	50
Operational pressure /Pa	690000	720000
Voltage /V	400	400
Current /A	920	590
Power / kW	525	315
Quantity	1	4

The schematic of the compressor's working operation is shown in Figure 11.1. One main heat source is identified and is denoted by a dotted box.

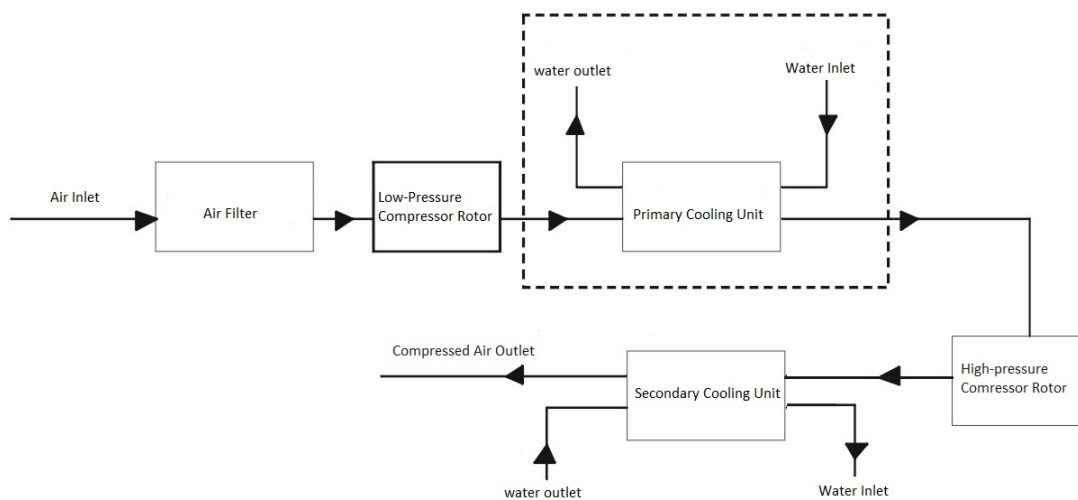


Figure 11. 1 Atlas Copco ZR500VSD-8.6 compressor working schematic

The outside air, via a filter, is supplied into the low-pressure compressor rotor to compresses the air: the air temperature rises sharply to 240°C and pressure increases to 7 bars. The initially compressed air enters the primary cooling unit where air temperature is lowered to 54°C before it enters the high-pressure compressor to further compress the air to even higher pressure and temperature. Finally, the compressed air is cooled again at the cooling unit to obtain the required low temperature high pressure compressed air.

11.2.2 Waste Heat Source and Sink Selection

The objective of this case study requires a complete understanding of the quantity of waste heat which recoverable from the air compression system and also the demand from the sink which is the boiler feed water. In order to provide decision support for specific technology to be used, the values must also be balanced and matched for optimal solution.

For this case study, the WHRS has been inputted with the data of an ordinary production day, for a full 24 hour period. It is specified during a waste heat survey that the manufacturer identified one major waste heat source and a possible heat demand to be met within the factory. Figure 11.2 presents the initialisation of the software tool by defining the time window, data resolution and number of source and sink.

Since one main heat source and potential sink are identified, an input page is tabulated with corresponding entries from the initialisation page as shown in Table 11.2.



Figure 11. 2 initialisation by defining time window, resolution and number of source and sink

Table 11. 2 Waste heat source and sink template generation

Source1					Sink1				
Time	Stream medium		Air		Time	Stream medium		Water	
	Th in	Th out	T_amb	Flow rate		Tc in	Tc out	T_amb	Flow rate
00:00					00:00				
01:00					01:00				
02:00					02:00				
⋮									
21:00					21:00				
22:00					22:00				
23:00					23:00				

The heat contained in the source medium can be calculated:

$$Q_1 = m_{w.boiler} \cdot C_w \cdot (T_{out} - T_{in}) \quad \text{[Equation 11.1]}$$

Where:

Q_1 – Heat energy demanded for boiler feed water pre-heating every second, kJ

$m_{w.boiler}$ – the average amount of boiler feed water, data captured from boiler operational record; $m_{w.boiler} = 2.36 \text{ kg/s}$;

C_w – specific heat capacity of water, taken as $C_w = 4.18 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$;

T_{out} – designed water outlet temperature from compressed air system, taken as $T_{out} = 70^\circ\text{C}$;

T_{in} – heat sink temperature or boiler feed water temperature, taken as the environment temperature, $T_{in} = 20^\circ\text{C}$.

The cooling of compressed air is a complex system that in order to estimate the waste heat energy involved, a simplified method is used, assuming a certain amount of air is being compressed instantly without heat energy leakage during its process. Equation 11.2 indicates the relation between inlet and outlet air temperature:

$$T_2 = T_1(P_2/P_1)^{(K-1)/K} \quad \text{[Equation 11.2]}$$

Where:

T_2 – air temperature after compression, K;

T_1 – air temperature before compression, K;

P_2 – air pressure after compression, Pa;

P_1 – air pressure before compression, assumed at atmospheric pressure of 98000 Pa;

K – adiabatic index or heat capacity ratio, is the ratio of the heat capacity at constant pressure, C_p to heat capacity at constant volume, C_v , for air $K = 1.4$.

After the compression, the cooling down phase of compressed air releases heat energy which can be calculated using the heat energy equation:

$$Q_{air} = C_p \times \rho \times V(t_2 - t_0) \quad \text{[Equation 11.3]}$$

Where:

Q_{air} – Heat energy released from cooling down of highly compressed air, kJ;

C_p – Specific heat capacity of air, $C_p = 1.005$ kJ/ (kg.°C);

ρ – Inlet air density, kg/m³;

V – Volume of inlet air, m³;

t_2 – Air temperature before cooling down, $t_2 = T_2 - 273$, °C;

t_0 – Air temperature after cooling down, usually taken as ambient temperature, assumed at 20 °C;

It is assumed that there is a busy production schedule in the plant and four of the five compressed air units are used to provide sufficient air to support production process (see Table 11.3). Using the specified flow rate and inlet/outlet temperature of the waste heat source and sink, the template (Table 11.2) is completed and shown in Table 11.4.

Table 11. 3 Compressed air units used during a production campaign

Brand	Atlas Copco	Atlas Copco
Series	ZR500VSD-8.6	ZR315-51E
Quantity	1	3
$T_{1,\#1}$ / K	293	293
P_1 /K	98000	98000
K_{air}	1.4	1.4
T_2 /K	511.7	518.0
C_p / kJ.kg ⁻¹ .°C ⁻¹	1.005	1.005
ρ / kg.m ⁻³	1.204	1.204
t_2 / °C	238.7	245
t_0 / °C	20	20
$P_{waste\ heat}$ / kW	352.1	680.65

Table 11. 4 completed input template for waste heat source and sink

Source1					Sink1					
Time	Stream medium		Air		Time	Stream medium		Water		
	Th in	Th out	T amb	Flow rate		Tc in	Tc out	T amb	Flow rate	
00:00	185.2	54.8	20.8	3.83	00:00	21.4	70.6	20.8	0.002376	
01:00	184.7	54.6	20.6	3.83	01:00	25	70.2	20.6	0.002376	
02:00	184.2	54.9	20.2	3.83	02:00	24.9	68.6	20.2	0.002376	
03:00	184.5	54.7	20.1	3.83	03:00	23.6	69.6	20.1	0.002376	
04:00	184.1	55.1	20.5	3.83	04:00	23.7	69.5	20.5	0.002376	
05:00	184.3	54.8	20.9	3.83	05:00	24.4	69.6	20.9	0.002376	
06:00	184.4	54.8	20.5	3.83	06:00	24.1	70.2	20.5	0.002376	
07:00	184.6	54.3	20.5	3.83	07:00	23.9	69.4	20.5	0.002376	
08:00	184.2	54.4	20.1	3.83	08:00	21.5	67.6	20.1	0.002376	
09:00	184.6	54.8	20.3	3.83	09:00	23.8	66.7	20.3	0.002376	
10:00	184.6	54.7	20.1	3.83	10:00	24.9	65.4	20.1	0.002376	
11:00	184.7	54.1	20.4	3.83	11:00	22.2	67.1	20.4	0.002376	
12:00	184.5	54.3	20.4	3.83	12:00	22.3	67	20.4	0.002376	
13:00	184.3	54.4	20.4	3.83	13:00	25.2	68.5	20.4	0.002376	
14:00	184.8	53.8	20.4	3.83	14:00	24.6	70.1	20.4	0.002376	
15:00	184.3	54.7	20.1	3.83	15:00	24.2	69.7	20.1	0.002376	
16:00	184.6	54.4	20.3	3.83	16:00	25.1	69.8	20.3	0.002376	
17:00	184.8	54.4	20.8	3.83	17:00	22.3	65.3	20.8	0.002376	
18:00	184.8	54.8	20.7	3.83	18:00	24.8	65.2	20.7	0.002376	
19:00	185.1	54.8	20.7	3.83	19:00	24.7	70	20.7	0.002376	
20:00	185.2	54.8	20.8	3.83	20:00	23	72.3	20.8	0.002376	
21:00	185.2	54.9	20.4	3.83	21:00	25.2	72.9	20.4	0.002376	
22:00	184.8	54.9	20.6	3.83	22:00	23.1	72.2	20.6	0.002376	
23:00	184.8	54.8	20.2	3.83	23:00	23.4	72.3	20.2	0.002376	

The template is then processed with the MATLAB based engine using the method discussed in Chapter 10 with the results for the recovery indexes displayed in Figure 11.3.

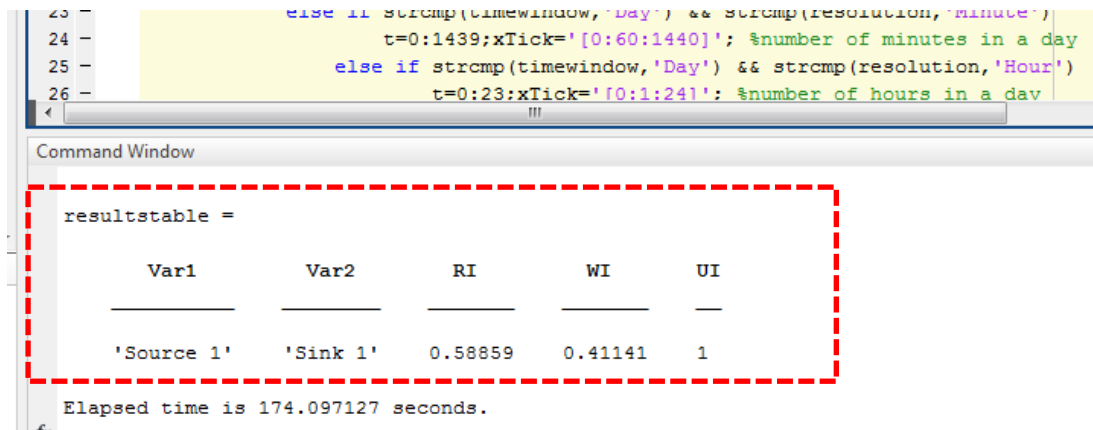


Figure 11. 3 MATLAB engine in operation for waste heat recovery solution

It can be seen from Figure 11.3 that the system had presented one combination possible with a RI ratio of 0.589 and UI ratio of 1. Limited by the quantity, quality and availability of waste heat energy between source and sink, 58.9% of the waste heat from source can be recovered and supplied to where needed. However, the entire heat requirement is satisfied.

11.2.3 Waste Heat Recovery Technology

Using the WHRS, the heat exchanger types are first reviewed and suitable alternatives selected. For this case, the appropriate types are the double-pipe, shell-and-tube, printed

circuit (Table 11.5). The exergy amount is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the manufacturer. The options are examined for feasibility and then costed approximately using the C-value method.

Table 11. 5 Initial technology selection

Solution #	Source(s)	Sink(s)	RI	WI	UI	Technology
2	Source 1	Sink 1	0.588591	0.411409	1	Double_pipe
4	Source 1	Sink 1	0.588591	0.411409	1	Shell_and_tube
3	Source 1	Sink 1	0.588591	0.411409	1	Printed_circuit
1	Source 1	Sink 1	0.588591	0.411409	1	Air_cooled

An exemplified computation using the method specified in section 10.4 is as follows:

$$Q = mC_p\Delta T = 609kW$$

Using the F_T method, to calculate the LMTD value:

$$\Delta T_m = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\log_e \frac{(T_{h,in} - T_{c,out})}{(T_{h,out} - T_{c,in})}} = 51.42K$$

From the above calculation, the ratio of $Q/\Delta T_m$ can be evaluated:

$$\frac{Q}{\Delta T_m} = \frac{6.09 \times 10^5}{51.42} = 11843.6 W/K$$

The following results are obtained from the ESDU database:

It is noted that the costing data given in the ESDU database is documented in 1992, therefore considering an inflation rate of 91.78% since this period (Browning, 2015), the estimated current cost of heat exchanger technologies listed are presented in Table 11.6.

11.2.4 Results and Decision Support

Having completed the MATLAB computation, a report is generated in MS Excel format as shown in Figure 11.5. The report consists of time series graph to show source and sink comparison of different heat exchange technologies in terms of cost, size, etc.

In this case study, PCB manufacturing process is used as an example to demonstrate the implementation of the decision support modelling for waste heat recovery. The time window considered is one day and the time resolution is one hour. The exergy amount is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the survey. As per exergy analysis results summarised in Figure 11.5, temporal

availability calculation was carried out leading to a RI=0.589. The temporal availability chart reported in Figure 11.5 displays power of waste heat source over 24 hours as a green line whereas waste heat sink is displayed in pink. The overlap function is represented by the blue dashed line and in this case shows that the particular waste heat sink is entirely satisfied by the amount of waste heat provided from the source.

Using the C method, four types of compatible heat exchangers for this case study were identified: double-pipe, shell-and-tube and printed circuit however air-cooled heat exchangers were excluded on the grounds of incompatible conditions.

Table 11. 6 Comparison of various heat exchangers cooling low pressure gas with treated cooling water

Heat exchanger type	C_1 & C_2 values (£/(W/K))		Overall C value	Costs (£)
	$Q/\Delta T_m = 5000$ W/K	$Q/\Delta T_m = 30000$ W/K	£/(W/K)	$Q/\Delta T_m \times C$
Double-pipe	1.4	1.4	1.4	31822
Shell-and-tube	1.56	0.71	1.50	34177
Printed-circuit	3.6	1.59	3.46	78760

Figure 11.5 demonstrates the computed results for relevant parameters for the selected heat exchanger. To enable a comparison of the three selected heat exchanger types, a cost-benefit analysis was carried out, including the computation of the heat exchangers areas and volumes, the cost, the payback period and the potential CO₂ savings. Finally, a summary of the qualitative descriptors involved in this case study indicates that there were no particular constraints in terms of spatial availability and contamination risks.

The next step for the plant's environmental manager is to use the results generated for further analysis. For example, based on the provisional payback period both the double-pipe and shell-and-tube heat exchangers can deliver similar results, however cost of maintenance, auxiliary equipment, pipework installation may differ. In addition, detailed heat exchanger design such as shell and tube diameter, number of tubes, and flow arrangement etc., also require specialised expertise for design support and fabrication, but these services are often provided by heat exchanger manufacturers.

Summary of results											
Solution #	Source(s)	Sink(s)	RI	WI	UI	Technology	Cost (£)	Area (m ²)	Volume (m ³)	Payback	CO ₂ reduction (tons)
2	Source 1	Sink 1	0.588591	0.411409		1 Double_pipe	31822.06	112.875	2.26	2 years 1 months	400.9109454
4	Source 1	Sink 1	0.588591	0.411409		1 Shell_and_tube	34177.11	112.875	2.26	2 years 3 months	400.9109454
3	Source 1	Sink 1	0.588591	0.411409		1 Printed_circuit	78760.21	31.521	0.06	5 years 2 months	400.9109454
1	Source 1	Sink 1	0.588591	0.411409		1 Air_cooled				NaN years NaN months	400.9109454

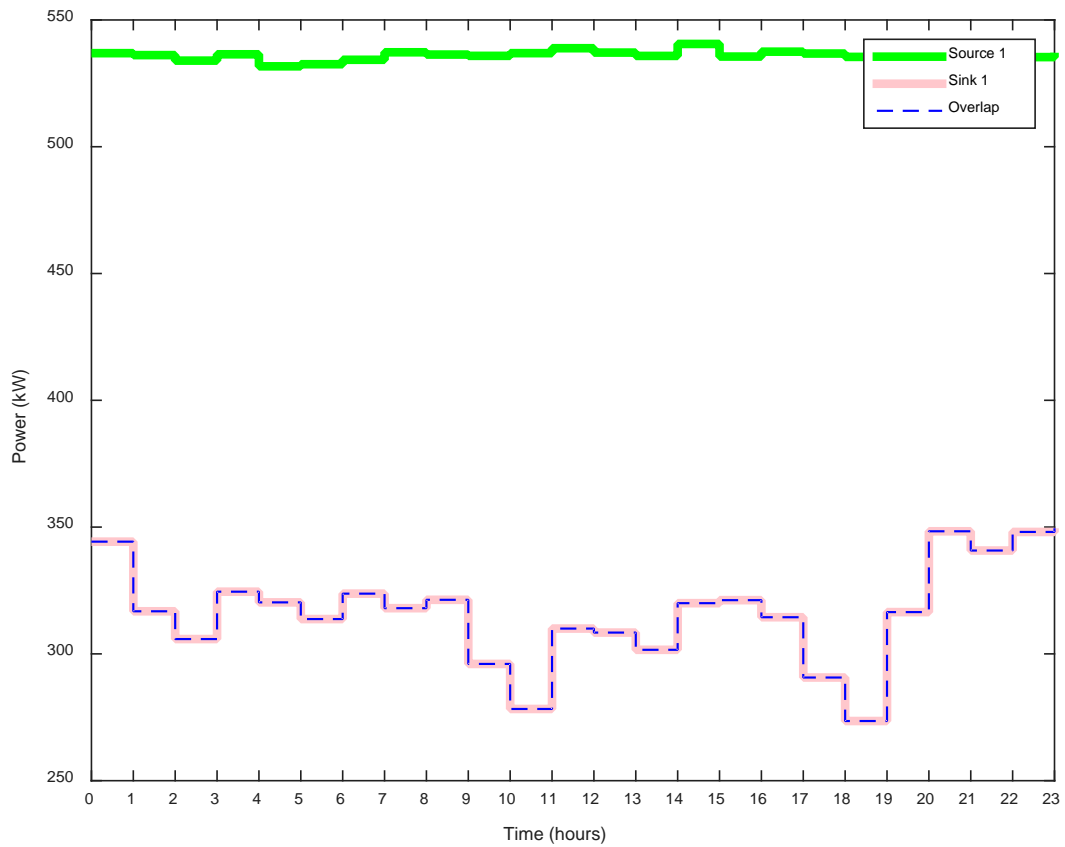


Figure 11. 4 Report summary page for case study 1

This case study serves as a demonstration of the applicability of the waste decision support tool. Although the problem involved in the case study appears disarmingly straight forward with only one source and one sink identified, the solutions are however difficult to obtain without the comparison of temporal availability of exergy between source and sink of waste heat energy. The determination of the quality match between source and sink, and the computational technology selection for the optimised energy recovery relies on the implementation of the WHRS.

