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Lean Energy: A methodology to characterise and optimise energy consumption within manufacturing lines

A dissertation submitted to the University of Dublin
for the Degree of Doctor of Philosophy
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Trinity College Dublin, February 2015
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Summary

With an ongoing increase in industrial energy demand anticipated in Europe over the next twenty years, energy efficiency continues to be an important focus within industrial environments. As consumer products have become more complex, the complexity of the manufacturing process chains and their energy consumption has also increased. This has resulted in manufacturing process chains which demand more resources such as power, water, natural gas, and industrial gases with increasing consumption. Consequently, energy management standards are being adopted by industries to focus on improving this capability through management systems. Research to date has concentrated on the development of approaches to characterise discrete manufacturing equipment and associated manufacturing states. While this has led to excellent contributions from many researchers, the research completed to date does not give appropriate consideration on how to reduce actual energy consumption of manufacturing equipment or comprehending potential impacts as a result of targeted reductions. This thesis is concerned with understanding how energy optimisation can be undertaken within factory environments. In this context three aspects were investigated: the development of a structured methodology to gather the appropriate data in order to correlate energy saving opportunity, characterisation of the impact of manufacturing process equipments operational behaviour on energy consumption and an examination of risk factors including the appropriate consideration of human factors and the development of risk models.

A structured approach was developed to support an enhanced characterisation of manufacturing process chains. This facilitated a study of Irish industrial energy and resource category usage highlighting the significance of both electricity consumption and production consumption. The sectors which supported the survey were all discrete manufacturing environments and included ICT, bio-medical and pharmaceutical environments. The application of the methodology allowed for the appropriate discrete production equipment to be identified for optimisation and experimentation. A structured problem solving approach was used to identify and evaluate risk factors associated with the implementation of improvements where qualitative workforce input is used to support the risk assessment. An assessment of an organisations capability was created to manage energy improvements in order to minimise risk to core Overall Equipment Effectiveness (OEE) metrics thereby ensuring opportunities are feasible and pragmatic. This supports a deeper understanding of energy use and potential operational impacts due to energy based change

Dedication

To Celma, Aisling, Emer and James. Thank you!

Acknowledgement

This has been without doubt one of the most challenging tasks I have undertaken in my life and it would be wrong not to acknowledge some of the brilliant people of have helped me along this journey.

I would firstly like to thank Dr. Garret O'Donnell for supervising my struggles to take on an initial idea and bringing it through to demonstrating the application of lean energy within industrial settings. Along this path Garret's guidance was crucial to ensuring an academic rigour was applied throughout the research and our countless conversations were a constant source of help in defining a direction for my work.

I would also like to acknowledge the support and teamwork shown to me by the '*Irish Centre for Manufacturing Research*', its C.E.O. Mr. Barry Kennedy for his constant encouragement and support, Barry's ability to present a different view point was always useful. Finally to Dr. Fergus Quilligan and Dr. David Kelly, their patience and ability to answer any questions I had, no matter how daft, was a tremendous help to me understanding and overcoming the many hurdles I had to cross.

Declaration

I hereby declare that this thesis has not been submitted as an exercise for a degree at this or any other University and that it is entirely my own work.