11.3 Case Study 2

The second case study offers a different perspective in comparison to the previous but is again performed using the waste heat energy recovery framework. The primary objective of this case study is to investigate the application of decision support software tool for a casting operations plant that produces automobile components. The casting operations produce a variety of high quality cylinder blocks, cylinder heads and crankshafts for V6 and V8 engines that power a wide range of vehicles. Using data supplied by the production plant, a simplified case study is set up to exemplify the use of the WHRS tool. The purpose of the case study is not to investigate every waste heat source and give technology selection but to selectively choose the most energy intensive processes with largest impact and financial benefit. The software tool is applied so as to provide an understanding of plant's energy research and performance improvement potentials.

Actual data has been used where available but where information is lacking, assumptions have been applied and estimations have been used based published data referring to similar processes or activities. As such, the absolute values given by the case study are by no means an actual representation of the energy consumption but an estimate based on the information available.

Through the use of the software tool, a number of waste heat sources and sinks can be considered for waste heat energy recovery. In addition, the flexibility offered by computation techniques enables a wide range of variation representing process routes, batch sizes, production lead times, queuing times, etc. to be incorporated within the software tool.

The production of engine blocks was selected as the focus of the study due to the relatively straight forward manufacturing process plan. The engine block is made by precision sand casting which consists of moulding a series of sand components and then assembling them into a single "core package". The core package then has molten aluminium poured into it. Upon cooling, the surrounding sand package is removed to reveal the solidified engine block. The block is then trimmed and cleaned prior to final delivery to the engine machining and assembly plant. It is assumed that 60 engine blocks are produced per hour.

A simple process plan of the manufacture of the engine block is shown in Figure 11.6 and specific casting process shown in Figure 11.7.

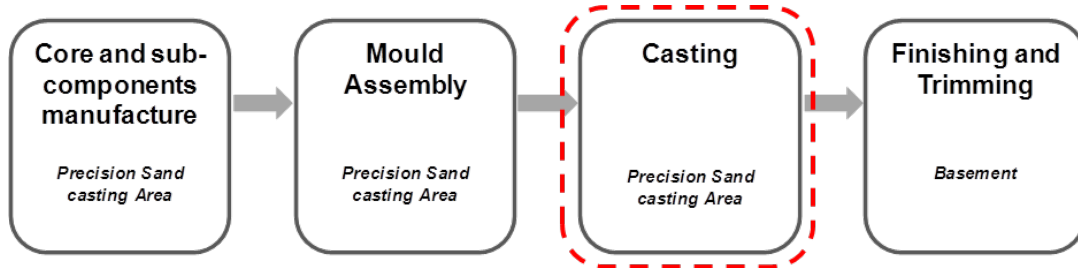


Figure 11. 5 Overview of simplified process plan for engine block production

It is provided by the plant's production manager that as the plant overfeeds coke the furnace efficiency drops and as they lower the coke feed then more melt loss occurs. Melt loss occurs when the metal being fed is oxidised as a fuel instead of coke. It also occurs when the metal reacts with the atmosphere in the furnace to form metal oxides. The furnace does a very good job of melting the iron and is not effective in adding heat to the molten metal. Conversely the electric holding furnaces after the main furnace are very poor at melting and excellent at adding heat to raise the molten metal temperature. In the furnace the process achieves a metal temperature of about 1500°C and then raises it to above 1550°C in the holding furnaces to offset heat loss prior to discharging the metal into a mould.

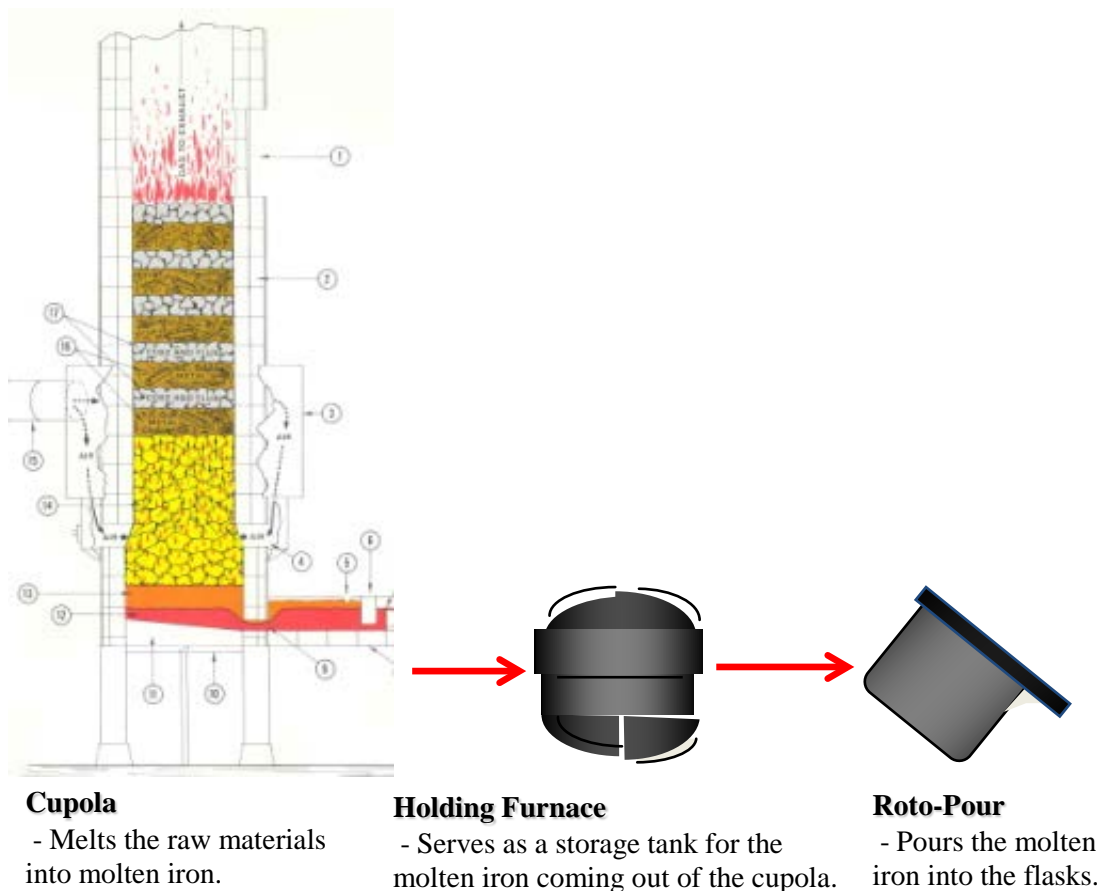


Figure 11. 6 An example schematic of casting process of engine block

11.3.1 Waste Heat Survey

Having understood the generic function of the process, it is requested that an industrial site visit should be carried out as part of the waste heat survey to help identifying waste heat sources and sinks in the plant. As part of the survey, process monitoring and data collection was carried out onsite in preparation for the implementation of the decision support tool. A summary of the activities involved in the survey and measurements taken are listed below:

1. Infrared thermography

By closely examining the casting process, it is possible to identify a number of heat losses which include:

- Heat losses from the exhaust discharge.
- Heat transported out of the equipment by the load conveyors.
- Radiation losses from openings, hot exposed parts, etc.
- Heat carried out by the excess air used in the burner.

Waste heat losses from the exhaust are considered the highest priority due to the high temperature gas discharge. The temperature of discharged exhaust varies from as low as 13°C to as high as 578°C. Combustion products themselves, generated from well-designed and well-operated modern burners using gaseous and light liquid fuels, are relatively clean and do not contain particles or condensable components that may require filtering before discharging into the atmosphere. However in this particular case, the furnace uses coal as its fuel as well as a reaction reagent, the combustion products may react with materials used in the construction of downstream waste heat recovery equipment and potentially create problems if treated carelessly. Potential issues include chemical reaction of exhaust gases and their solid or vapour content with the materials used in the waste heat recovery equipment; deposit of particulates in or on surfaces of WHR equipment. Many of these problems are compounded by the high temperature of the exhaust gases and uneven flow patterns of the hot gases inside the heat exchanger.

There are a number of common characteristics of exhaust gas discharged from a furnace, amongst which some contribute to the contaminant of the waste heat sources, including:

- i. **High temperature:** although the process temperature might be around 1500°C, according to the temperature sensors installed on the stack, the highest temperature of the exhaust during the recording period is 577.8°C. The barriers/challenges to waste heat recovery for this temperature range include

reduced thermodynamic potential for the most efficient heat recovery due to materials limitations that require gases to be diluted.

- ii. **Presence of corrosive agents, such as salts, calcium, chlorides and fluorides:** the amounts of these agents or their compounds depend on the heating process and the final product specifications. These agents can introduce corrosive elements that may promote degradation of materials in WHR equipment. For example, chemical reactions may happen between the corrosive exhaust gases and metal tube surfaces in a heat exchanger device which could result in an extremely short life for the heat exchanger. Challenges to waste heat recovery include availability or cost of materials that are designed to resist the corrosive effects of contaminants, requirement of cleaning systems that allow removal of deposits of material on heat transfer surfaces.
- iii. **Presence of particulates such as metal oxides, carbon or soot particles:** fine particles entrained in exhaust gases may react with the heat exchanger materials, resulting in reduction of heat transfer and damaging heat exchanger materials. The overall consequence of these reactions is a substantial reduction in lifespan for heat exchanger parts and, often, premature failure of metals at critical locations.
- iv. **Presence of combustibles such as carbon monoxide, hydrocarbons:** the presence of combustibles in exhaust gases could result in higher temperatures than designed for heat exchanger due to air leaks or the addition of cooling air to exhaust gases. The combustibles may also react with heat exchanger part surfaces to form soot that deposits on heat transfer surfaces and reacts with metal leading to shortened lifespan of equipment components.
- v. **Variations in flow, temperature and composition of gases:** this can result in cycling of materials and thermal fatigue of metals used in the heat recovery equipment. Thermal fatigue reduces the lifespan of materials.

11.3.2 Waste Heat Source and Sink Selection

This case study requires a comprehensive study of the quantity of waste heat source, i.e. recoverable heat energy from furnace exhaust gases discharged to the atmosphere and also the demands from potential sinks, such as combustion air pre-heating and heat supply to the holding tank. For this case study, the exhaust gas temperature has been provided over a typical one week of operation. The production campaign is weekly and begins late on to initiate the warm-up operation of the furnaces such that they are ready for production early

Monday morning. Eight 10 hour shifts (two per 24 hours) are conducted with the production campaign ending on Thursday for cleaning and maintenance.

In the current study, it is identified that there is one waste heat source and two possible heat demands (sinks) to be paired that may increase overall energy efficiency within the plant. Figure 11.8 presents the initialisation of the software tool by defining time window, resolution and the number of sources and sinks.

As the time window is selected as weekly and resolution is in minute, an input page is tabulated with corresponding entries from the initialisation page with 10080 lines of entry (see Table 11.7). This makes the data transfer simpler since users only have to copy and paste data from sensor's data logger.

Using Equation 11.1, Q_i is defined as the heat energy available from exhaust gas discharge per second; m and C_p are the mass flow rate and specific heat capacity of the exhaust gas discharge respectively. T_{out} represents the target temperature to be cooled post heat recovery and T_{in} characterise the inlet temperature of the exhaust gas discharged from furnace. Since there is not a specific pre-defined C_p value available for the exhaust gas mixture, an additional calculation is performed to evaluate its value based on the gas composition.



Figure 11. 7 Initialisation by defining time window, resolution and number of source and sink

Table 11. 7 waste heat source and sink template from decision support tool

Time	Source1				Sink1				Sink2			
	Stream medium		Exhaust gas		Stream medium		Air		Stream medium		Air	
	Th in	Th out	T amb	Flow rate	Tc in	Tc out	T amb	Flow rate	Tc in	Tc out	T amb	Flow rate
00:00												
00:01												
00:02												
00:03												
00:04												
00:05												
00:06												
00:07												
00:08												
nn:nn												

Although the flowrate of the exhaust gases is not given, calculation is carried out to approximate a reasonable value with reference to the flue-gas stack effect analysis. The flue-gas stack effect is that movement or flow of combustion air and flue gas is called the stack effect. The taller the stack, the more draft is created. The equation below provides an approximation of the flue-gas flow-rate induced by the draft. The equation assumes that the molar mass of the flue gas and the outside air are equal and that the frictional resistance and heat losses are negligible.

$$V = CA \sqrt{2gH \frac{T_i - T_o}{T_i}} \quad \text{[Equation 11.4]}$$

Where:

V = flue-gas flow-rate, m^3/s

A = cross-sectional area of stack, m^2

C = discharge coefficient (taken as 0.7)

g = gravitational acceleration at sea level, 9.807 m/s^2

H = height of stack, m

T_i = absolute average temperature of the flue gas in the stack, K

T_o = absolute outside air temperature, K

Using the Equation 11.4 above, the flow-rate of the exhaust gas is calculated:

$$V = CA \sqrt{2gH \frac{T_i - T_o}{T_i}} = 18.048 \text{ m}^3/\text{s}$$

Table 11. 8 completed input template for waste heat source and sink

Source1				Sink1				Sink2			
Stream medium		Exhaust gas		Stream medium		Air		Stream medium		Air	
Th in	Th out	T_amb	Flow rate	Tc in	Tc out	T_amb	Flow rate	Tc in	Tc out	T_amb	Flow rate
27.24065	27.24065	27.24065	18.0485	27.24065	27.24065	27.24065	13.24	27.24065	27.24065	27.24065	6.75
27.22222	27.22222	27.22222	18.0485	27.22222	27.22222	27.22222	13.24	27.22222	27.22222	27.22222	6.75
27.20152	27.20152	27.20152	18.0485	27.20152	27.20152	27.20152	13.24	27.20152	27.20152	27.20152	6.75
27.18076	27.18076	27.18076	18.0485	27.18076	27.18076	27.18076	13.24	27.18076	27.18076	27.18076	6.75
27.15993	27.15993	27.15993	18.0485	27.15993	27.15993	27.15993	13.24	27.15993	27.15993	27.15993	6.75
27.13904	27.13904	27.13904	18.0485	27.13904	27.13904	27.13904	13.24	27.13904	27.13904	27.13904	6.75
27.11807	27.11807	27.11807	18.0485	27.11807	27.11807	27.11807	13.24	27.11807	27.11807	27.11807	6.75
27.09703	27.09703	27.09703	18.0485	27.09703	27.09703	27.09703	13.24	27.09703	27.09703	27.09703	6.75
538.4698	171.7349	21.92785	18.0485	21.92785	291.9503	21.92785	13.24	21.92785	200.2503	21.92785	6.75
538.46	171.73	21.93942	18.0485	21.93942	291.9405	21.93942	13.24	21.93942	200.2405	21.93942	6.75
538.4503	171.7251	21.95156	18.0485	21.95156	291.9308	21.95156	13.24	21.95156	200.2308	21.95156	6.75
538.4405	171.7203	21.96424	18.0485	21.96424	291.9211	21.96424	13.24	21.96424	200.2211	21.96424	6.75
538.4308	171.7154	21.97742	18.0485	21.97742	291.9113	21.97742	13.24	21.97742	200.2113	21.97742	6.75
538.4211	171.7105	21.99109	18.0485	21.99109	291.9016	21.99109	13.24	21.99109	200.2016	21.99109	6.75
538.4113	171.7057	22.00521	18.0485	22.00521	291.8918	22.00521	13.24	22.00521	200.1918	22.00521	6.75
538.4016	171.7008	22.01975	18.0485	22.01975	291.8821	22.01975	13.24	22.01975	200.1821	22.01975	6.75
538.3918	171.6959	22.03469	18.0485	22.03469	291.8723	22.03469	13.24	22.03469	200.1723	22.03469	6.75
538.3821	171.691	22.05	18.0485	22.05	291.8626	22.05	13.24	22.05	200.1626	22.05	6.75
538.3723	171.6862	22.06566	18.0485	22.06566	291.8528	22.06566	13.24	22.06566	200.1528	22.06566	6.75
538.3626	171.6813	22.08162	18.0485	22.08162	291.8431	22.08162	13.24	22.08162	200.1431	22.08162	6.75
538.3528	171.6764	22.09786	18.0485	22.09786	291.8333	22.09786	13.24	22.09786	200.1333	22.09786	6.75
538.3431	171.6715	22.11436	18.0485	22.11436	292.3519	22.11436	13.24	22.11436	200.6519	22.11436	6.75
538.3333	171.6667	22.13108	18.0485	22.13108	292.8704	22.13108	13.24	22.13108	201.1704	22.13108	6.75
538.8519	171.9259	22.148	18.0485	22.148	293.3889	22.148	13.24	22.148	201.6889	22.148	6.75
539.3704	172.1852	22.16508	18.0485	22.16508	293.9074	22.16508	13.24	22.16508	202.2074	22.16508	6.75
539.8889	172.4444	22.18231	18.0485	22.18231	294.4259	22.18231	13.24	22.18231	202.7259	22.18231	6.75
540.4074	172.7037	22.19965	18.0485	22.19965	294.9444	22.19965	13.24	22.19965	203.2444	22.19965	6.75

Using the approximated flowrate and inlet/outlet temperature of the waste heat source and sink, the template is completed and presented in Table 11.8.

The filled template is then processed with the MATLAB engine (Figure 11.9) using the method discussed in section 10.4. As can be seen from the figure that there are three different combinations, each provides a unique solution as to how waste heat source and sink is arranged and option 2 is immediately discarded on the ground of low recoverability (RI=0.139) compared to options 1 and 3. Source 1 and sink 1 is the simplest heat recovery solution yet yields a reasonable recovery index (RI=0.472) whereas source 1 and combined sinks 1 and 2 provides higher recovery index (RI=0.611) but requires additional equipment capacity to achieve the desired recoverability. Despite the variation in recovery index, the utilisation index for all of the combinations is similar (0.999) which is indicative that the demand for heat energy and availability of waste heat energy is well aligned quantitatively, qualitatively and temporally.

```

17 - else if strcmp(timewindow,'Hour') && strcmp(resolution,'Minute')
18 -     t=0:59; xTick='[0:1:60]'; %number of minutes in an hour
19 - else if strcmp(timewindow,'Hour') && strcmp(resolution,'Hour')
20 -     t=0; xTick='[0:1:1]'; %number of hour in an hour
21 - else if strcmp(timewindow,'Day') && strcmp(resolution,'Second')
22 -     t=0:86399; xTick='[0:3600:86400]'; %number of seconds in a day
23 - else if strcmp(timewindow,'Day') && strcmp(resolution,'Minute')
24 -     t=0:1439; xTick='[0:60:1440]'; %number of minutes in a day
25 - else if strcmp(timewindow,'Day') && strcmp(resolution,'Hour')
26 -     t=0:23; xTick='[0:1:24]'; %number of hours in a day

```

Command Window

```

resultstable =

```

Var1	Var2	RI	WI	UI
'Source 1'	'Sink 1'	0.4718	0.5282	0.99963
'Source 1'	'Sink 2'	0.13921	0.86079	0.99958
'Source 1'	'Sink 1 + Sink 2'	0.61101	0.38899	0.99962

Figure 11. 8 MATLAB engine in operation for waste heat recovery solution

11.3.3 Waste Heat Recovery Technology

The heat exchanger types are first reviewed and suitable alternatives selected. For this case, there are three possible waste heat source and sink combinations, i.e. source #1 with sink #1, source #1 with sink #2, and source #1 with sink #1 plus sink #2, as shown in Figure 11.11. The exergy amount is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the manufacturer. The options are examined for effectiveness for recovering waste heat (Table 11.9) and then cost evaluated using the C-value method (Table 11.10).

It should be noted that due consideration is required in the costing of the technological solutions for the reasons described in section 11.2.2.

Table 11. 9 Waste heat source/sink combination and corresponding technology choice.

Solution #	Source(s)	Sink(s)	RI	WI	UI	Technology
9	Source 1	Sink 1 + Sink 2	0.611011	0.388	0.999	Shell_and_tube
6	Source 1	Sink 1 + Sink 2	0.611011	0.388	0.999	Air_cooled
4	Source 1	Sink 1	0.471801	0.528	0.999	Shell_and_tube
1	Source 1	Sink 1	0.471801	0.528	0.999	Air_cooled
8	Source 1	Sink 1 + Sink 2	0.611011	0.388	0.999	Printed_circuit
7	Source 1	Sink 1 + Sink 2	0.611011	0.388	0.999	Double_pipe
3	Source 1	Sink 1	0.471801	0.528	0.999	Printed_circuit
2	Source 1	Sink 1	0.471801	0.528	0.999	Double_pipe
10	Source 1	Sink 1 + Sink 2	0.611011	0.388	0.999	Welded_plate
5	Source 1	Sink 1	0.471801	0.528	0.999	Welded_plate

Table 11. 10 Comparison of various heat exchangers cooling exhaust gas with medium pressure air

Heat exchanger type	C_1 & C_2 values (£/(W/K))		Overall value	Costs (£)
	$Q/\Delta T_m = 30000$ W/K	$Q/\Delta T_m = 100000$ W/K		
Shell-and-tube	0.62	0.35	0.54	217020
Double-pipe	0.35	0.35	0.35	341770
Printed-circuit	0.87	0.74	0.75	787600
Air-cooled	1.12	1.12	1.12	450120

11.3.4 Results and Decision Support

In this case study, a more complex problem has been used to demonstrate the implementation of the decision support modelling for waste heat recovery. A casting process is considered over the period of one week, the time resolution is one minute and the production down time is also include to represent a true production campaign in the plant. Exergy is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the survey. As per exergy analysis results summarised in Figure. 11.10, temporal availability calculation was carried out leading to a RI=0.61. The temporal availability chart reported displays power of waste heat source over week-long of production campaign as a green line whereas waste heat sink is displayed in pink. The overlap function is represented by the narrow blue dashed line.

Using the C method, four types of compatible heat exchangers for this case study were identified: double-pipe, shell-and-tube, printed circuit respectively however air-cooled was excluded on the ground of incompatible conditions. Figure 11.10 shows the computed results for relevant parameters for the selected heat exchanger. To enable a comparison of the three selected heat exchanger types, a cost-benefit analysis was carried out, including the computation of the heat exchangers areas and volumes, the cost, the payback period and the potential CO₂ savings, as shown in the figure. Finally, a summary of the qualitative descriptors involved in this case study indicates that the primary concern is corrosive substances and particulates contained in the exhaust.

Summary of results											
Solution #	Source(s)	Sink(s)	RI	WI	UI	Technology	Cost (£)	Area (m ²)	Volume (m ³)	Payback	CO ₂ reduction
9	Source 1	Sink 1 + Sink 2	0.611011	0.388989	0.999615728	Shell_and_tube	379937	1772.75	35.87	2 years 1 months	
6	Source 1	Sink 1 + Sink 2	0.611011	0.388989	0.999615728	Air_cooled	459773	907.13	1.81	2 years 7 months	
4	Source 1	Sink 1	0.471801	0.528199	0.999625224	Shell_and_tube	515802	2651.35	53.02	3 years 8 months	
1	Source 1	Sink 1	0.471801	0.528199	0.999625224	Air_cooled	624102	1231.771	2.46	4 years 6 months	
8	Source 1	Sink 1 + Sink 2	0.611011	0.388989	0.999615728	Printed_circuit	838734	1053.737	2.11	4 years 8 months	
7	Source 1	Sink 1 + Sink 2	0.611011	0.388989	0.999615728	Double_pipe	864280	1793.53	35.87	4 years 9 months	
3	Source 1	Sink 1	0.471801	0.528199	0.999625224	Printed_circuit	1138030	1430.845	2.86	8 years 2 months	
2	Source 1	Sink 1	0.471801	0.528199	0.999625224	Double_pipe	1173586	2651.043	53.02	8 years 5 months	
10	Source 1	Sink 1 + Sink 2	0.611011	0.388989	0.999615728	Welded_plate	1536499	3209.846	6.42	8 years 6 months	
5	Source 1	Sink 1	0.471801	0.528199	0.999625224	Welded_plate	2086375	4358.574	8.72	14 years 12 months	

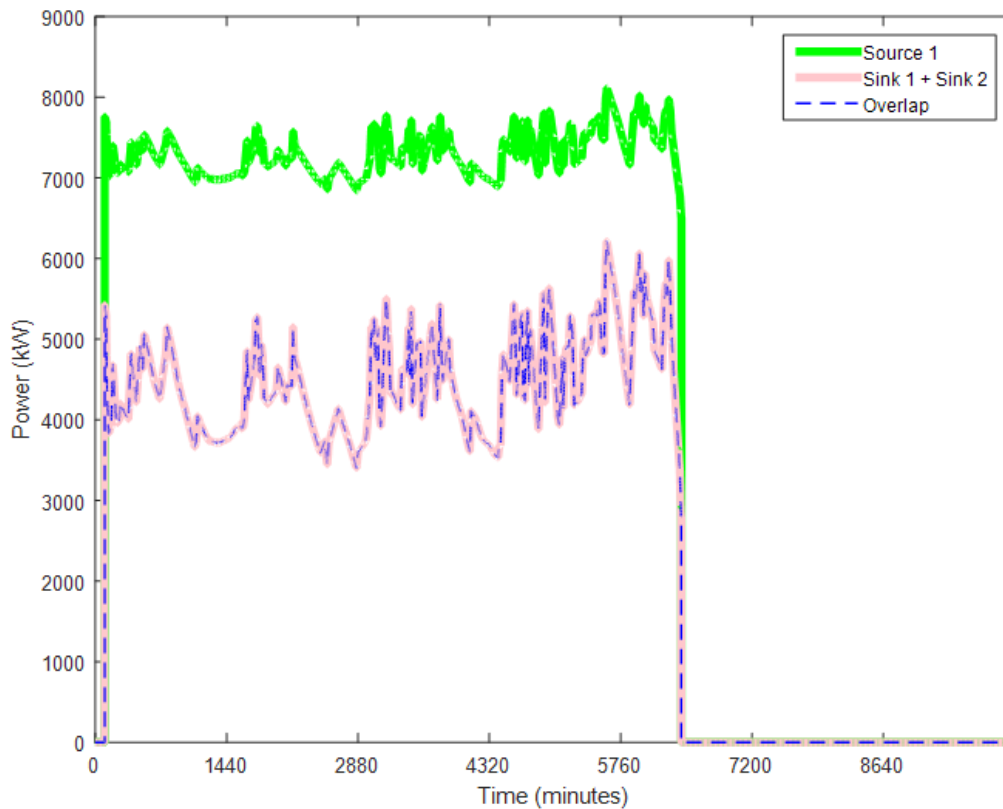


Figure 11. 9 Report summary page for case study 2

11.4 Chapter Summary

Energy minimisation within a facility is not limited to technological process improvements or changes in operation performance, but can also be achieved by taking a more holistic view of energy flows. In particular, by coupling sources of waste heat energy with suitable sinks, can lead to substantial energy savings, with short payback period for any new infrastructure required. For successful implementation of this approach within the manufacturing environment it is essential to consider the exergy balance of the potential sources and sinks alongside the temporal availability of energy. In this work a conceptual and computational methodology for decision support on waste heat recovery was developed and applied to an industrial case study. The main conclusions that can be drawn from this case study are:

- The decision support system is able to compare temporal availability of exergy between sources and sinks of waste heat energy
- A range of recovery indexes can be obtained to determine the quality of the match between multiple sources and sinks
- Such an analysis can be used in a computational technology selection for optimised energy recovery and minimised financial payback of implementation
- The user-facing system is straight-forward enough to be utilised by competent facility or energy management teams.

Beyond the scope of the current research, there are three scenarios where using this decision support tool could be utilised to improve overall plant energy efficiency:

- Recovery of waste heat energy within an existing manufacturing plant;
- Implementing waste heat recovery within a reconfigurable manufacturing system;
- Process design stage of a manufacturing system with waste heat recovery consideration.

Chapter 12 Concluding Discussions

12.1 Introduction

This chapter begins with a summary of the principal research contributions proposed in the thesis. These are followed by subsequent sections that discuss the results achieved, and the main research activities undertaken in this body of work. The original research scope and the thesis structure are used to evaluate the research achievements.

12.2 Research Contributions

The research in this thesis has investigated the recovery of waste heat energy within manufacturing. The principal contributions from the research can be summarised as follows:

- i. The research has established the current barrier in waste heat energy recovery and identified a potential for improving energy efficiency within manufacturing by understanding the availability of waste heat energy which arises during the production process and the feasibility for its recovery. The research has also learnt that energy minimisation within a manufacturing facility is not limited to technological process improvements or changes in operational performance, but can also be achieved by taking a more holistic view of energy flows. In particular, coupling sources of waste heat energy with suitable sinks can lead to substantial energy savings, with short payback periods for any new infrastructure required. For successful implementation of this approach within the manufacturing environment, it is essential to consider the exergy balance of the potential sources and sinks alongside the temporal availability of energy.
- ii. Generation of a comprehensive waste heat energy recovery framework to provide a systematic approach to identify and evaluate waste heat streams. The framework consists of four steps in which quantitative and qualitative descriptors have been assigned to define a process for identification and matching of waste heat sources and potential sinks within a manufacturing facility.
- iii. The research has defined a new approach to recovering waste heat energy generated by a manufacturing process (waste heat source) and utilising recovered heat energy to support another process (waste heat sink) within the facility through the use of exergy and temporal availability analysis. The approach maximises energy recovery by comparing multiple waste heat sources and sinks and providing a

combination with the most energy recovery potential in terms of quantity, quality and temporal availability. This provides a greater understanding of the amount of waste heat energy available in a facility (how much and how often it is available), and the best use for the waste heat energy thus answering the research question “How do we identify the quantity, quality and availability of waste heat from a manufacturing process, and determine the maximum potential and selection of the most appropriate technology for recovery of this energy?”.

- iv. Design of a novel decision support software tool to carry out complex analyses of waste heat sources and sinks and of potential heat recovery technology. Incorporated with the waste heat recovery framework, the system is capable of assessing waste heat sources and sinks quantitatively and qualitatively, identifying appropriate source-sink combinations and recommending the most suitable technology based upon energy recovered and utilised, cost-benefit, and CO₂ savings.
- v. Implementation of the decision support tool on two industrial case studies has shown how technology decisions can influence energy efficiency improvements through the definition of a novel ‘waste heat energy recovery’ framework. The tool has provided support in maximising waste heat recovery and utilisation over a number of production processes in the case studies by systematically assessing the quantity, quality and temporal availability between source and sink of waste heat energy and applying a computational technology selection for optimised energy recovery and maximised financial payback of implementation.

12.3 Concluding Discussion

The following sections discuss the outcomes of the research under each of the headings defined within the original research objectives and scope.

12.3.1 Review of the current status of energy management, waste heat energy recovery research and technology

To establish the context for the research, a comprehensive review was conducted on a wide range of issues ranging from energy management strategies to energy related research and their implications for the manufacturing industry. Three areas of literature were identified as being of particular relevance to the research: the review of energy management within manufacturing is reported in Chapter 3 of the thesis, a review of state-of-the-art waste energy recovery technology is reported in Chapter 4 and a review of current waste energy recovery research is reported in Chapter 5.

The review of energy management within manufacturing has highlighted that energy considerations can be defined at various manufacturing levels from very detailed turrett scale energy requirements to broad enterprise scale activities. Clearly there is a substantial amount of work carried out across these different manufacturing levels to improve energy efficiency. However energy recovery should not be applied at one particular manufacturing level only. Hence the manufacturing levels defined to address energy consumption issues become less useful. Waste energy is potentially recoverable from plant level activities, from individual processes and from actual products as they leave their respective processes (3P perspective). With these categorisations it is then possible to identify potential sinks for where the recovered energy can be reutilised. Waste energy is typically suitable to be used at the same manufacturing level or cascade to a higher level with the exception of the product level, in which it is generally not feasible to reuse the energy outside of the context of a process. As such the literature review has identified a gap in the existing approaches for energy efficiency improvement, just like the proactive and reactive approaches that are adopted for materials recycling, there was also an opportunity for energy to be considered via the reactive approach to explore energy recovery, options including tools and technologies that are capable of harnessing waste energy and reutilising this within a manufacturing environment.

The review of current waste energy recovery research activities has shown there is an interest in improving energy efficiency through methods and tools for energy minimisation management. The literature review covered a broad spectrum of waste energy recovery research, including recovery from waste heat energy, an energy recovery system for an electric motor drive system and harvesting energy from vibrations. The review especially emphasised waste energy recovery from heat, the primary components of energy demand as industrial heating or heat related treatment accounts for about 72% of industrial energy use. In recovery from other sources of waste such as vibration, sound and light is difficult to achieve desired efficiency and therefore less likely to be cost effective, waste heat energy is of significant value and more likely to recover and benefit manufacturers. There are numerous waste heat recovery technologies on the market, however because of the lack of knowledge and informed decision making; industrial waste heat is often not recovered in a systematic and therefore optimised way. Based on the literature review carried out and a number of industrial visits performed , the initial research assertion was then redefined, narrowing down the scope of waste energy to investigate how quantity, quality and

availability of waste heat energy from a manufacturing process is identified and the most appropriate technology for recover is determined.

12.3.2 Development of a framework for waste heat energy recovery

In the initial part of the research, it became apparent that there was a wide range of waste energy recovery consideration within manufacturing industry including various techniques and tools that need to be identified. From the literature review, it was noted that detailed procedure to waste heat energy and potential heat energy demand evaluation within manufacturing facilities is often lacking and research recognises that there may be occasions where choosing a cost effective heat recovery equipment maybe difficult. Therefore, a simple but holistic waste heat energy recovery (WHER) framework has been developed. The WHER framework consists of four steps that aim to define a process for the identification and matching of waste heat sources and potential sinks within a manufacturing facility.

The firstly step of the WHER framework aimed at the identification of sources and sinks of waste heat within a manufacturing environment from both the plant and process perspectives, is carried out using either invasive techniques i.e. thermometers, Resistor Temperature Detectors (RTDs) and thermistors, as well as non-invasive devices (infrared thermography). Flow rates are measured using a range of flowmeters and flow sensors can be used according to the types of media involved i.e. liquid, gas. The output from this survey often highlights a limited number of opportunities to recover large quantities of waste heat within a facility using a number of specific parameters such as range and number of heat sources and sinks; temporal information in terms of time window and time resolution; inlet and outlet and ambient temperature and the flow rate for the sources and sinks. The data generated by this survey is used by the subsequent steps in WHER for the quantitative and qualitative assessment of waste heat and selection of appropriate technologies to recover this energy.

For the second step of the framework, in order to quantitatively and qualitatively evaluate waste heat energy in a manufacturing environment, parameters such as temperature, exergy, temporal availability for sources and sinks selection, carrying medium of waste heat sources and sinks, spatial availability, and risk of contamination are utilised. Based on the information obtained from the comparison between waste heat sources and potential uses, the framework also allows for identification of appropriate methods and technologies to harness waste heat provided by the knowledge of technology database from extensive literature survey and waste heat energy survey.

In the third step of the framework, a pre-selection phase is carried out using media, pressure, and temperature range to exclude non compatible heat exchanger types listed in the ESDU database. This is followed by a consideration of cost, volume and area based on the C value method. This enables a direct comparison between heat exchangers in terms of the heat duty carried out and the available temperature driving force, which are related to the process specification. This also provides a structured approach, identifying advantages and disadvantages of each method and technology, and visually compares many different solutions to give decision support guidance for complex problems. The results from this step are carried forward into the decision support stage of the framework, which utilises environmental and other economic analysis methods to compare between the selected options to provide the final recommendation.

The last step of the framework provides final recommendations for manufacturers to identify an appropriate heat exchanger technology to recover waste heat energy. A computational model is developed to utilise the data generated in the previous steps together with a cost and benefit analysis to assess the list of feasible technologies.

In addition, the interpretation of obtained information and calculation is also required to process data and make informed decisions for industries to quickly react. Thus a software tool is implemented to aid the framework in an accessible way.

12.3.3 Design of a decision support tool for waste heat energy recovery

It may appear that undertaking data analysis and decision making manually is sufficient for simple problems with small amount of data, i.e. time window of one day and time resolution of one hour for demonstration purposes. However in a real manufacturing facility, manufacturers such as energy managers and production engineers may be faced with large quantity of data captured for many more complex processes and conditions, for example production time window of one week and resolution of one minute, which can results in a yield of 10080 sets of temperature, flow rate data for the waste heat sources alone, besides they are equally large amount of data except more for the waste heat sinks. Therefore it became apparent that manual process of data is inadequate. In order to analyse the obtained information and generate useful decision support for the energy managers and production engineers, a user-friendly, fully automated decision support software tool is developed to implement the WHER framework.

The tool is able to control the flow of data such as initial stage of user input, analysis and computation, data search within the system, data storage, transfer, visualisation to the final data output. More specifically, the decision support tool is not only able to compare temporal availability of exergy between sources and sinks of waste heat energy, to obtain a range of recovery indexes to determine the quality of the match between multiple sources and sinks, to undertake computational technology selection for optimised energy recovery and maximised financial payback of implementation; but also able to be used by expert or non-expert users thanks to its straight-forward user-interface and control system.