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Signed, Niall Aughney

Niall J Aughney

February 22, 2015

Table of Contents

List of symbols

I_{A1}^{L}	Importance of how likely (L) a change will be detected to the availability metric (A_1)
L_{A1}^{Z1}	Likelihood of a change in metric A_1 if project Z_1 was implemented
A_1	Availability
A_2	Quality
A_3	Cost
AHP	Analytical Hierarchy Process
$B_{1\text{-}3}$	Normalised priorities 1 to 3
C/C	Cassette Chamber
CIRP	College International pour la Recherche en Productique
CO_2PE!	Cooperative Effort on Process Emissions in manufacturing
$Cost\ \Delta$	Difference between normal vs. future state recovery costs (€)
$Cost_{capital}$	System upgrade costs to realise energy efficient future state (€)
$Cost_{recovery}$	Cost of recovery from an energy efficient future state (€)
$Cost_{total}$	Cost over the time from realising an energy efficient future state (€)
CtQ	Critical to Quality
C_v	Molar heat capacity at constant volume ($J \cdot mol^{-1} \cdot K^{-1}$)
D	Detectability
DMAIC	Define, Measure, Analyse, Improve & Control
dQ	Quantity of heat (J)
DSM	Demand Side Management
dT	Temperature change (^{o}K)
$E\ (T1)_{\frac{y}{m}}$	Total yearly metered energy consumption of tool T_1 (€)
$E(T_n)$	Energy consumed by tool n (kWh)
E_c	Current energy consumption (€)
$E_c(T_1)_m$	Current metered energy consumption of tool T_1 (kWh)
EED	Energy Efficiency Directives
E_f	Future energy consumption (€)
$E_f(T_1)_m$	Future metered energy consumption of tool T_1 (kWh)
$E_{f2\text{-}4}(T_1)_m$	Future states 2 to 4 metered energy consumption of tool T_1 (kWh)
E_n	Energy Category
EnMS	Energy Management System
E_{NP}	Non Productive energy consumption (kWh)
E_P	Productive energy consumption (kWh)
EPC	Energy Performance Contract
EREE	Energy, Resource, Efficiency and Effectiveness
$E_{savings}$	Energy savings potential (€)
EU	European Union
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Critical Analysis
FoF	Factories of the Future
GMP	Good Manufacturing Practice

H_A	Alternative hypothesis
HD CVD	High Density Chemical Vapour Deposition
HMI	Human Machine Interface
H_o	Null hypothesis
HVAC	Heating, Ventilation and Air conditioning
i2e2	Innovation for Irelands Energy Efficiency
ICT	Information and Communications Technology
I_{module}	Impact of module project to tool functionality
$I_{operations}$	Impact to operations from module optimisation
IPCC	Intergovernmental Panel on Climate Change
IR_{module}	Integrated Risk measurement of impact of project to production line performance
ISMI	International SEMATECH Manufacturing Initiative
ISO	International Organization for Standardisation
IT	Information Technology
KAP	Knowledge Awareness Prediction
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt hour
L	Likelihood
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
MCB	Miniature Circuit Breaker
MOP	Manufacturing Operating Procedure
MTTF	Mean Time To Fail
N	Total number of time periods (years)
n	The number of times the state was triggered in a time period
n	Moles of gas (mol)
NP	Non Production
NPV	Net Present Value
NSAI	National Standards Authority of Ireland
NVA	Non Value Add
o/s	Operating System
OECD	Organisation for Co-operation and Development
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
P	Production
P/C	Process Chamber
PDCA	Plan-Do-Check-Act
PLC	Programmable Logic Controller
PM	Preventative Maintenance
PSI	Pounds per Square Inch
PV	Present Value
QFD	Quality Function Deployment

$R(t)$	Probability of tool functional performance over time
RF	Radio Frequency
RFC	Response Flow Checklist
RM_{module}	Risk Measurement of tool module functionality
R_n	Resource Category
R_t	Net cash flow at time *t*
S	Severity
s/w	Software
SEAI	Sustainable Energy Authority of Ireland
SEMATECH	Semiconductor Manufacturing Technology
SEMI	Semiconductor Equipment and Materials International
SETAC	Society of Environmental Toxicology and Chemistry
S_n	System level consumer n
SPLOD	Society for the Promotion of Life-cycle Assessment Development
t	Time
T/C	Transfer Chamber
TMP	Turbo Molecular Pump
T_n	Manufacturing tool n
T_{NP}	Non Productive Time (hrs)
UNEP	United Nations Environment Programme
VSM	Value Stream Mapping
w	Importance of weighting category
Z_1	Project 1
Z_2	Project 2
z	Test statistic

1 Introduction

This chapter provides a background and purpose for the research outlined within this manuscript. The continuing and increasing need for energy within manufacturing environments demands it is used efficiently due to the significance of industrial energy consumption with respect to CO_2 emissions. Being at the heart of all manufacturing environments, production system energy demand can play a significant part in this consumption. Characterising the significance of production systems is an area of research where the academic and industrial communities have contributed through the application of both life cycle analysis methodologies and standards development respectively. However, energy characterisation within industrial environments can be challenging due to the variation in energy end use, defining boundaries of study, the compliance obligations that exist in industrial operations and gaining organisational support.