It is an interactive software-based system intended to help users compile useful information from a combination of raw data to identify and solve problems and to provide decision support. In addition, the implementation of the waste heat energy recovery framework within a complex manufacturing environment also needs software tool support in order to deal with the large amount of data required for a range of waste heat sources and sink that need to be computed. With the improved level of automation higher performance is achieved by faster problem-solving: users are able to upload captured data into the waste heat source and sink template generated according to time period and resolution and choose stream medium identified, a complicated problem can be rectified within minutes; by generating new insights: the software tool is able to incorporate visualisation techniques into decision making, not only to rank technology solutions in terms of cost, but also present top solutions in a radar chart based on a number of parameters including cost, payback period, CO₂ reduction, heat transfer area and size of the unit. However the software tool is currently running with a combination of programming languages. Visual basic for applications (VBA) within MS Excel is used for generation of waste heat sources and sinks template and MATLAB is used to undertake exergy and temporal availability analysis to generate source and sink combinations, to execute C-value method to selection appropriate technology for each combination, and finally present result in tabular and graphical format back into Excel. The drawback of this setup is that it may be inconvenient having to use two software platforms to complete the task. In order to address the issue, future improvement to the software tool plans to consider the integration of the VBA and MATLAB codes and export into a standalone decision support tool for waste heat recovery. Another consideration for improving applicability of the decision support software tool lies upon the scope of technology database. Limited by the computational algorithm, C-value method is able to estimate the capital cost for heat exchanger technologies, whereas in real industrial waste heat recovery applications wider range of technology including heat lift (heat pump),

absorption refrigerators, or generation of electricity (ORC or heat engines) should also be included.

12.3.4 Demonstration and validation of framework and software tool

The decision support software tool has been validated to demonstrate that the system complies with the requirements and performs functions for which it is intended, meeting the initial needs and expectation of the user (plant's environmental manager). Two industrial case studies were carried out to demonstrate the framework for waste heat energy recovery, and the applicability of the decision support tool developed in the research. The primary objective of the case studies was to implement the framework for waste heat energy recovery, as defined in Chapter 8 of the thesis, in a systematic manner in order to support decision making regarding the selection of the most appropriate heat recovery technology. The case studies were specifically selected to demonstrate the applicability of the evaluation and selection methodology in a low temperature, simple process (case study 1) and a relatively high temperature, more complex manufacturing process (case study 2).

In the first case study, a compressed air system used in a PCB manufacturing process is used as an example to demonstrate the implementation of the decision support modelling for heat recovery. In this case study, the objective is to recover waste heat energy from five compressors to be fed into their plant boiler system in order to supply hot water and plant heating. The waste heat survey was conducted using two Temperature Data Loggers, inlet flow rate was measured using standard flow meter, and the outlet flow rate was calculated theoretically according to the hot water demand in the facility. The time window considered is one day and the time resolution is one hour. The exergy amount is calculated based on the inlet and outlet temperature and flowrate of the waste heat source and sink provided by the survey. As exergy analysis was undertaken, temporal availability calculation was carried out a chart generated to display the power of waste heat source and sink over 24 hours period as well as the overlap function. Using the selection criteria and the C value method, three types of compatible heat exchangers for this case study were identified: Double-pipe, Shell-and-tube, printed-circuit; and their computed values for relevant parameter are also shown. In order to enable a comparison of the three selected heat exchanger types, a cost-benefit analysis was carried out, including the computation of the heat exchanger areas and volumes, the cost, the payback period and the potential CO₂ savings.

The second case study was undertaken for a cupola of an engine block casting plant to demonstrate the applicability of the WHER framework and decision support software tool in

a high temperature waste heat, multiple heat sinks condition. In this case study, the objective is to recover waste heat energy from high temperature exhaust gas rejected from the cupola to be used as an additional source to pre-heat the inlet combustion air and to maintain temperature level in a holding furnace aside. Although temperature data is provided by the manufacturer, inlet and outlet flow rate was calculated theoretically according to the cupola's stack dimension. The time window considered is one week and the time resolution is one minute. The computation followed the same procedure undertaken in the first case study, except there were one source and two sinks, resulting in wider possibility of source and sink combination and technology choices to be considered. In addition, the comprehensive selection criteria and C value method and subsequent cost-benefit analysis provided by the software tool underlines the capability for large quantity of data to be handled and more complex case to be analysed within a manufacturing facility. Overall, the case studies have sufficiently demonstrated that the framework and software tool work with real industrial data

Furthermore, both case study shows the complexities associated with acquiring accurate exergy information required for the implementation of the software tool. This emphasises the importance of the following issues:

- i. The importance of implementation of advanced temperature and flow rate monitoring systems to collect actual data for waste heat source and sink,
- ii. The demand for integrating the software tool with other existing technology database for more up-to-date data analysis as the validation of the software tool highlighted some of the inherent problems in the system particularly that the data for heat exchanger costing was out-dated since the database published in 1992,
- iii. Finally, the requirements for careful design and customisation of such decision support tool tailored to the specific requirements of various potential users within a manufacturing application. There were three scenarios where using this software tool can be beneficial, ranging from the recovery of waste heat energy within an existing manufacturing plant, implementation of waste heat recovery within a reconfigurable manufacturing system and at the process design stage of a manufacturing system with waste heat recovery consideration. However case studies used to validate the applicability of the software tool were only able to test and prove it beneficial with first scenario. In order to gain different

perspectives of the software tool, a wider range of case studies should be used. Additional case studies may come from manufacturers with the need to reconfigure its production capacity and functionality in response to market and system change or process designers where waste heat energy recovery is considered as part of a holistic design process.

12.3.5 The vision for the future of waste heat energy recovery systems

Future work should focus on improving the system and addressing the drawbacks highlighted by testing. The main improvement required is to the method for obtaining capital cost estimates as the accuracy of cost factor methods employed maybe subjective, particularly considering that various sources were used for each of the technologies. In order to improve this, significant input will be required from current manufacturers of these technologies. However, this is a difficult task given the wide range of technologies featured in the system, but it would considerably improve the validity of the economic results of the system, which in turn would considerably improve the system overall.

Beyond the scope of the current research, there are two additional scenarios where this decision support tool could be utilised to improve overall plant energy efficiency:

- Implementing waste heat recovery within a reconfigurable factory;
- Improving process design within a manufacturing system with waste heat recovery consideration.

A reconfigurable manufacturing system is designed at the outset for rapid change in its structure and location, as well as its hardware components. The flexibility is required in order to quickly reconfigure its production capacity and functionality within a manufacturing plant in rapid response to market and system changes. Hence, for each configuration the quantity, quality and availability of waste heat energy may be different. In this setup, the waste heat energy recovery system needs to be applied periodically in order to track system performance and make informed decisions accordingly. In addition, the selection of heat recovery technology is also required to be more flexible and adaptable to reconfigurations.

Another scenario where the waste heat energy recovery system may be useful is at the design stage, where processes are to be planned and implemented in order to meet specifications. The system can be considered as part of holistic design process, through matching of potential waste heat sources and sinks, and designation of floor space to host heat recovery technology. However, potential unforeseen problems may arise at the process

design stage where data on inlet and outlet temperature, pressure drop, flowrate, contamination, and other associated parameters is not available and prediction or expert knowledge is required. These problems may be overcome by the dynamic nature of the software tool which allows for iterative use with defined parameters to obtain the most suitable waste heat recovery recommendation to serve as a guideline for process designers.

Chapter 13 Conclusions and Further Work

13.1 Introduction

This chapter identifies the major conclusions drawn from the author's research, and proposes possible avenues for further extension of this work.

13.2 Conclusions

The conclusions drawn from this research are as follows:

- i. The research has clearly highlighted the importance of improvement of energy efficiency within manufacturing environment due to commonly raised environmental impact associated with energy production and the rising cost of fuel. The research has also identified that for many applications, the most cost effective solution (with short payback times) for improvement in plant energy efficiency is the use of recovered energy.
- ii. The research has identified that thermal treatment processes require a large percentage of energy demand in the manufacturing industry. In order to address the inevitable thermal energy losses within these processes the research question "How do we identify the quantity, quality and availability of waste heat from a manufacturing process, and determine the maximum potential and selection of the most appropriate technology for recovery of this energy?" was formed.
- iii. The survey of current research on industrial energy management has shown that it can be defined at different manufacturing levels from the very detailed turret level, looking at energy management of physical processes, up to the more broad enterprise level, which focusses on, for example, supply chains, product networks, R&D, product distribution. There are also some studies that have been carried out from different perspective, such as the Embodied Product Energy Framework which have focused on decreasing energy per product by minimising non-productive energy. However, very little literature is found on regarding management of waste energy, which indicates a distinct lack of energy recovery approaches for industry.
- iv. The review of state-of-the-art energy recovery technology has shown a variety of methods and technologies for recovering waste energy and such range of technology include thermoelectric, heat exchangers, thermodynamic cycles, and heat pumps. The review has established that despite the variation in technology, the

aim is to collect and reuse or recycle waste energy arising from processes that would otherwise be lost. Recovered waste energy is typically suitable to be used at the same manufacturing level or cascade to a level above, with the exception of the product level, in which it is generally not feasible to reuse the energy outside of the context of a process.

- v. The review of current waste energy recovery research has identified that recovering and reutilisation waste heat energy could be one of the greatest efforts towards a sustainable future. The review has examined currently existing waste heat recovery research and established that numerous research activities have sought to improve energy efficiency through methods and tools for energy minimisation management, however limited research has been reported on assessing the appropriateness of a specific technology for a particular industrial application, although a number of researchers have identified suitability of technologies for waste energy recovery and methods for assessing their environmental benefits and payback time.
- vi. The consideration of current applications of waste energy recovery in this research has indicated that waste energy recovery is an area of broad aspects, including waste mechanical, light, sound, and chemical energy which are generally of insignificant value compared to waste heat. Waste heat energy is more likely to be recoverable and benefit manufacturers whilst other type of energy recovery may be difficult and less likely to be cost effective. Hence this research has introduced waste heat energy recovery, narrowing down the initial research scope to specifically target the capture and reuse of thermal energy. Further review of the topic identified the lack of knowledge in understanding the quantity and quality of waste heat energy, and thus existing waste heat energy is not necessarily recovered in a systematic and optimised way. The research has presented a methodical approach to investigate how quantity, quality and availability of waste heat energy are identified and the most appropriate technology for recovery is determined from a manufacturing plant and processes viewpoint.
- vii. The research has underlined the shortcomings associated with existing approaches to waste heat energy recovery, thus the requirement for a structured method to understand the amount of recoverable waste heat energy within respective processes and to provide decision support to choose the most suitable heat recovery technology. The waste heat energy recovery framework created as the core part of this research provides capabilities such as a systematic method for

collecting energy data through theoretical estimation and/or empirical measurement or through existing and relevant databases; assessment of waste heat quantity and quality and availability using a combination of exergy analysis and temporal availability method; use of heat exchanger selection methodology to generate a number of feasible heat exchanger options and finally; a dashboard style report is generated to evaluate the impact of decisions provided including annual CO₂ reduction, capital cost and payback period.

- viii. The research has found that, due to the complexity of the quantitative evaluation of waste heat and the considerations of available technologies, in order for the decision making process to be fully suitable for use by industrial members, there was clearly a need for a software tool. The waste heat energy recovery decision support tool produced fulfils this demand through a user-friendly interface (waste heat source and sink template generation and dashboard style report etc.), large capacity of technology database (technology parameters, surface area, estimated volume, cost factor etc.), intelligent data analysis and computation (exergy and temporal availability calculation, heat exchanger selection and costing procedure etc.) and finally recommended technology for the particular process investigated.
- ix. The case studies described in this thesis have effectively demonstrated the applicability of the research concepts. These case studies have also shown the requirements for a significant amount of technology data to be able to develop effective decision support for a wide range of potential users (process designers, manufacturers for reconfigurable plant, existing plant environmental managers etc.). This on one hand is indicative of the time and effort required to develop a customised decision support tool tailored to the specific requirements of a manufacturing facility, but on the other hand has clearly highlighted waste heat energy recovery potential that can be exploited through exergy and temporal availability analysis of waste heat availability and demand in a manufacturing facility, identification of suitable waste heat source and sink combinations and implementation of suitable technology accordingly.
- x. The fundamental conclusion drawn from this research is that investments in process energy efficiency alone are insufficient, in the short term, to deal with the rapid rise in energy demand, thus waste heat energy recovery with a systematic approach within manufacturing industry is of high importance for a sustainable energy strategy.

13.3 Future work

The author recognises the following areas of work as the most valuable extensions of the current research.

13.3.1 Further Improvement of the Waste Heat Survey

This research has developed a systematic approach to address the issues of how much heat energy goes to waste in terms of quantity and quality, whether waste heat energy can be efficiently recovered with the provision of cold side heat sinks, association of waste heat availability and demand and what technologies are suitable to use. This approach can help to ensure decision support is provided to expert or non-expert users.

In addition, there are still a wider range of improvements to be considered such as the requirement of a systematic approach for carrying out the initial waste heat survey. The survey should be carried out as an integral part of the energy audit of the plant, consisting of a systematic study of the sources of waste heat in the plant and of the opportunities for its use. Empirical measurement remains as the most regarded method of obtaining accurate data, and adequate instrumentation should be installed for accurate metering and monitoring including either invasive (temperature sensors, flow meters etc.) and non-invasive (infrared thermography). The acquired data should also be stored and used for conducting cost-benefit analysis at later stage.

13.3.2 Further Development of the Framework and Decision Support Tool

The issue addressed in this research with regard to waste heat energy recovery are not unique to manufacturing industry only. It is believed that the framework for waste heat energy recovery provides a systematic approach for exploring and evaluating these issues, and could be applied to other industrial disciplines. In particular, other alternative applications, such as oil industry, energy production, food and drink processing, face similar challenges to waste heat losses as they aim to improve energy efficiency of their processes. As well as the general framework for waste heat energy recovery, it is believed that the decision support software tool could further be developed to support wider range of technology selection with broader industrial applications. In addition to the current capability, further improvement of functionality of the decision support software tool could be facilitated by interactive scenario planning (changes to parameter are fed back to the users in real time) and better graphical presentation (use of graphical charts for better visualisation).

13.3.3 Enhancement of the Technology Database

In this work, only the best available (according to constraints in the system scope) were considered for selection due to time constraints of the project. However, future iterations of the system should include other heat recovery technologies such as absorption heat pumps, thermal vapour recompression and specialist heat exchangers (scraped surface, for example), all of which can provide useful solutions in certain circumstances. The existing technology databases are still limited in the range and the detail of the technology information on operational criteria such as allowable pressure drop, resistance to corrosion, cost of maintenance, and impact on energy use. In addition, different technology types have specific criteria for selection, for example a shell-and-tube heat exchanger may require different heat recovery mechanism and input/output media compared to an Organic Rankine Cycle (ORC) engine. This makes the tabulation of the comprehensive technology database challenging where such data cannot be obtained from existing databases or literature. Therefore further research is needed to develop an understanding of the various equipment parameters (technology types and condition) and selection procedure through which a holistic and detailed database can be established. The provision of such a database would augment the existing understanding of potential method for recovery of waste heat energy and their suitable applications. The author appreciates that the establishment of such database are beyond the means and capabilities of any single organisation, thus highlighting the importance of collaborative efforts nationally and internationally.

13.3.4 The Development of an Accessible and Comprehensive Decision Support Tool

The decision support tool developed in this research was designed primarily to demonstrate applicability of the waste heat energy recovery framework. The development of an industrial based decision support tool requires substantial computation and software competency. The improvement on software implementation is required not only to simplify the use of this tool for a range of potential users within manufacturing applications, but to also data handling and integration via modules developed using programming language such as MATLAB. In order to achieve better accessibility and ease of use, the author has planned to develop a standalone software application without the need for MATLAB software to be installed, so that the tool can be used as a normal executional application that can run on any computer operating system, as well as smart electronic devices.

13.3.5 Consideration of Additional Case Studies to Optimise the Decision Support Tool

The research has not been able to conduct a wide range of case studies and some of the data used to produce decisions is result of scientific simulation and assumption. It is believed that in order for the software tool to be market ready, extensive testing should be using case studies across wider range of industrial facilities and processes. Despite the common use of heat exchanger technology in this research, other types of technology still remain an important position, the author believed that substantial effort could be made to test the software tool with other technology options, such as the Organic Rankine Cycle, heat pump etc. industrial collaboration is key to the success of software tool testing, it is thus suggested that early access of software tool could be made to organisations that interested in using the software tool for their heat energy recovery projects whilst testing is carried out.

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Appendices

Appendix 1

Journal Paper

Improving Energy Efficiency within Manufacturing by
Recovering Waste Heat Energy

Appendix 2

Journal Paper

A Decision Support System for Waste Heat Recovery in
Manufacturing

Appendix 3

Journal Paper

Infrared Monitoring of Aluminium Milling Processes for
Reduction of Environmental Impacts

Appendix 1

Journal Paper

Improving Energy Efficiency within Manufacturing by Recovering Waste Heat Energy

Introduction

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IMPROVING ENERGY EFFICIENCY WITHIN MANUFACTURING BY RECOVERING WASTE HEAT ENERGY

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ABSTRACT

In the UK, 25% of final energy consumption is attributed to the industrial sector (DECC, 2013) which also accounts for one third of the electricity consumption. However it is estimated that between 20 to 50 percent of industrial energy consumption is ultimately wasted as heat (Johnson et al., 2008). Unlike material waste that is clearly visible, waste heat can be difficult to identify and evaluate both in terms of quantity and quality. Hence by being able to understand the availability of waste heat, and the ability to recover it, there is an opportunity to reduce energy costs and associated environmental impacts. This research describes the design of a novel framework that aids manufacturers in making decisions regarding the most suitable solution to recover Waste Heat Energy (WHE) from their activities. The framework consists of four major sections: 1) survey of waste heat sources in a facility; 2) assessment of waste heat quantity and quality; 3) selection of appropriate technology; 4) decision making and recommendations. In order to support the implementation of the framework within the manufacturing industry, an associated software tool is discussed.

1. INTRODUCTION

In the 21st Century, fossil fuels remain a dominant component of the global energy grid. Therefore the depletion of

these natural resources and increased environmental damage still plagues governments, industry and the public. Coupled with the growing energy demand with emerging economies, such as China and India, it is projected that worldwide energy consumption is to increase by more than 40 percent by 2035 (Chevron, 2014). Taking all new technology developments and policies into account, the world is still failing to put the global energy system onto a more sustainable path, currently with over 80% of the global primary energy demand is met by fossil based fuels (figure 1) (IEA, 2014). The problem is confronted by increased population, development of 'comfortable countries' and industrial development based on economic drivers which relegates energy to a minor consideration. New policy development, the introduction of economic incentives, wide spread publication of environmental concerns has been ineffective on large scale.

For the manufacturing industry, a reduction in activity is not an ideal solution as manufacturing activities are typically driven by production and sale business models (Spring, 2013) and would thus impact profitability, the primary objective of businesses. A large number of research programmes have sought to improve energy efficiency, but have not been hugely successful at achieving radical reductions on overall consumption due to difficulties in implementing new technologies and operational procedures in companies,

especially where the renewal of equipment happens only over long timescales. In general, it is difficult to justify the time, expenditure and effort to implement energy efficiency improvements in light of the financial and energy gains achievable. The third option, recovery of waste energy, has not been studied extensively in research due to the perceived low return in energy saving in comparison to the required effort and expenditure to implement such solutions. Energy recovery as an energy efficiency approach is consequently under-developed and forms the focus of this research.

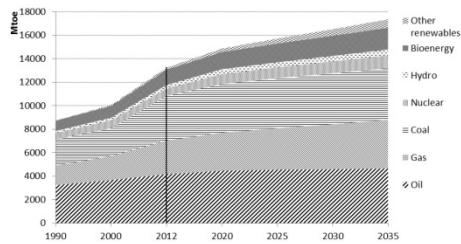


FIGURE 1 WORLD PRIMARY ENERGY DEMAND, SOURCE: IEA, 2014

The aim of this paper is to provide an overview of a novel framework which offers a systematic approach to evaluate the potential waste heat energy (WHE) available in a manufacturing plant and consequently determine the proportion of this WHE that is suitable for recovery. The originality of this research is that it is the first attempt to provide a systematic framework for understanding the WHE available within a manufacturing environment and that provides decision support in terms of identifying suitable energy recovery technologies for individual scenarios. The framework thus identifies suitable technologies and applications for the reutilisation of this WHE with the objective of improving overall energy efficiency. This paper begins with a review of literature to provide a background understanding of the current research in improving overall plant level energy efficiency and establishes the lack of structure in the understanding of WHE available within manufacturing businesses and suitable applications of this energy. The review is followed by a detailed description of the framework and uses a synthesised case study to demonstrate detailed functionality of it. The paper concludes with a discussion of the applicability of the framework for use in an industrial environment and a description of proposed future work.

2. LITERATURE REVIEW

Energy efficiency is a general term that does not define a particular set of actions or equipment and so can be misleading if used in isolation. To address this, and to provide some structure to research carried out in this field, a number of levels

within a manufacturing enterprise have been identified and defined (Vijayaraghavan & Dornfeld, 2010). In manufacturing, energy using activities generally fall under five levels ranging from the detailed turret scale energy requirements to the broad enterprise scale activities (figure 2), and are useful for describing different energy requirements across the various manufacturing activities.

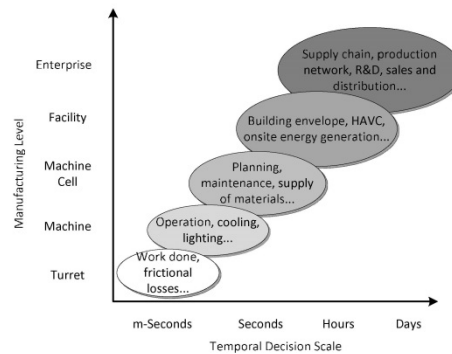


FIGURE 2 ENERGY CONSIDERATIONS AT THE VARIOUS MANUFACTURING LEVELS (ADAPTED FROM VIJAYARAGHAVAN & DORNFELD (2010))

Based on these five levels, there has been a significant amount of research carried out to improve energy efficiency of a wide range of manufacturing activities. At the enterprise level, Kara & Ibbotson (2011) identified that supplier location was a major factor that can increase overall energy requirements for the raw materials, thus by selecting local rather than international suppliers avoids use of energy intensive transport. At the facility level, investment of capital in energy-saving equipment such as insulation and waste-heat recovery could reduce overall energy demand with little or no effect on product quality (Despeisse, et al., 2012). At the machine cell level, most of the work involves process planning for improved energy performance. For example, Tan et al. (2006) combined manufacturing process planning and environmental impact assessments using check list analysis and suggested an optimal decision making algorithm for new components that involves energy consumption as part of the sustainable development evaluation. At the machine level of manufacturing, Dahmus and Gutowski (2004) reported that machine tools with increasing levels of automation have higher basic energy consumptions which result from the amount of additional integrated machine components. For example CNC machines carry a number of key components such as pumps, hydraulic systems, and numerical control systems which dominate the energy consumption of the process. Turret level of the manufacturing system represents the actual material transformation process and is typically studied based on theoretical analysis such as in the work of Sarwar et

al. (2009) who carried out a detailed analysis on the specific energy consumption of bandsawing different work piece materials, Rajemi et al. (2010) have looked at the minimal energy required for turning and the optimal conditions for machining a product and finally Kuzman (1990) have carried out an energy evaluation of the cold forming process.

Clearly there is a substantial amount of work carried out across these different manufacturing levels to improve energy efficiency. However energy recovery should not be applied at one particular manufacturing level only. WHE is potentially recoverable from facility level activities, from individual processes and from actual products as they leave their respective processes. Here the manufacturing levels described by Vijayaraghavan and Dornfeld (2010) and used by so many to address energy consumption issues, become less useful. Instead it is useful to adopt another set of terminologies defined by Rahimifard et al. (2010) called the 3P perspective which describes energy modelling techniques which use either the Plant, Process or Product as the central perspective. As well as energy modelling, these three perspectives can be used to define potential sources of WHE and are useful for identifying possible waste heat flows within a manufacturing facility (figure 3). WHE available from plant level activities might include flue gases from boiler systems, heat generated by air compressors, or heat from lighting, all of which can be either concentrated or disperse. WHE available from process level activities includes sources such as heat from pumps, cooling fluids and exhaust gases, conduction and convection from hot castings (e.g. furnace). Finally WHE from products will typically be in the form of heat emanating from hot bodies (e.g. cooling cast or kilned parts).

With these categorisations it is then possible to identify potential sinks for where the waste heat can be reutilised. As

shown in figure 3, WHE is typically suitable to be used at the same manufacturing level or cascade to a level above, with the exception of the product level, in which it is generally not feasible to reuse the energy outside of the context of a process.

Various published articles of energy recovery research in the categories of plant, process and product have been found which include development and application of new technologies. Khattak et al. (2014) undertook a case study into the use of waste heat from an engine machining line within an automotive factory to supplement the factory heating system whilst Bisio (1997) reported in their study of energy recovery potential of molten slag from a blast furnace, that a significant amount of energy can be recovered to produce either steam or heated air which can then be reutilised in the same blast furnace. In this way the recovered energy is supplied to match demand without having to be transported over long distances. Bell (2008) has presented work in the field of waste heat energy recovery with thermoelectric systems whose combination of thermal, electrical, and semiconducting properties allows them to be used either to convert waste heat into electricity or electrical power into cooling and heating.

Clearly there are a number of pieces of research which have developed technologies and applications for the recovery of waste heat within manufacturing and other environments, but these have been done as isolated pieces of work, without taking into account the manufacturing system within which the WHE is generated. In this respect, it is hypothesised that providing a structured framework within which one can measure, define and understand available WHE, and that can identify suitable applications for the use of recovered WHE in the context of available supporting technologies, could reveal additional financial and environmental benefit for manufacturers.

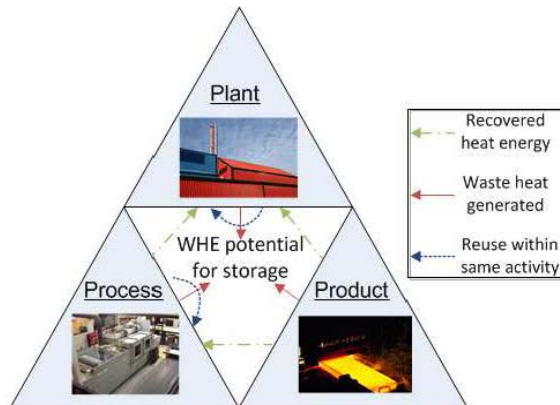


FIGURE 3 PLANT, PROCESS AND PRODUCT PERSPECTIVE FOR WHE RECOVERY

3. WASTE HEAT ENERGY RECOVERY FRAMEWORK

The literature survey of this research highlighted a lack of structure around the understanding of available WHE which limits the success of the application of heat recovery techniques. The framework presented in this paper has been developed to provide a systematic approach to evaluate and recover this heat energy and to identify optimised uses based on a range of suitable energy recovery technologies. The novelty of such framework is that it is an initial endeavour to enable manufacturers to methodically understand the amount of recoverable WHE within their manufacturing environment and to provide decision support to choose the most suitable energy recovery technologies for respective scenarios.

The structure of the framework is such that information gathered from a survey is processed and compared with a technology database to provide suitable options for WHE recovery. As shown in Figure 4, the framework consists of four main stages: collection of data; processing using predefined quantitative and qualitative defined terms; comparison of key parameters from a database of available technologies; and utilisation of a decision making algorithm to provide a number of options for waste heat recovery based on cost and environmental benefit analysis. The four waste heat recovery framework stages are:

- Stage 1: Survey of waste heat sources in facility
- Stage 2: Assessment of waste heat quantity and quality
- Stage 3: Selection of appropriate technology
- Stage 4: Decision making and recommendations

Although these stages define a generalised flow of information with which to follow to analyse the recovery potential of WHE from any industry, this research is concerned with overall energy efficiency within manufacturing facilities. The following sections hence describe in detail the four stages of the framework with respect to the information flow required to inform investment decisions within manufacturing business.

3.1 Stage 1: Survey of waste heat sources in facility

Undertaking a waste heat survey is the first stage in the WHE Recovery Framework. This stage provides a detailed description of how identification of waste heat sources within a manufacturing environment from the Plant, Process and Product perspectives is undertaken. In general, there are three approaches to which data collection for the survey of waste heat sources can be carried out by the energy or environmental manager of a particular facility. These approaches consist of empirical measurement, data acquisition from equipment manufacturers' specification or factory's existing database and theoretical calculation, and among which empirical measurement approach should always be prioritised. A facility-wide energy audit or useful data may already exist as part of an increased level of automation and monitoring by manufacturers. In the absence of a database or insufficient information, experimental measurement is recommended e.g. utilising a combination of thermocouple or infrared camera. In addition,

data acquisition can be achieved by referencing a database from supplier data sheets or published research studies of the process equipment. Theoretical calculation also provides a useful tool when database or empirical measurement is not suitable, provided that the assumptions made be as close to the real scenario as possible. However, due to the demand in time and effort, and errors the approach may potentially introduce, this is the least preferable approach to generate data. These methods can not only be used to identify the hotspots of WHE sources but also to evaluate and visualise the amount of WHE in a manufacturing facility. Data acquired from this step can be both numerical and descriptive which is then fed into the next stage of the framework for conversion and categorisation into standardised descriptors that can be interpreted by a decision making algorithm.

3.2 Stage 2: Assessment of waste heat quantity and quality

The applicability of this stage is that the acquired data can be used for assessment and analysis by the following stages of the framework in a structured way to quantify and qualify the WHE sources in a facility. Investigation of the waste heat generated within a plant is able to reveal some potential opportunities from generic and sector-specific manufacturing processes. This research defines a number of quantitative and qualitative descriptors to be assigned to each of these opportunities with the aim of assessing their recoverability in the context of the plant, process and product perspectives and using best suitable recovery techniques. In order to quantitatively evaluate the heat source in a manufacturing environment, a number of key parameters must be defined to provide essential data for carrying out calculations using mathematical modelling techniques. The quantitative descriptors established in this framework include temperature (or temperature difference between waste heat source and sink), useful energy content (or exergy) content and temporal availability of the WHE sources. Unlike quantitative evaluation (use of numbers), qualitative evaluation is a more subjective approach which uses very different methods of processing information, the parameters defined in the framework are carrying medium of WHE sources, accessibility and potential risk of contamination. Using a combination of qualitative and quantitative descriptors of the available WHE enables targeted evaluation and ensures more effective matching of potential heat recovery solutions with the available sources.

3.3 Stage 3: Selection of appropriate technology

The objective of this framework is to understand the potential recoverability of WHE and this will invariably involve the use of heat transfer mechanism (technology). The types of which will depend on the specific properties of waste heat source, such as the temperature or temperature difference between the source and sink, waste heat carrier form, contaminant of the exhaust stream, as well as the nature of the desired end-use for recovered heat.

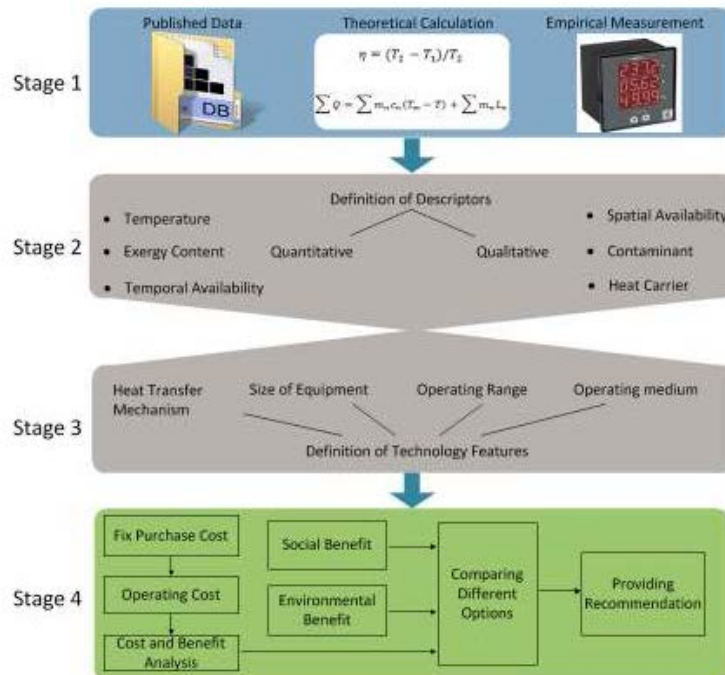


FIGURE 4 OVERVIEW OF THE WHE RECOVERY FRAMEWORK

It is essential to define the selection criteria for the available heat recovery technologies which consist of four fundamental properties. These selection criteria are heat transfer mechanism, medium of waste heat carrier, size of the equipment and operating temperature range. With the defined properties of WHE and heat recovery technology, matching and comparison can be carried out. The purpose is to use results from the waste heat quantity and quality assessment to filter down the range and number of technology options from the database created based on the existing heat recovery research and technology from a literature survey. This process yields a maximum of three feasible technology solutions which score similar in the comparison of criteria. The output results of this stage can be useful in the next stage of the framework, which carries out environmental, economic and social benefit analysis methods to further compare between the selected technology solutions to support decision making. Despite the variation in technology the objective is identical, which is the collection and reutilisation of recoverable WHE from any process that would otherwise be lost. The process might be inherent to a factory

building, such as space heating, air conditioning and ventilation, or could be carried out as supportive manufacturing activity, such as the use of compressed air system, ovens or furnace etc. WHE recovery can be beneficial to reduce energy consumption of the process itself, or provide a useful energy source for other purposes, thus improving the overall energy efficiency within the factory.

3.4 Stage 4: Decision making and recommendations

It is to the interest of all manufacturers to evaluate the impact of their decisions and therefore a financial analysis is performed and measures are optimised for either environmental or economic potential. In the financial analysis both the annualised net financial benefit and overall payback period are calculated. For small scale WHE recovery technology with low capital cost, a rough estimate of the economic return should be sufficient to justify investment, while for larger WHE recovery systems with integrated components where there is a high capital cost, a full appraisal should be carried out. In addition, the implementation of environmental and social impact analysis

such as the overall reduction in CO₂ emission based on the fuel that is displaced to each of the feasible technology options and comparisons are undertaken to provide an optimised final solution for manufacturers.

4 CASE STUDY

A case study example of an installed air compressor is analysed using the waste heat energy recovery framework described in this paper. This case study is undertaken to demonstrate the applicability of the framework to a simulated installation of a plant level energy demand.

An air-cooled 300(635)l/s(cfm), 160kW capacity compressor is installed to provide compressed air 24 hours a day and 365 days a year for a manufacturing plant in order to support its activities. It has been suggested by the energy manager of the plant that the heat produced by the compressor could be harnessed and utilised for a useful purpose within the plant.

Stage 1: Survey of waste heat sources in facility

By consulting the air compressor manufacturer and carrying out an onsite WHE sources survey, the cooling air mass flow at 10°C is 4.5kg/s based on cooling air flow of 3.6m³/s and air density of 1.25kg/m³, measured inlet and outlet temperatures are 10°C and 38°C respectively. Therefore, theoretical heat available from compressor is 125kW. Since the compressor is constantly working throughout the year, the temporal availability is 1. It is known from the survey that the heat is generated in the surrounding air but is mainly concentrated around the compressor pump.

Stage 2: Assessment of waste heat quantity and quality

The data from the survey in stage 1 is reformatted into the quantitative and qualitative descriptors defined in the framework. (Table 1)

TABLE 1 INFORMATION ACQUISITION AND REFORMATION

Quantitative		Qualitative	
Descriptor	Value	Descriptor	Assessment
Temperature difference, °C	28	Spatial availability	From single outlet
Temporal Availability	1	Contaminant	None
Exergy content, GJ	3600	Heat Carrier	Air

Stage 3: Selection of appropriate technology

There are a number of potential technologies that can be utilised to harness the WHE in this case study constrained by the conditions given. Since the temperature difference between inlet and outlet of the waste heat carrier is only 28°C and the availability of WHE is constant, a number of approaches are suggested. Hot air can be recovered with a fully integrated

control system to directly supply into a factory area or used to preheat air for combustion (figure 5a). Plate heat exchangers can be utilised to recover WHE from air or water-cooled machines, creating a closed circuit to avoid contamination and fouling of the compressor cooling system (figure 5b). The approach undertaken is likely to depend upon spatial availability and the particular requirements for space heating in individual building.

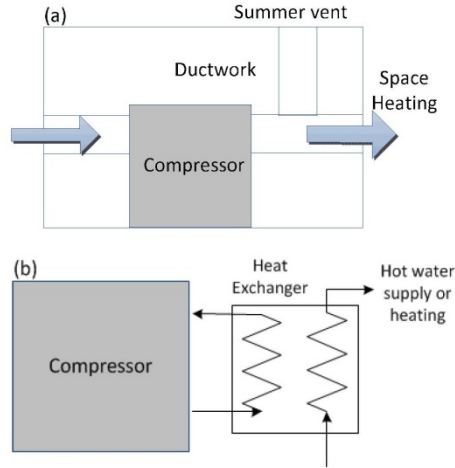


FIGURE 5: (A) SCHEMATIC OF A TYPICAL AIR-COOLED COMPRESSOR WITH DIRECT HEAT RECOVERY; (B) USING A HEAT EXCHANGER TO RECOVER WHE

The simple approach that redirects heat into the factory space and let space heating controls respond to this input can however cause overheating for more environmentally-sensitive manufacturing activities. In which case, integrated hot air recovery systems should be considered to avoid overheating and maximise savings.

Stage 4: Decision making and recommendations

It is also established that a large nearby workshop area requires space heating for half the year, currently heated by an onsite gas-fired boiler. Boiler efficiency is estimated at 75% and the current cost for gas is 0.6p/kWh (DECC, 2014). The workshop area is heated for 10 hours per day for five days of the week, and 5 hours on Sunday before the Monday shift start. A quote from the compressor supplier to install the necessary ductwork for transport of hot air to nearby workshop is £2,500. The payback period for such an installation is calculated in table 2. In addition to the financial benefit, installing a suitable heat recovery system also provides wider environmental benefits. Saving energy can produce substantial reduction in

CO₂ emissions at atmosphere and it is estimated that burning natural gas emits 0.21 kg CO₂/kWh (Grant & Clarke, 2010).