This thesis is focused on developing a deeper understanding of energy use within production systems and the potential impacts that need to be considered to operational compliance when reducing energy consumption. In this context, the subsequent work outlined focuses on developing this understanding within production systems. The methodology developed builds on lean thinking by applying lean principles and tools to energy consumption in particular value stream analysis and 'future state' improvement identification through kaizen workshops. Two use case applications are presented representing varying levels of complexity within discrete tool manufacturing environments. The production systems studied are both installed in legacy factory environments: existing manufacturing sites with financially depreciating infrastructure and annual investment cycles.

Chapter 1 focuses on putting the subsequent work outlined in context in terms of the need to support the ongoing characterisation of process chains. An outline is presented of methodologies used in work completed to date while describing the complexities that exist in industrial environments in terms of energy consumption.

Chapter 2 provides a literature review of the state of the art research completed in the field of energy research relating to production systems and the manufacturing of discrete products. It explores both academic and industrial contributions and how the use of organisational capabilities such as human factor experience, structured problem solving and lean thinking can be leveraged to support energy reduction in production.

Chapter 3 provides an overview of the methodology and the detail needed to develop an understanding of production system energy consumption. The methodology structure focuses on identifying and building the right information sources to support characterisation and experimentation, the flow breaks down into a series of sub tasks or sub flows which in turn use an input-output template approach to data requirements.

Chapter 4 provides a survey relating to energy and resource use in a range of industrial environments in Ireland and the significance of production system energy consumption in these environments. An application of the methodology is also provided which explores how a significant energy user within a biomedical production environment was identified and its energy consumption behaviour was modified for a defined manufacturing state.

Chapter 5 provides a more detailed application of the methodology in terms of considering a significant energy user within a semiconductor production environment and the impact to prioritised operational metrics by four energy efficient states identified through the research completed. The application and potential limitations to the production environment of these states are also explored.

Chapter 6 provides a summary of the work completed in terms of the application of the methodology, the significance of production systems in the environments studied and the need to consider both the risk of implementation and cost implications when researching energy improvements. An outline of future work which could be undertaken as a result of the research outlined is also presented.

1.1 The need for energy and resource characterisation of manufacturing process chains

Industry continues to contribute significantly towards the total value add of the OECD economies, accounting for an average 20.6% of GDP in terms of production and income within these economies [1]. A consequence of this level of industrial activity is a large environmental burden. Within the European Union, industrial CO_2 emissions as a direct consequence of this activity accounts for 22.3% of the regions emissions [2]. Due to this awareness, the industrial impact on the environment is increasingly being critically considered within manufacturing as part of the industrial sector. Manufacturing industry directly emits CO_2 through the combustion of fossil fuels within their factory environments and indirectly through the consumption of electricity. Figure 1.1 highlights this in terms of category, final energy consumption by industry within the EU-27 [3] and EU industrial final energy demand predictions for 2030 and beyond [4].