TABLE 2 WORKED EXAMPLE OF AN AIR COMPRESSOR FOR HEAT RECOVERY

Entries	Working	Results
Average heat that can be utilised	-	125 kW
Hours per year where waste heat can be used	(50h + 5h) x 24 weeks/yr	1,320 h/yr
Annual energy saved	125 kW x 1,320 h/yr	165,000 kWh/yr
Gross cost of fuel saved	£0.006/kWh / 75%	£0.008/kWh
Annual fuel cost saving	165,000 kWh/yr x £0.008/kWh	£1,320/yr
Capital cost	-	£2,500
Payback period	£2,500 / £1,320	1.9 yrs
CO ₂ reduction	165,000 kWh/yr x 0.21 kg CO ₂ /kWh	35 tonnes CO ₂ /yr

5 DISCUSSION AND CONCLUSIONS

The framework presented in this paper is developed to be useful and adaptable for all sectors, to enable the analysis of available WHE and to identify and assess potential energy recovery technologies. The novelty of such framework lies in an ability to provide a systematic approach to some of the energy recovery activities already being utilised within industry and it is therefore proposed that by applying this framework, the enhancement of overall energy efficiency improvement using energy recovery technologies can be achieved.

The framework has been developed with the manufacturing industry as the target implementer and hence the defined

descriptors used are more aligned to the needs of manufacturers over other potential users (e.g. domestic users, service sectors). However in order for the framework to be fully suitable for use by industry members, there is a need for the development of accompanying software tools. Such a programme should include a user-friendly interface of data input module, a quality and quantity assessment module in conjunction with a technology database, a cost-benefit analysis to support decision making algorithm and finally a dashboard type output module which enables data visualisation and better decision and investment justification (figure 6).

In this paper it has been identified that there is an opportunity for creating a structure around which waste heat energy sources are analysed and considered in terms of implementing energy recovery technologies. A four stage framework has been proposed to provide this structure which can be implemented within any manufacturing site to highlight a number of the most beneficial recovery opportunities. The paper also provides a decision model for waste heat energy recovery based on a range of parameters such as temporal requirement, temperature, flow rate, pressure and input medium in addition to physical locality and accessibility. The described decision support software makes the link between available waste heat energy, potential use options and the most appropriate technologies to support energy recovery. Benefits to industry include streamlined implementation of optimised energy recovery technologies, minimising payback times and improving plant energy efficiency with minimal disruption to existing processes and operation procedures are illustrated using a case study of an industrial scale air compressor, which demonstrates the ease of use of the framework and the output which can be expected from its implementation, and the scope of the application of the framework has been discussed.

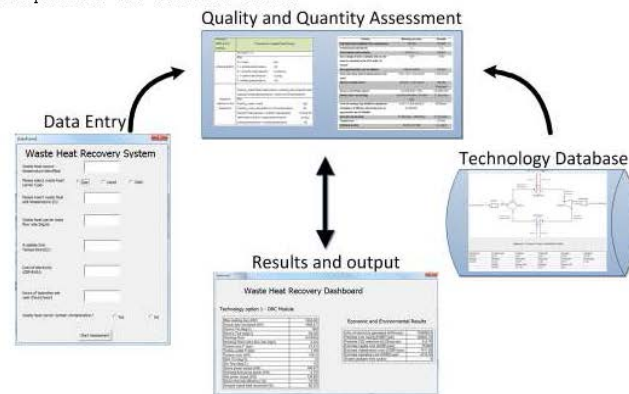


FIGURE 6 OVERVIEW OF THE SOFTWARE TOOL

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Appendix 2

Journal Paper

A Decision Support System for Waste Heat Recovery in Manufacturing

Introduction

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A decision support system for waste heat recovery in manufacturing

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One third of energy consumption is attributable to the industrial sector, with as much as half ultimately wasted as heat. Consequently, research has focused on technologies for harvesting this waste heat energy, however, the adoption of such technologies can be costly with long payback time. A decision support tool is presented which computes the compatibility of waste heat source(s) and sink(s), namely the exergy balance and temporal availability, along with economic and environmental benefits of available heat exchanger technologies to propose a streamlined and optimised heat recovery strategy. Substantial improvement in plant energy efficiency together with reduction in the payback time for heat recovery has been demonstrated in the included case study.

Energy efficiency; Environment; Sustainable Development

1. Introduction

Energy security is of significant concern for governments, industry and the public because of the increasing level of consumption, depletion of resources and its known contribution to climate change. Global energy demand is expected to increase by 50% in 2040 compared to today's levels [1]. Of this energy consumption, the manufacturing sector is particularly important since it is directly and indirectly responsible for one-third of global energy use [2]. Industrial heating or heat related treatment is one of the largest components of energy demand, and in the UK, accounts for about 72% of industrial energy use as depicted in Fig. 1 [3]. Of this demand two-thirds can be attributed to low and high temperature processes [4].

Rising costs of energy along with severe targets for the reduction of greenhouse gas emissions have led to an impetus towards efficiency improvements in industry. In the short to medium term, the reduction in primary energy demand is reported to be more cost-effective than implementation of renewable energy technologies [5].

Consequently numerous research activities have sought to improve energy efficiency through methods and tools for energy minimisation management [6], [7]. Limited research has been reported on assessing the appropriateness of a specific technology for a particular industrial application, although a number of researchers have identified suitability of technologies for waste energy recovery [8] and methods for assessing their environmental benefits and payback time [5], [9], [10]. In particular, waste heat may be used for heat pumps [11], or absorption refrigerators, [12]. Moreover, waste heat may be converted into electricity [10].

This paper presents a framework and an associated decision support tool specifically focused on waste heat recovery as an input to processes where heat is required within the same facility.

2. Decision support tool for waste heat energy recovery

The WHER framework consists of four steps that aim to define a process for the identification and matching of waste heat sources

and potential sinks within a manufacturing facility as shown in Fig. 2 and described below:

2.1. Step 1: Waste heat survey

Waste heat survey, aimed at the identification of sources and sinks of waste heat within a manufacturing environment from both the plant and process perspectives, is carried out using either invasive techniques i.e. thermometers, Resistor Temperature Detectors (RTDs) and thermistors, as well as non-invasive devices (infrared thermography). Flow rates are measured using a range of flowmeters and flow sensors can be used according to the types of media involved (see Fig. 3). The output from this survey often highlights a limited number of opportunities to recover large quantities of waste heat within a facility using a number of specific parameters such as:

- Range and number of heat sources and sinks
- Temporal information in terms of time window (hour, day or week) and time resolution (seconds, minutes, hours).
- T_{in} , T_{out} , T_{amb} (inlet and outlet hot medium and ambient temperature respectively) and the flow rate (m^3/s) for the source(s).
- T_{cin} , T_{coul} (inlet and outlet cold medium temperature respectively) and flow rate (m^3/s) for the sink(s).

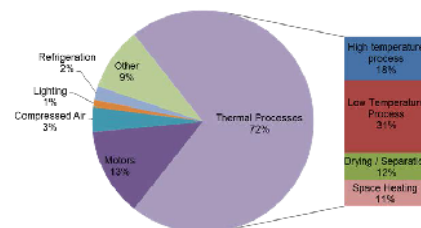


Fig. 1. Energy consumption in UK manufacturing industry [4]

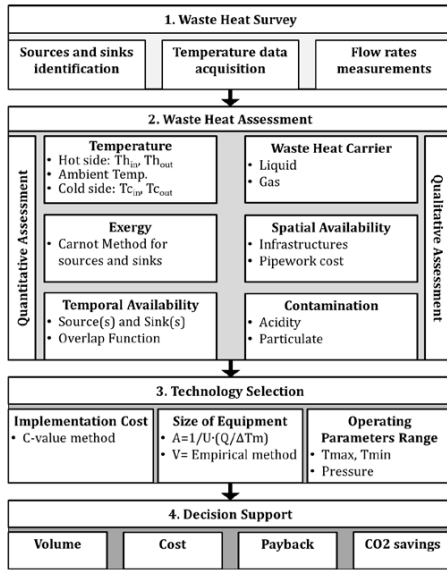


Fig. 2. Overall framework scheme

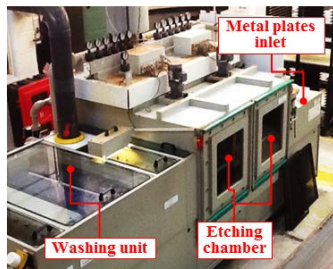
The data generated by this survey is used by the subsequent steps in WHER for the quantitatively and qualitatively assessment of waste heat and selection of appropriate technologies to recover this energy.

2.2. Step 2: quantitative and qualitative assessment of waste heat

In order to quantitatively evaluate waste heat in a manufacturing environment, the following parameters are utilised:

i) Temperature

Clearly, the heat transfer and recovery can be enabled only if the waste heat source temperature is higher than the heat sink temperature. Hence, the magnitude of the temperature difference between the heat source and sink is an important determinant of the quality of waste heat, along with the heat transfer rate per surface area unit, and the maximum theoretical efficiency of converting thermal energy from the heat source to another form of energy, i.e., mechanical or electrical.



(a)

ii) Exergy

The exergy is that part of energy that is convertible into all other forms of energy. The common energy analysis methods ignore the degradation of energy quality, and therefore exergy analysis is required to distinguish between recoverable and non-recoverable energy. The exergy can be calculated as outlined in publication by Taheri et al. [13] and formulated in the Equation 1.

$$Exergy = m c_p \Delta T (1 - T_{amb}/T) \quad (1)$$

Where m is the mass flow rate (kg/s), c_p is the stream specific heat capacity (kJ/kgK), ΔT is the temperature difference between the hot and the cold streams, T_{amb} is the ambient temperature and finally T is the measured temperature.

The exergy analysis is utilised to identify and quantify the heat energy loss and calculate the recoverable energies for each process [14].

iii) Temporal availability for sources and sinks selection

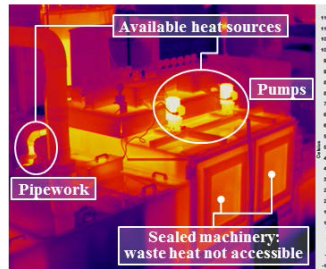
One of the key factors in maximising the potential of energy recovery is the consideration for temporal availability for sources and sinks. A methodical approach is used to undertake source and sink selection. This procedure for evaluating the best source and sink matchup using exergy and temporal availability analysis starts with listing of all the possible combinations of sources and sinks. For each combination, the exergy availability from the source(s) and exergy demand from the sink(s) are computed using the Carnot Method [13] and plotted according to the time window and resolution defined by users.

The next step is the computation of the overlap function $O(t)$ between sinks and sources, which is defined as:

$$\begin{aligned} O(t) &= Exergy_{sink}(t) & \text{if } Exergy_{sink}(t) < Exergy_{source}(t) \\ O(t) &= Exergy_{source}(t) & \text{if } Exergy_{sink}(t) \geq Exergy_{source}(t) \end{aligned} \quad (2)$$

This operation is repeated for all of the possible combinations of sources and sinks.

Finally, the Recovery Index (RI), defined as the ratio of areas under the Overlap function and the Source exergy curves, is used for ranking the temporal availability. In this research, the values of $RI > 0.5$ are only considered for heat recovery. Given amount of heat flow, ambient temperature, and temperature difference between hot and cold streams, the material properties library in MATLAB® is accessed to supply physical properties (i.e. density, specific heat capacity) for selected stream media type. Similarly, qualitative assessment of waste heat is carried out taking into account, the following parameters:



(b)

Fig. 3. Identification of waste heat hotspots in a chemical etching production line (a) using an infrared camera (b)

i) *Carrying medium of waste heat sources and sinks*

Waste heat medium can be in the form of liquid, gas or solid. The physical nature of the stream media can strongly influence the compatibility between the sources, sinks and the heat recovery equipment, its installation cost and other requirements.

ii) *Spatial availability*

The need of a spatial availability assessment is important to evaluate possible constraints in the area where the heat recovery equipment needs to be installed. This assessment must take into account the following factors:

- Accessibility to the units for installation and maintenance
- Positioning, i.e. underground or over ground pipework, for health and safety reasons
- Locality of the waste heat sources and sinks to minimise the heat transportation costs and maximise the recovery

iii) *Risk of contamination.*

Fouling and corrosion are the main causes of degraded performance or failure in heat recovery units [15]. Contamination can occur through fluid leakages in the equipment highlighting the need of a very careful selection of the construction materials, in order to ensure their compatibility with the working fluids and to avoid other mechanical and chemical failure.

These qualitative and quantitative descriptors of the available waste heat energy are used to compare potential heat recovery solutions with the available sources.

2.3. Step 3: Selection of appropriate technology

A pre-selection phase is carried out using media, pressure, and temperature range to exclude non compatible heat exchanger types listed in the ESDU database [16]. This is followed by a consideration of cost, volume and area based on the C method as described by Hewitt [17]. This enables a direct comparison between heat exchangers in terms of the heat duty carried out (Q) and the available temperature driving force (ΔT_m), which are related to the process specification. The quotient $Q/\Delta T_m$ is characteristic of the heat exchanger duty being carried out. From

the point of view of the software tool, the key target is the overall cost of the particular duty, specified in terms of $Q/\Delta T_m$. The cost factor C is defined as the cost in pounds sterling per unit $Q/\Delta T_m$, and as the units $£/(W/K)$.

The procedure for evaluation of the alternative feasible types of heat exchanger using C value method [17] starts with the computation of the heat load, defined as $Q=m c_p \Delta T$.

The next step involves the estimation of the mean temperature difference, ΔT_m , for which, the F_T method [18] is used taking into account the F_T correction factor designed for worst case scenario. For each proposed configuration the quotient $Q/\Delta T_m$ is then calculated and used to access the ESDU data tables [16] provided for each heat exchanger type in order to obtain the value of cost factor C , through a logarithmic interpolation between the levels of $Q/\Delta T_m$ given in the tables. Other technical constraints are taken into account, such as operating temperatures and pressure in order to exclude the non-compatible solutions.

The cost of each heat recovery configuration can be calculated by multiplying $Q/\Delta T_m$ by C . In this way it is possible to make a comparison of the selected configurations.

The results from this step are carried forward into the next stage of the framework, which utilises environmental and other economic analysis methods to compare between the selected options to provide the final recommendation.

The output of this tool provides a starting point for a detailed heat exchanger design at which point additional energy loss consideration of the chosen technology are required.

2.4. Step 4: Decision support tool for waste heat recovery

The last step of the framework provides final recommendations for manufacturers to identify an appropriate technology to recover waste heat energy. A computational model is developed to utilise the data generated in the previous steps together with a cost and benefit analysis to assess the list of feasible technologies. The most suitable technologies are ranked according to the cost (£), the payback period (years) and CO₂ savings (Tons/year) and presented in a dashboard style user interface for ease of use, as shown in Fig. 4 and explained in the next section.

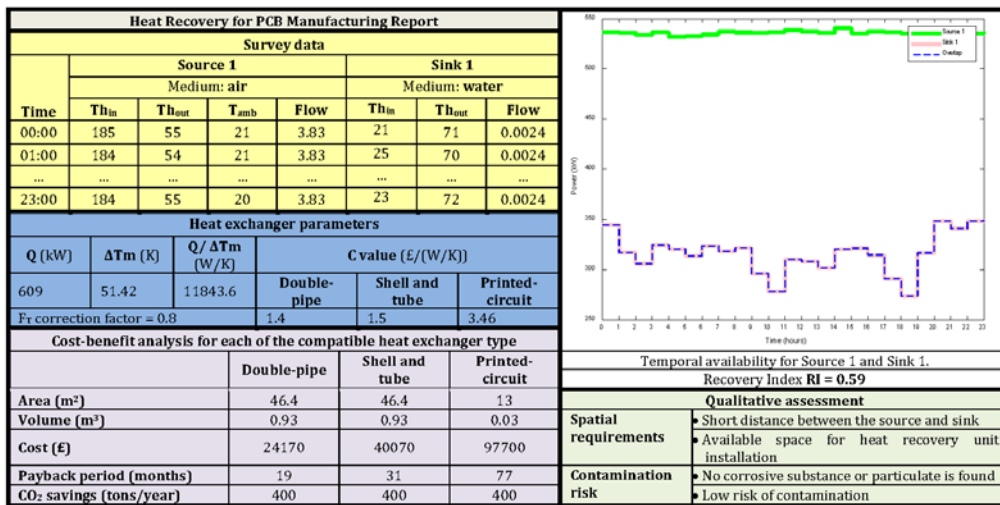


Fig. 4. Dashboard of results generated by the decision support tool

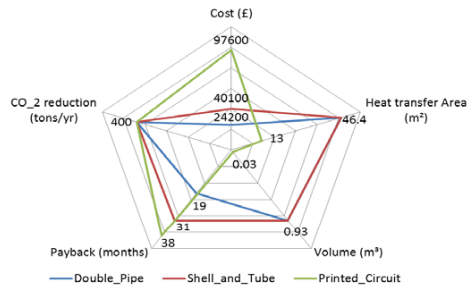


Fig. 5. Visual comparison of the solutions generated by the decision support tool

PCB manufacturing process is used as an example to demonstrate the implementation of the decision support modelling for heat recovery. In this case study, the objective is to recover waste heat energy from 5 compressors to be fed into their plant boiler system in order to supply hot water and plant heating. All the compressed air units are positioned in the same location which is close to the boiler room; therefore it is possible to cluster the individual compressors as one single source of waste heat.

Step 1: The waste heat survey was conducted using two Temperature Data Loggers, inlet flow rate was measured using standard flow meter, and the outlet flow rate was calculated theoretically according to the hot water demand. The time window considered is one day and the time resolution is one hour. These data appear in Fig.4 (yellow section).

Step 2: The exergy amount is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the survey. As per exergy analysis results summarised in Fig. 4, temporal availability calculation was carried out leading to a RI=0.59. The temporal availability chart reported in Fig. 4 displays power of waste heat source over 24 hours as a green line whereas waste heat sink is displayed in pink. The overlap function is represented by the blue dashed line.

Step 3: Using the selection criteria and the C method, three types of compatible heat exchangers for this case study were identified: double-pipe, shell-and-tube, printed circuit respectively. Fig. 4 shows (blue section) the computed values for relevant parameters for the selected heat exchanger.

Step 4: To enable a comparison of the three selected heat exchanger types, a cost-benefit analysis was carried out, including the computation of the heat exchangers areas and volumes, the cost, the payback period and the potential CO₂ savings, as shown in Fig. 4 (purple section).

Finally, a summary of the qualitative descriptors involved in this case study is summarised in Fig. 4 (in the green section), indicating that there were no particular constraints in terms of spatial availability and contamination risks.

A further way to display all the solutions generated by the decision support tool is reported in Fig. 5 in which the five axes represent the cost-benefit analysis parameters and a visual simultaneous comparison is allowed.