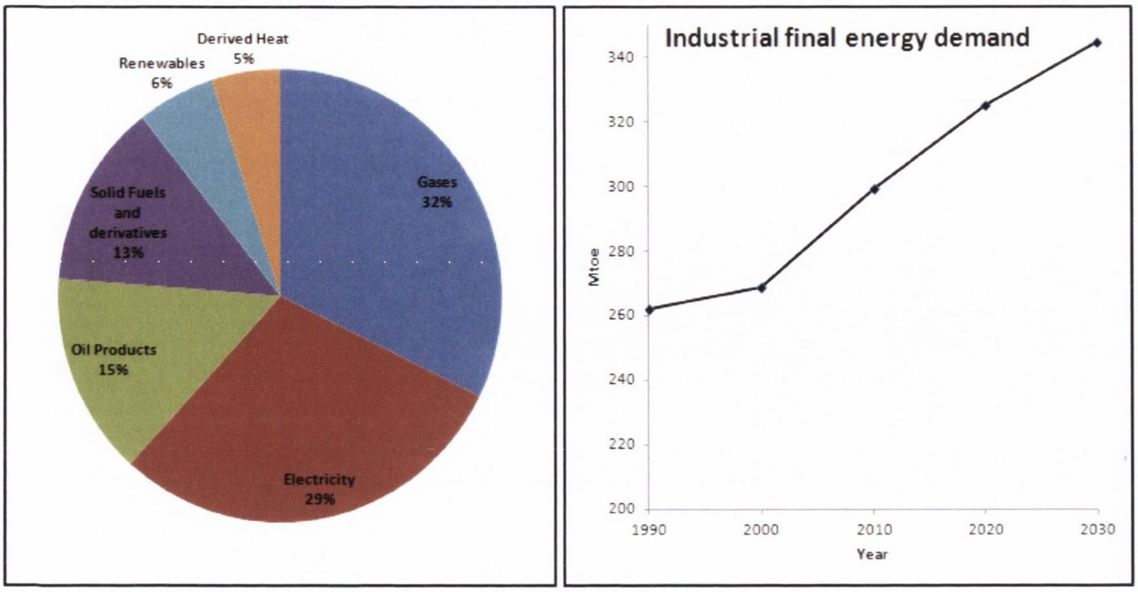


Figure 1.1 – EU-27 Final energy consumption in industry (Mtoe) [3] and projections [4]

It can be seen from this data that the anticipated increased demand over the next 20 years for energy within the industrial sector. This will necessitate a continued focus on characterisation and understanding of all aspects of energy use within industrial environments with a view to ensuring efficient usage.

1.2 Inventory analysis

Life cycle analysis as a method for characterising and understanding the environmental impact of a material, product or service throughout its entire life cycle has been significant in terms of setting direction for more sustainable manufacturing practices [5]. These directions include an increased focus on life cycle design in terms of environmental considerations [6] and the development of a more holistic understanding to the overall cost of products throughout their life cycles [5]. Both industry and practitioners now have a range of methodologies to support impact assessments of products [7]. This ongoing impactful academic support has led to the adoption of LCA as a standard by the International Organisation for Standardisation [8].

Despite the extensive work ongoing in the field of life cycle analysis, there are varying degrees of implementation of life cycle approaches at a tactical level within manufacturing facilities. Kellens et al [9] presented a methodology, with industry application to machine tool use phase in manufacturing unit processes within the boundaries shown in Figure 1.2 to address this gap. This has the potential to improve life cycle inventory understanding for unit processes.

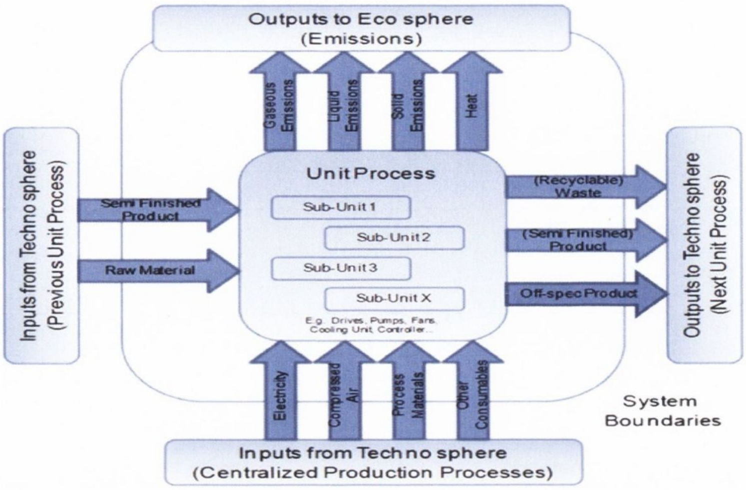


Figure 1.2 – System boundaries of a unit process [10]

It can be seen from this figure that there are many inputs into this system, specifically when considering the unit process from both energy and resource input point of view. This highlights a high degree of complexity which must be faced in terms of characterisation of unit processes.

1.3 Trends and initiatives

It is notable in the last 5 years through initiatives such as CO_2PE [10] and the CIRP collaborative working group on Energy and Resource Efficiency and Effectiveness [11] that tangible examples of life cycle approaches are being published further indicating the interest of companies in this field.

The control and improvement of cost performance such as energy and resource consumption is a key strategy, which companies focus on in order to deliver ongoing improved competitiveness [12, 13]. This is particularly challenging for manufacturing based companies who are adding manufacturing capability to legacy sites within their manufacturing network. Consequentially, many companies choose a strategy of early design adoption when possible and upgrading improvements to deliver efficiencies in these legacy industrial sites [14].

Historically within manufacturing organisations, energy and facility managers have been targeted to facilitate energy reductions in building environments [15] challenging both the role itself and management commitment. As consumer products have become more complex, production line complexity has increased as a result. This complexity has resulted in manufacturing process chains and equipment which demand more energy and resource categories [16] such as power, water, natural gas and industrial gases which is reflected in Figure 1.3.

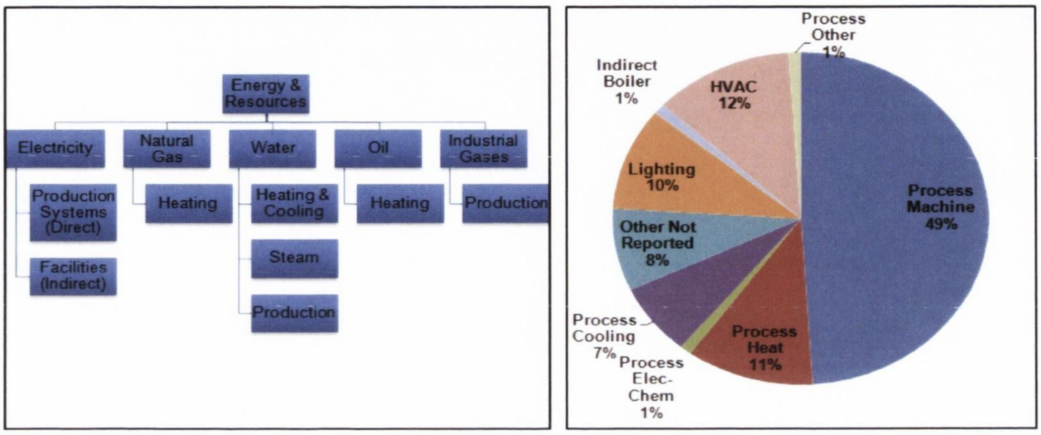


Figure 1.3 – Manufacturing end-use energy and resource categories breakdown of electric consumption [17]

This can result in manufacturing process chains and equipment within a modern factory consuming up to 50% of a factory's energy bill [18]. As a consequence, this highlights the need for further characterisation of energy use within factory settings to increase the understanding of performance and improvement identification. Figure 1.4 illustrates from a national perspective, current energy use within the Irish industrial network [19].

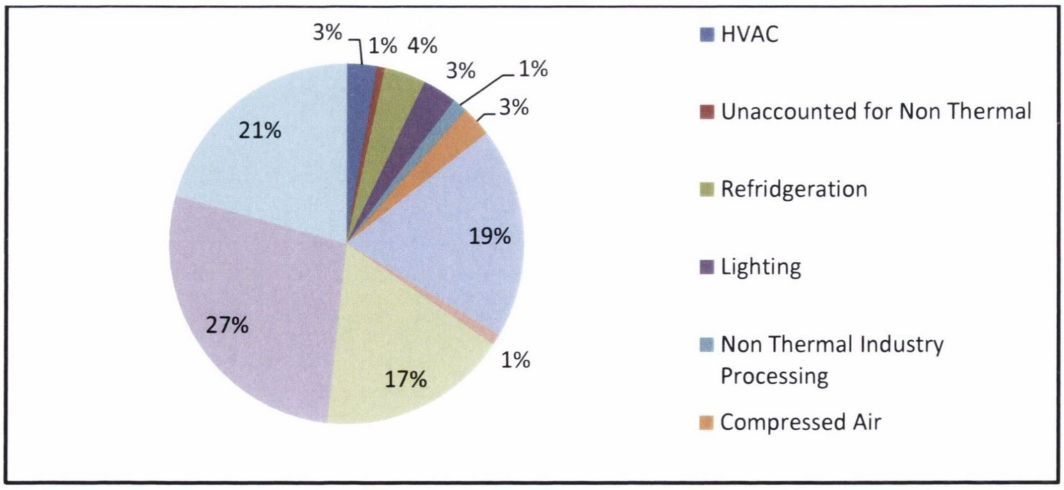


Figure 1.4 – Break out of energy usage categories within industrial network adapted from the SEAI [19]

It can be seen from the figure that the evidence base is generally at a macro level initially when life cycle, energy and resource metrics are examined. Leading authors in the field such as Duflou et al [12], Hermann et al [20], Selinger [21] and Kara [22] promote the examination of all levels of the manufacturing system including unit process, multimachine systems, facility level, multifactory networks and the global supply chain [23]. More recently however the leaders in this field are recognising that there is merit in developing methodologies for the characterisation of manufacturing process chains at an in-depth level in order to determine the energy input for units produced. This will empower and facilitate change at a more local level within a manufacturing enterprise [12].