3. Conclusions

Energy minimisation within a facility is not limited to technological process improvements or changes in operation performance, but can also be achieved by taking a more holistic view of energy flows. In particular, by coupling sources of waste

heat energy with suitable sinks, can lead to substantial energy savings, with short payback period for any new infrastructure required. For successful implementation of this approach within the manufacturing environment it is essential to consider the exergy balance of the potential sources and sinks alongside the temporal availability of energy. In this work a conceptual and computational methodology for decision support on waste heat recovery was developed and applied to an industrial case study. The main conclusions that can be drawn from this case study are:

- The decision support system is able to compare temporal availability of exergy between sources and sinks of waste heat energy
 - A range of recovery indexes can be obtained to determine the quality of the match between multiple sources and sinks
 - Such an analysis can be used in a computational technology selection for optimised energy recovery and minimised financial payback of implementation
 - The user-facing system is straight-forward enough to be utilised by competent facility or energy management teams.
- Beyond the scope of the current research, there are three scenarios where this decision support tool could be utilised to improve overall plant energy efficiency:
- Recovery of waste heat energy within an existing manufacturing plant;
 - Implementing waste heat recovery within a reconfigurable manufacturing system;
 - Process design stage of a manufacturing system with waste heat recovery consideration.

It is envisaged that this methodical approach to implementing waste heat energy recovery within manufacturing will form part of a standard practice for new and old facilities striving to reduce overall energy demand.

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Appendix 3

Journal Paper

Infrared Monitoring of Aluminium Milling Process for Reduction of Environmental Impacts

Introduction

This paper has been submitted for publication in the International Journal of Computer Integrated Manufacturing, August 2015

Infrared Monitoring of Aluminium Milling Processes for Reduction of Environmental Impacts

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Infrared Monitoring of Aluminium Milling Processes for Reduction of Environmental Impacts

In modern manufacturing contexts, process monitoring is an important tool aimed at ensuring quality standard fulfilment whilst maximising throughput. In this work, a monitoring system comprised of an infrared (IR) camera was employed for tool state identification and surface roughness assessment with the objective of reducing environmental impacts of a milling process. Two data processing techniques, based on statistical parameters and polynomial fitting, were applied to the temperature signal acquired from the IR camera during milling operations in order to extract significant features. These features were inputted to two different neural network based procedures: pattern recognition and fitting, for decision making support on tool condition and surface roughness evaluation respectively. These capabilities are discussed in terms of reducing waste products and energy consumption whilst maximising productivity.

Keywords: word; infrared monitoring; milling; neural networks

Introduction

Recent decades have seen a growing understanding of the environmental impacts associated with global manufacturing activities, resulting in a developing field of research which seeks to reduce these impacts. Such research has, for example, targeted improvements in manufacturing energy efficiency (Rajemi, Mativenga, and Aramcharoen 2010) (Seow, Rahimifard, and Woolley 2013) (Luo et al. 2015) since this industry has been identified as a significant contributor to atmospheric greenhouse gases and their associated ramifications on global climate. Equivalent research on material efficiency, water consumption, and the generation of solid, liquid and other airborne waste streams, amongst others, have also become prevalent.

The current body of research into reducing environmental impacts typically seeks to fully understand the various factors before developing a strategy to reduce them via either: i) physical changes to products or processes to improve efficiency or reduce

waste; or ii) through operational or control improvements that seek to use the existing infrastructure more effectively. Clearly the first of these two options typically requires longer term investment, changes of equipment or process and is therefore more costly, whilst the second is easier, but may be more challenging when attempting to achieve more than incremental improvements.

This research is concerned with the second of these two approaches, which can be easily implemented and yield early results, whilst physical changes can be implemented over longer time periods. However, any reduction in environmental impact must also preserve and enhance speed, quality or practicability of manufacturing products. In this context, there is the opportunity to extract information from data acquired from a diverse range of manufacturing processes, and use this to actively control operational parameters to improve the environmental performances of these processes.

In this work infrared monitoring is used to investigate an aluminium milling process with the objective of reducing the amount of material and energy required for processing through the following improvements: prevention of rejects from defects (particularly for high value manufacturing); ensuring quality to prevent re-work; avoidance of excessive tool wear; fulfilment of surface integrity requirements; prediction and prevention of catastrophic failures; and reduction in processing time.

All of these improvements not only reduce the environmental impact of the processes, but also are in line with the current manufacturing objectives of increasing speed, quality, reliability and cost effectiveness.

In this paper a literature review is reported covering sustainable machining, sensor monitoring of machining processes, tool wear assessment and surface roughness modelling. The experimental work and the equipment utilised are described. Data

processing procedures are illustrated, consisting of feature extraction and the development of a decision making support system. The results are reported and discussed from two perspectives: the tool state identification and surface roughness assessment.

Literature review

An important objective for sustainable machining is improving efficiency in resource utilisation and raw materials extraction. It is necessary to improve the proportion between incoming raw materials and outgoing products during the production phase which implies reducing waste and eliminating mechanical and chemical degradation of machined surface (Rajemi, Mativenga, and Aramcharoen 2010).

At present, the environmental factors associated with manufacturing processes have become an emerging problem for manufacturers due to stricter regulations on wastes, effluents, emissions, health and workers' safety (Fratila 2009). Therefore, in parallel with manufacturing process optimisation, efforts must be made to reduce the impact of industrial activity on environment and health (Devillez et al. 2007).

Tool Condition Monitoring (TCM) is an essential part of automating modern machining processes to ensure efficiency and minimise waste (Rivero, López de Lacalle, and Penalva 2008). The work of Teti et al. (Teti et al. 2010) gives a comprehensive overview of this area. The approaches to TCM are categorised as either "direct" or "indirect"; for direct monitoring the tool wear is measured optically or physically, whereas for indirect monitoring another, more accessible quantity is measured, then used to deduce the tool wear (Kalpakjian 2009). Common indirect measurement quantities include: cutting forces, power, temperature rise, work piece surface finish, vibration, and chatter (Kalpakjian 2009). Whilst direct methods often show the best accuracy, their use is typically restricted to the laboratory, due to practical

access and illumination problems in industrial environments (Teti et al. 2010). An example of such an approach is that of Kerr et al. (Kerr, Pengilley, and Garwood 2006), who used digital image processing techniques on a close-up video image of a tool to monitor “on-line” tool wear (whilst the machine is running). It is vital for practical use in industry that any TCM system must be on-line, to prevent wasted manufacturing time (Rivero, López de Lacalle, and Penalva 2008). For indirect measurements, this is made easier by the fact that the measurand can be selected such that it is not obscured by the work piece, chips, or cutting fluid. Often several quantities are measured simultaneously, such as in the work by Segreto et al. (Tiziana Segreto, Simeone, and Teti 2012), who correlated measurements of force, vibration and Acoustic Emission (AE) to the wear level in a turning operation, or (Boud and Gindy 2008) who used pressure, force, vibration and AE to assess the tool condition in broaching operations.

One key area of research in indirect TCM relates to the measurement of temperature. As first recognised by Taylor in 1907 (Davies et al. 2007; Young 1996) this is a particularly important “tool wear indicator” (Rivero, López de Lacalle, and Penalva 2008), as heat build-up is both a symptom and a contributing factor to tool wear (Davies et al. 2007; Young 1996). High temperatures in machining can cause problems in the work piece as well, including poor dimensional accuracy and surface finish, and residual stresses (Davies et al. 2007). A thorough overview of the monitoring of temperature in material removal processes can be found in the work of Davies et al. (Davies et al. 2007). Common approaches to the measurement of temperature for TCM include the use of resistance methods, thermocouples (such as that by Kitagawa et al. (Kitagawa, Kubo, and Mackawa 1997) and thermo physical processes; however, the approach that currently has the best spatial and temporal resolution is the use of “Spectral Radiation Thermometry” (infrared monitoring) (Davies et al. 2007; Valiorgue

et al. 2011). This method, exploiting the correlation between the temperature of an object and the wavelength of the electromagnetic radiation energy that it emits, has a number of other significant advantages for the monitoring of machining processes. Chief amongst these is the remote nature of the measurement method, meaning that no holes or sensors need to be incorporated into the cutting tool, which might affect the accuracy of reading (Davies et al. 2007; Young 1996). This technique also looks at the local surface temperatures on the faces and edges of the cutting tool, which are more important than the average temperatures in the tool when considering tool wear (Valiorgue et al. 2011).

Surface properties strongly influence the performance of a finished part. They have an enormous impact on features such as dimensional accuracy, friction coefficient and wear, thermal and electric resistance, fatigue limit, corrosion, post-processing requirements, appearance and cost (Quintana, Garcia-Romeu, and Ciurana 2009). The measurement of the surface roughness is commonly carried out off-line when the part is already machined (Quintana, Garcia-Romeu, and Ciurana 2009) and it is often used as an acceptability criterion for mechanical products (Benardos and Vosniakos 2002). A review of literature highlights a wide research focused on surface generation to understand the process and provide the necessary knowledge to guarantee surface quality before the start of the metal removal operation.

In terms of intelligent decision making support systems, neural network approach is surely one of the most reported methodologies. In particular, for surface roughness assessment applications, Anuj Kumar (Anuj Kumar Sehgal 2013) describes a model for surface roughness prediction for turning of rolled aluminium. The model is tested by using the Analysis of variance (ANOVA) and an Artificial Neural Network analysis is adopted with the experimental values as input-output pairs. Otkem et

al. (Oktem, Erzurumlu, and Erzincanli 2006) presents an approach for determination of the best cutting parameters leading to minimum surface roughness in end milling mould surfaces by coupling a genetic algorithm with neural network. Two techniques, namely factorial design and neural network were used in the work of Esmel et al (Esmel, Sagbas, and Kahraman 2009) for modelling and predicting the surface roughness of AISI 4340 steel.

Literature also details a range of research comprising the use of neural networks applied on sensor data aimed at surface roughness assessment. Benardos and Vosniakos (Benardos and Vosniakos 2002) propose a neural network modelling approach for SRP in face milling. The factors considered in the experiment were the depth of cut, the feed rate per tooth, the cutting speed, the engagement and wear of the cutting tool, the use of cutting fluid and the three components of the cutting force.

An on-line surface recognition system was developed by Lee and Chen (Lee and Chen 2003) based on artificial neural networks using a sensing technique to monitor the effect of vibration produced by the motions of the cutting tool and workpiece during turning processes. Tsai et al (Tsai, Chen, and Lou 1999) developed an in-process based surface recognition system. An accelerometer and a proximity sensor were employed during cutting to collect the vibration and rotation data, respectively. An artificial neural networks model was developed to predict the roughness values. Risbood et al. (Risbood, Dixit, and Sahasrabudhe 2003) using neural networks, predicted surface roughness within a reasonable degree of accuracy by taking the acceleration of radial vibration of tool holder as a feedback.

An intelligent sensor fusion technique to estimate on-line surface roughness during steel turning was proposed by Azouzi and Guillot (Azouzi and Guillot 1997) who utilised a dynamometer, an accelerometer, an acoustic emission transducer and two

capacitance sensors to build a neural network based decision making support system. Another technique of surface roughness prediction has been developed by Aguiar et al. (Aguiar et al. 2008) using multi-sensor method with an AE sensor and power meter for grinding process. Acoustic emission and cutting power signals are shown to be very good input parameters to the neural network for surface roughness prediction of ground parts.

Neural networks have the capability to analyse a number of measurements from a machining operation to provide data regarding a seemingly unrelated parameter. This removes the need for direct measurements and opens up opportunities for low cost, remote sensing technologies to provide critical data about machining condition and performance. To meet the need of manufacturers to reduce their environmental impacts, from the excessive use of energy and time, and to reduce the occurrence of sub-standard parts production, the current research is concerned with the use of remote sensing to determine tool bit and work piece condition, to better manage these impacts in real time.

Materials and experimental procedures

Among several CNC industrial machining processes, milling is a fundamental machining operation. End milling is the most common metal removal operation encountered and is widely used in a variety of manufacturing industries including the aerospace and automotive sectors, where quality is an important factor in the production of slots, pockets, precision moulds and dies (Lou, Chen, and Li 1999). Hence in this research, an end milling process was selected to be monitored by use of an infrared camera for detection of tool wear state and surface finish.

The cutting experiments were carried out on a XYZ SMX2000 CNC three-axis vertical milling machine, with a 2.25 kW drive motor, and a maximum spindle speed of 4200 RPM. This allowed for accurate control of the machining feed rate and spindle

speed, whilst maintaining simplicity and ease of access for the infrared camera. Two Sherwood four-toothed, 12mm diameter end mills were used, made of M2 High Speed Steel (HSS). One of these was in a “worn” state, having been used for standard machining processes on both steel and aluminium; the other was unused. The work piece material was square stock, 6068 Aluminium, measuring 51 x 51 x 610 mm. All the machining operations were done under “dry” cutting conditions. This condition was chosen to ensure clean and clear results, as the addition of coolant or lubricant was found to interfere with the thermographic image, and dramatically reduce the temperature in the relatively low-temperature machining of aluminium. This “dry” condition is common to many similar investigations, such as Lauro et al. (Lauro, Brandão, and Ribeiro Filho 2013), Kodácsy & Molnár (KODÁCSY and MOLNÁR 2011) and Kitagawa et al. (Kitagawa, Kubo, and Maekawa 1997). The tool was, however, allowed to cool to room temperature between tests to ensure a constant starting temperature.

Table 1. Cutting conditions for milling tests

Cutting conditions	
Work piece Material	6068 Aluminium
Cutting Tool	End mill Material: HSS M2
Tool Geometry	Diameter: 12 mm 30° Helix, 4 flutes
Conditions	Dry. Tool allowed to cool to room temperature between each test
Wear criterion	VB > 0.3 mm
Depth of cut	0.5 mm

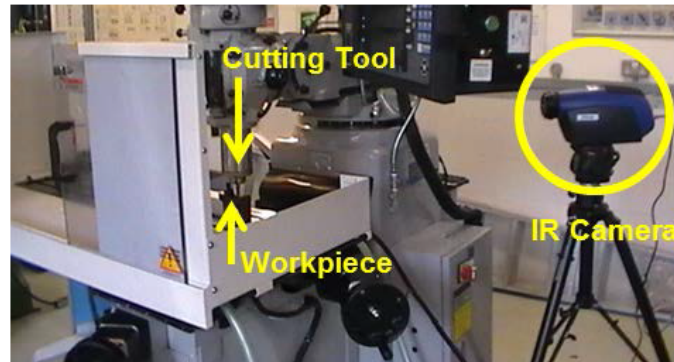


Figure 1. Experimental setup

A range of feed rate and spindle speed process parameters were investigated during the experimental procedure, in order to evaluate their effect on the ability of the system to identify wear. The cut depth was fixed at 0.5 mm. The chosen experimental parameters are summarised in Table 2. These were chosen based upon the recommended speeds and feeds for the tool and work piece materials, adjusted due to the dry conditions. One of the most critical causes of tool wear in the dry machining of aluminium is the build-up of material on the tool, caused by excessive temperatures (Rivero, López de Lacalle, and Penalva 2008). The lower feed rates, cut depth and spindle speeds were therefore chosen to avoid this situation, which would otherwise skew the results. These equate to a feed per tooth of between 0.0017 in/tooth and 0.0083 in/tooth. Figure 1 shows the experimental setup used. The data acquisition was done using a Cedip Infrared Systems Silver 450M InSb type infrared camera, with a frame rate of 383 per second, and a calibration range of 5 to 300°C.

Before commencing the experimental procedure, it was important to confirm quantitatively that the fresh and worn tools were in the expected state prior to machining, and that the wear on the fresh tool remained negligible throughout. The

criteria used for determining the point at which a tool became worn was the same as that used by Azmi (Azmi 2012), who defined an end mill cutting tool as worn when it exhibited any of the following: "reach maximum uniform flank wear, VB_{max} of 0.3 mm on any cutting flute, or reach an average flank wear, VB of 0.3 mm on all four cutting flutes, or excessive edge, nose deformation/rounding or chipping on more than 2 cutting flutes." This is confirmed by Kalpakjian & Schmid (Kalpakjian 2009), who define the average allowable wear land (VB) for end milling to be 0.3 mm. For these tests, this was measured using a SmartScope Flash 200 automatic measurement system, accurate to approximately 2 μm . It is to be noted that this criteria does not take into account catastrophic wear, but accounts for common wear in normal usage.

The recorded values for the wear of the worn tool also represent a minimum value for the wear as the original point that they would have been measured relative to was chipped, or worn away. They are, however, sufficient to show the worn tool to have surpassed the wear criteria (0.3 mm), and that the wear on the fresh tool remained well below 0.1 mm throughout.

In order to take practical, but accurate measurements of the temperature of an object using infrared monitoring its emissivity must be known. This is a complicated parameter, depending on a range of factors, including the temperature, material and surface finish of the measured object (Valiorgue et al. 2011); this, in itself is a simplification (the "grey body" assumption (Davies et al. 2007)), as the emissivity can also vary with both wavelength and direction (Valiorgue et al. 2011). However, a practical value for emissivity was derived by synchronous measurement of the temperature of the cutting tool using both the infrared camera and a K-type thermocouple over a range of temperatures, as delivered using a hot air gun.

Table 2. Design of experiments

Feed Rate	Cutting Speed	Test ID	
(mm / min)	(RPM)	Fresh Tool	Worn Tool
254	900	T_1_Fresh_1	T_1_Worn_1
		T_1_Fresh_2	T_1_Worn_2
254	1200	T_2_Fresh_1	T_2_Worn_1
		T_2_Fresh_2	T_2_Worn_2
254	1500	T_3_Fresh_1	T_3_Worn_1
		T_3_Fresh_2	T_3_Worn_2
508	900	T_4_Fresh_1	T_4_Worn_1
		T_4_Fresh_2	T_4_Worn_2
508	1200	T_5_Fresh_1	T_5_Worn_1
		T_5_Fresh_2	T_5_Worn_2
508	1500	T_6_Fresh_1	T_6_Worn_1
		T_6_Fresh_2	T_6_Worn_2
762	900	T_7_Fresh_1	T_7_Worn_1
		T_7_Fresh_2	T_7_Worn_2
762	1200	T_8_Fresh_1	T_8_Worn_1
		T_8_Fresh_2	T_8_Worn_2
762	1500	T_9_Fresh_1	T_9_Worn_1
		T_9_Fresh_2	T_9_Worn_2

This is similar to the approaches used by a number of other authors (Teti et al. 2010; Kitagawa, Kubo, and Maekawa 1997; Valiorgue et al. 2011; Quintana, Garcia-Romeu, and Ciurana 2009). A similar, although more thorough approach to emissivity calibration was taken by Valiorgue et al. (Valiorgue et al. 2011), who integrated the emissivity curve with the IR radiation measurements over a full range of temperatures in order to account for the dependence of emissivity on temperature.

Table 3. IR thermography input conditions

IR thermography input conditions	
Tool emissivity	0.393
Distance to tool	0.91 m
Atmospheric temperature	22°C
Reflected temperature	22°C

In this work, once these values were acquired, the optimisation function in Microsoft Excel was used to select a value for emissivity that most closely matched the IR camera readings to those recorded using the thermocouple; the emissivity coefficient and the other influencing factors on the IR camera temperature reading are summarised in Table 3.

Data processing and feature extraction

Data pre-processing

The temperature signals used for analysis were extracted from the recorded IR film using FLIR's "ResearchIR" software. Within the infrared video acquired during the cutting tests, Regions of Interest (ROIs) are defined in order to retrieve signals related to the zones of interest.