1.4 Research objectives

This research is concerned with characterising energy consumption, related risk and cost benefit opportunities in manufacturing process chains within legacy factories involved in discrete manufacturing. Two aspects were investigated, first is the development of a methodology to enable a structured examination of energy and resource consumption in a factory, and secondly the quantification of energy saving opportunity, risk and cost benefit.
The aims of this research are:

- To develop a structured methodology to gather the appropriate data in order to correlate energy saving opportunity, risk and cost benefit.
- To characterise the impact of manufacturing process equipments operational behaviour on energy consumption.
- To examine risk factors including appropriate consideration of human factors and to develop risk models.
- To develop cost benefit models using risk and energy saving data.

The manufacturing environments which are investigated within this research to support these aims are based in the Information and Communication Technology (ICT) sector, specifically semiconductor manufacturing and the medical device sector, specifically orthopaedic implant manufacturing which utilise manufacturing chains which consist of discrete part manufacturing. This characterisation of energy will allow both productive and non productive manufacturing states to be understood in terms of targeted discrete equipment's energy consumption, optimisation of energy consumption and an implementation process to allow optimisation.
The second major component of the research will involve an investigation of the factors which can affect decision making in terms of implementing energy optimisation solutions

identified using the methodology developed in manufacturing process chains. In this regard, risk information is collated, examined and assessed, and correlated with cost benefit elements that also inform decision making. The methodology proposed provides a structure for the examination of energy saving in operational discrete manufacturing enterprises.

2 Literature review

The field of energy research is extensive and has resulted in many valuable contributions from a range of sources. The purpose of this chapter was to review contributions from both the academic and industrial communities which have improved the understanding of sustainable manufacturing. Themes explored include production system energy consumption, energy focus within industrial environments and the application of methodologies such as lean and life cycle analysis. A review of how human factor experience can be leveraged to improve organisational performance is also considered and how a structured problem solving approach such as an analytical hierarchy process can be used to breakdown problem statements into a range of criteria which can lead to alternative solutions. Through this review a perspective is gained into how the development of a methodology which characterises risk and impact in terms of energy optimisation in production systems was realised.

2.1 The need for sustainability

The impact (I) of human activity on the environment can be described in terms of population (P), affluence (A) or average consumption of each person and technology (T) or how resource intensive the production of affluence for example goods and services [24] as shown in equation 1:

$$I=P.A.T \qquad (1)$$

There has been a historical viewpoint that if population and industrial expansion continue their exponential growth trends in light of a world with finite natural resources, economic expansion and prosperity will slow [25]. As manufacturing also uses natural resources, this poses a challenge to manufacturing based industries, in terms of limiting capacity to manufacture products. This viewpoint is still believed to be valid despite the predictions originally expressed of slower growth not being realised exactly as expected [26]. Even if an improved understanding of the variables which consume natural resources takes place, the fact remains, in terms of the world population, there will be a 25% increase over the next 40 years as shown in Figure 2.1.