Three different rectangular ROIs were chosen to investigate the tool-chip interface area: 11 x 4 pixels, 11 x 22 pixels and 11 x 36 pixels respectively as shown in Figure 2 (Simeone, Woolley, and Rahimifard 2015). A number of advantages are gained by this approach: firstly, by averaging over an area, the temperature spike effect of flying chips intersecting with the field of measurement (Rivero, López de Lacalle, and Penalva 2008) is reduced; secondly, by looking at an area slightly removed from the tool-work piece interface, any "dazzle" from the high infrared radiation output at the interface is minimised, which might otherwise skew the results (Valiorgue et al. 2011;

Lauro, Brandão, and Ribeiro Filho 2013). However, the positioning was chosen to still be sufficiently close to the interface that the response time to changing temperatures would be kept low.

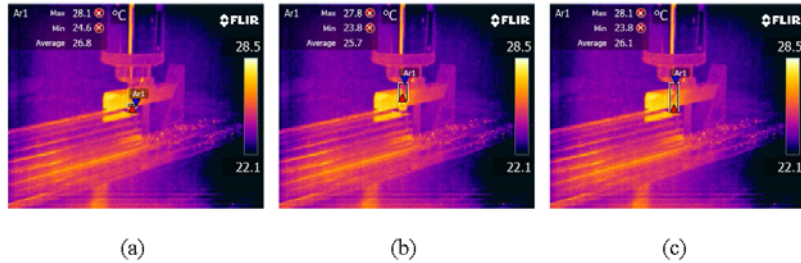


Figure 2. The three ROIs selected for data acquisition and processing: (a) 11×4 pixels $\approx 55 \text{ mm}^2$, (b) 11×22 pixels $\approx 300 \text{ mm}^2$, (c) 11×36 pixels $\approx 480 \text{ mm}^2$

This positioning also meant that the temperature drop was not excessively low, which was important to maintain a high “Noise Equivalent Temperature Ratio” – the “noise” in this case being the heating and cooling cycle due to the intermittent nature of milling cutting (Kitagawa, Kubo, and Maekawa 1997).

For each ROI, a signal segmentation procedure was implemented on the raw infrared signals, by trimming the signal, to include only the segment where the tool is in contact with the workpiece, as shown in Figure 3. This operation was performed on each milling test signal.

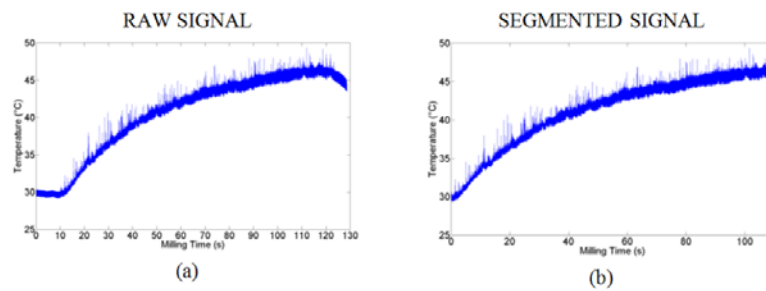


Figure 3. Raw (a) and segmented (b) IR temperature data for test T_1_Fresh_1

Dataset preparation

A data set is a matrix whose rows are represented by a certain number of samplings with the columns corresponding to the 36 milling tests. Four different data sets were prepared, consisting of 1000, 2000, 4000 and 7500 rows (samplings) respectively. In Table 5 an example of 7500-samplings dataset is reported.

Feature extraction

The extraction of signal characteristic features from sensing systems is of primary importance in many information processing fields such as pattern recognition, predictive modelling, industrial process fault diagnosis and control, etc. (Teti et al. 2010; Wang et al. 2014)

Table 4. 7500 samplings dataset

Samplings	T_1_Fresh_1	T_1_Fresh_2	...	T_9_Worn_1	T_9_Worn_2
1	29.5097	30.0168	...	31.6677	32.8816
2	29.8423	30.0033	...	31.3615	33.5475
...
7500	36.5076	34.4815	...	50.1302	52.1439

In this paper two methodologies were adopted to extract features:

Statistical features

Four statistical features were extracted from the segmented signal of each test:

- Mean value
- Variance
- Skewness

- Kurtosis

The four statistical features mentioned above were grouped into feature vectors to be used as input to a neural network based decision making system (Simeone, Segreto, and Teti 2013).

Polynomial features

An alternative approach to the statistical features extraction is proposed in this paper. For each milling test, the coefficients of the polynomial $p(x)$ of degree 4 that fits the IR temperature signal in a least squares sense, have been calculated. An example of 4th degree polynomial fitting is reported in Figure 4 for Test T_1_Fresh_1.

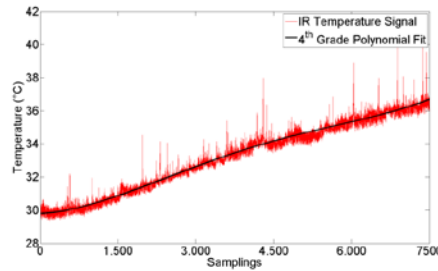


Figure 4. 4th polynomial fit for Test T_1_Fresh_1

The result is 5 elements feature vector containing the polynomial coefficients in descending powers:

$$p(x) = \alpha x^4 + \beta x^3 + \gamma x^2 + \delta x + \varepsilon$$

Therefore a set of 5 features, the polynomial coefficients, was extracted from the segmented signal of each milling test: $[\alpha \beta \gamma \delta \varepsilon]$.

The infrared data processing and features extraction procedure can be summarised in the Table below.

Table 5. Summary of signal processing and features extraction procedure

	1. ROIs definition			
	11 x 4 px	11 x 22 px	11 x 36 px	
Pre	2. Segmentation			
Processing	3. Dataset construction			
	1000	2000	4000	7500
	samp.	samp.	samp.	samp.
	4. Features Extraction			
Signal Processing	Statistical			4 th degree
	Features			Polynomial
				Coefficients
	Mean	Var	Skew	Kurt
				α β γ δ ε

Neural network based decision making support system

The features vectors obtained with the two methodologies were used to construct feature vectors to input to a neural network (NN) based pattern recognition procedure (Teti et al. 2010; T. Segreto, Simeone, and Teti 2014) for decision making on tool wear state identification as well as to a neural network based fitting procedure for surface roughness assessment.

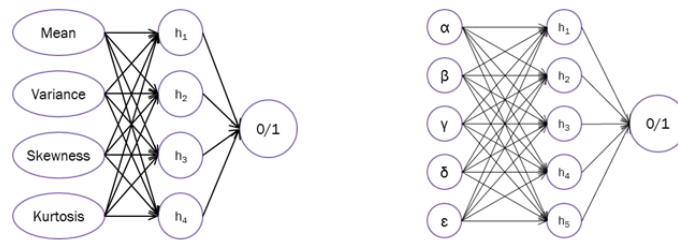
Neural Network Pattern Recognition for Tool State Identification

The feed-forward (FF) back-propagation (BP) NN is the most commonly used family of NN for pattern classification purposes (Haykin 1998). Its structure is made of three layers (input, hidden and output layer respectively) as shown in Fig 5.

In this application the following NN architecture configurations were adopted:

- The number of input nodes was equal to the number of input features vector elements:
 - 4 nodes for statistical features as the feature vector is made of 4 elements: Mean, Variance, Skewness and Kurtosis.

- 5 nodes for polynomial features as the features vector elements are the polynomial coefficients α , β , γ , δ and ε
- The number of hidden layer nodes is equal to the number of input layer nodes.
- The output layer had only 1 node, yielding a binary value associated with the tool wear state: 0 = fresh tool; 1 = worn tool.



Statistical Input Features Vector Polynomial Input Features Vector

Figure 5. Neural Network schemes for tool state identification: (a) statistical features, (b) polynomial features

Training, validation and testing

The FF BP NN learning algorithm adopted in this work was the Levenberg-Marquardt algorithm (Levenberg and Levenberg 1944; Marquardt 1963) which is considered one of the fastest methods for learning moderate-sized FF BP NN (Haykin 1998).

The algorithm's principal mode of action is to find the minimum of a multiple variable function, which is expressed in the form of the sum of squares of nonlinear real-valued functions making it an iterative procedure and it is mostly used for nonlinear optimisation tasks (Levenberg and Levenberg 1944; Haykin 1998). Data division for Levenberg-Marquardt training algorithm was carried out randomly with the

following percentages: 70% of test cases were used for training; 15% for validation; 15% for testing.

The input matrix is composed of a number of rows equal to the number of test cases i.e. 36, and a number of columns equal to the number of elements of the input feature vectors (4 for statistical features and 5 for polynomial features).

During testing, the NN output is correct if the error $E = (Oa - Od)$, where Oa is equal to the actual output and Od is equal to the desired output, is $-0.5 \leq E \leq +0.5$; otherwise, a misclassification case occurs. The ratio of correct classifications over total training cases yields the NN success rate (SR).

Neural network fitting for surface roughness assessment

Roughness Measurements were carried out using a Taylor Hobson roughness device at the end of each milling test on the workpiece surface.

The roughness parameter considered in this work was the average roughness (Ra) reported for each test in Table 6. Ra is the arithmetic mean of the absolute departures of the roughness profile from the mean line. It is universally recognised and is the most often used international parameter of roughness ("Http://www.taylor-Hobson.com/" 2015), it is defined by the formula below:

$$R_a = \frac{1}{l} \int_0^l |z(x)| dx$$

Table 6. Surface Roughness Measurements

ID Test	Ra (µm)	ID Test	Ra (µm)
T_1_Fresh_1	4.03	T_1_Worn_1	0.48
T_2_Fresh_1	2.01	T_2_Worn_1	0.71
T_3_Fresh_1	3.86	T_3_Worn_1	0.53

T_4_Fresh_1	8.20	T_4_Worn_1	1.10
T_5_Fresh_1	4.75	T_5_Worn_1	1.48
T_6_Fresh_1	4.09	T_6_Worn_1	0.59
T_7_Fresh_1	9.93	T_7_Worn_1	2.89
T_8_Fresh_1	7.99	T_8_Worn_1	1.09
T_9_Fresh_1	5.03	T_9_Worn_1	1.22

- The input matrices used for tool state identification were used also for surface roughness assessment.
- Two configuration of hidden layer nodes number were utilised for each set of input layer nodes, respectively:
 - 8 and 16 hidden layer nodes for the 4 statistical input features
 - 6 and 18 hidden layer nodes for the 5 polynomial features.
- The output layer had only one node containing the Ra value (in μm).

For the evaluation of the generalisation ability of the trained neural network a linear fit between the output of the model and the experimental data for all the measured values presented in Table 6 was performed. The fitness indicator is hence the regression coefficient R-value.

Results and discussion

Tool state identification

The success rate was calculated for both the features extraction methodologies and for the three ROIs applied to the four datasets and illustrated in Figure 6.

Results show that SR range from 85.01% to 98.61%, the average success rate of all the NN configurations is 93.73%, demonstrating the capability of both features extraction methodologies in generating valuable features for tool condition monitoring.

The results reported in Figure 6 show that statistical features always yield a higher success rate compared to the polynomial features.

The best success rates were obtained using the 11x36 px ROI, with an average SR equal to 94.30%. Using 11x4 px ROI, the average SR slightly decreases to 93.72% while SR=90.17% is obtained using 11x22 px ROI.

The success rate increases as the number of processed samplings increases. However, by considering 1000 samplings (2.6 seconds milling time) the tool state identification is performed with a very high success rate (85.01% – 91.65%), showing a quick response of infrared temperature signals for identifying the tool wear state.

The ability to be able to detect reliably when a tool bit has reached a the state of wear, where by the likelihood of predicting substandard work, expenditures of excess machine energy or the potential of catastrophic failure could thus lead itself to the production of a number of undesirable consequences. Environmental impacts that may be prevented by using this monitoring approach include parts rejection (waste), excess cutting friction (energy consumption, CO₂ production, machine wear) and unplanned maintenance (loss of production time / output).

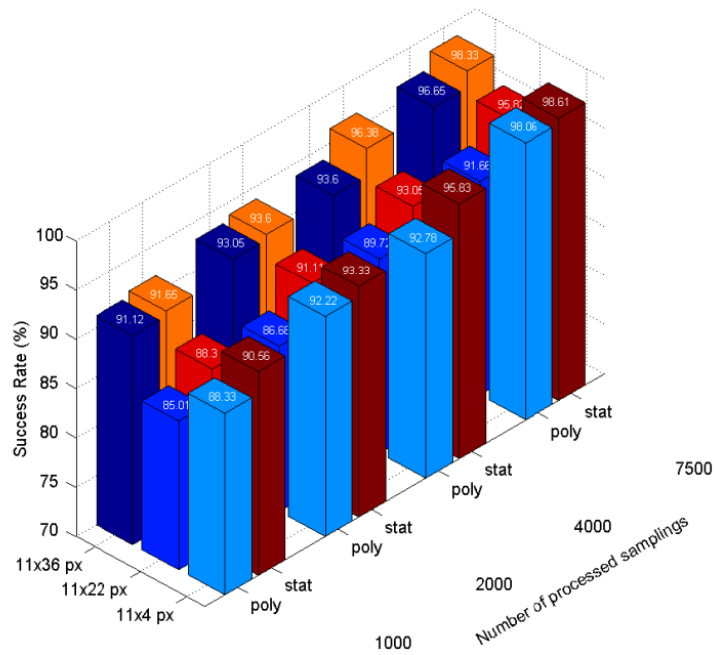


Figure 6. Tool State Identification Success Rates

Surface roughness assessment

In Tables 9 to 9, the R-values obtained from all the neural network configurations are reported. Each table reports results for one ROI. The best linear fitting in terms of R-value is reported in bold for each dataset, for the three ROIs respectively.

The surface roughness assessment was carried out with R-values ranging from a minimum of 0.6367 to a maximum of 0.981. The average fitting R-value is 0.8793. This confirms that the features extracted with both methodologies are suitable for surface roughness assessment.

Generally the statistical features lead to a better fitting, in fact the results show an average R-value equal to 0.9085 for statistical features against 0.8500 obtained using polynomial features.

The number of hidden layer nodes does not have a great impact on the results. The “low number” configurations (4-8 and 5-6) in fact, give better results than the “high number” configurations (4-16 and 5-18) with only a very small difference in R-value equal to 0.01.

Best results are obtained extracting signals and features from the smallest ROI (11 x 4) showing an average fitting equal to 0.90.

The fitting increases as the number of processed samplings increases. However, considering the 1000 samplings datasets, the surface roughness assessment can be carried out with R-values ranging from 0.6367 to 0.9448 (with an average R-value equal to 0.83). These results confirm the capability of the temperature to be a suitable quick indicator of the surface roughness. In Figures. 7-9 the best fitting is reported for each ROI.

Table 7. 11x4 pixels ROI table of results

11x4 px			
1000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9227	5_6	0.7214
4_16	0.9092	5_18	0.7413
2000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9272	5_6	0.8864

4_16	0.9716	5_18	0.8488
4000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.8921	5_6	0.9583
4_16	0.9355	5_18	0.8502
7500 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9811	5_6	0.9445
4_16	0.9675	5_18	0.9803

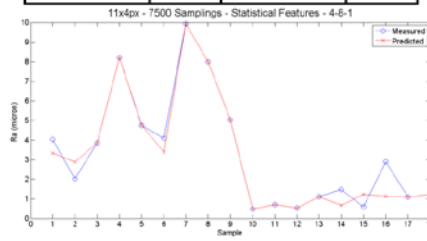


Figure 7. Best Fitting for 11x4 pixels ROI

Table 8. 11x22 pixels ROI tale of results

11x22 px			
1000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.8652	5_6	0.7847
4_16	0.8259	5_18	0.6367
2000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R

4_8	0.8684	5_6	0.811
4_16	0.8164	5_18	0.8666
4000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9363	5_6	0.8275
4_16	0.9252	5_18	0.8289
7500 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9097	5_6	0.8647
4_16	0.9064	5_18	0.8463

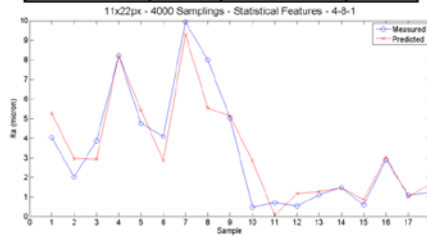


Figure 8. Best Fitting for 11x22 pixels ROI

Table 9. 11x36 pixels ROI table of results

11x36 px			
1000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9448	5_6	0.8589
4_16	0.8808	5_18	0.8246
2000 samplings			
Statistical Features		Polynomial Features	

Configuration	R	Configuration	R
4_8	0.9678	5_6	0.9443
4_16	0.9134	5_18	0.9362
4000 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.8458	5_6	0.8293
4_16	0.8431	5_18	0.8903
7500 samplings			
Statistical Features		Polynomial Features	
Configuration	R	Configuration	R
4_8	0.9128	5_6	0.8236
4_16	0.9356	5_18	0.8962

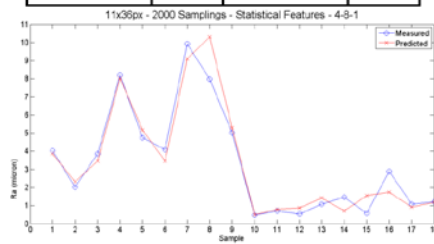


Figure 9. Best Fitting for 11x36 pixels ROI

The closeness of the relationship between temperature profile and the surface properties of the workpiece regardless of tool state provides potential opportunity to adjust the cutting parameters of the milling process in real time to maximise the rate of production (minimising energy) whilst ensuring desired surface finish is obtained (minimise reject and rework).

Conclusions

Infrared monitoring of an aluminium milling process was performed to identify the tool wear state and to model the surface roughness. An experimental campaign of milling tests was carried out on an aluminium workpiece using a diverse range of cutting parameters. During machining, infrared temperature signals were acquired by using an infrared camera and surface roughness measurements were carried out after every cutting test on the milled surface.

Signal processing procedures were implemented on infrared signals and two methodologies of signal features extraction were adopted, obtaining statistical features and polynomial coefficients features. An intelligent decision making support system was built for tool state identification through the implementation of Neural Networks Pattern Recognition. The results showed that both feature typologies are suitable for tool state identification with very high NN performance for decision making on cutting tool conditions during aluminium milling, but revealing a more reliable analysis from statistical features.

Moreover the Neural Network paradigm was applied to the signal features in order to assess the surface roughness and results showed that surface roughness assessment can be successfully carried out by monitoring temperature during milling.

An efficient and effective monitoring system aimed at tool state identification and surface integrity requirements can improve environmental performances of machining operations by minimising the risk of dangerous faults which may damage the product. Also, avoiding additional operations due to non-acceptable tool conditions and surface finishing requirements helps in energy, time and resource saving.

It is important to underline that prediction of tool wear and surface roughness plays a fundamental role in maintaining quality standards in machining processes while

contributing to the reduction of environmental impact by optimising the utilisation of energy and resources.

Future experimental research activities will involve similar methodology applied on different materials and machining processes to evaluate the applicability of the described technology and signal processing techniques for evaluating tool bit condition and production parameters in a range of manufacturing applications. Importantly, low cost IR sensors are required for sensing in the presence of cutting fluid in order to present an industry-ready monitoring technology.

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