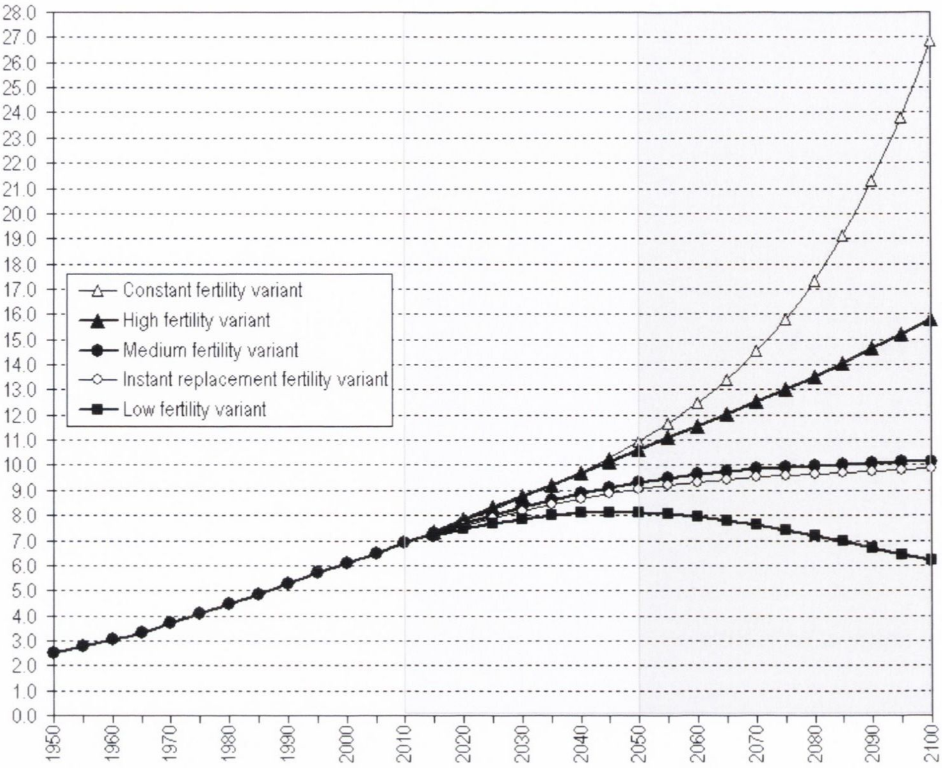


Figure 2.1 – Population of the World, 1950-2050, according to different projections [27]

With this increased population and affluence, there will be an anticipated increased demand for energy in the order of 40% as shown in Figure 2.2 [28, 29]. This increase will be primarily driven by non-OECD consumption with only marginal increased demand by OECD countries expected. This highlights the differences between saturated markets and growing markets and shows in a very stark way the urgency required to develop and proliferate environmentally benign power generation technologies as well as energy efficient consumption technologies which can influence T in equation 1. Production and consumption of products may follow a similar trend, as a result 'there may be a growing volume of industrial manufactured products and the consumption of natural resources as well as environmental impacts', as stated by Westkämper et al [30]. This is because it is widely anticipated that the growing world population will fuel a growing middle class consumer market [31].

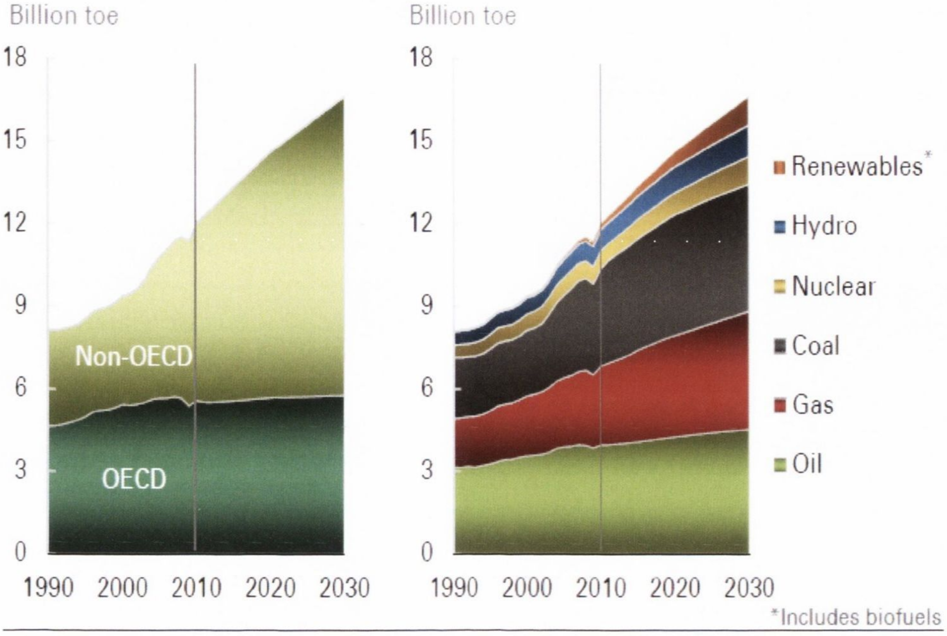


Figure 2.2 – BP Energy Outlook 2030 [28]

As world energy generation is heavily dependent on fossil fuel supply, this will have a knock on effect to emissions: in particular green house gas emissions as shown in Figure 2.3.

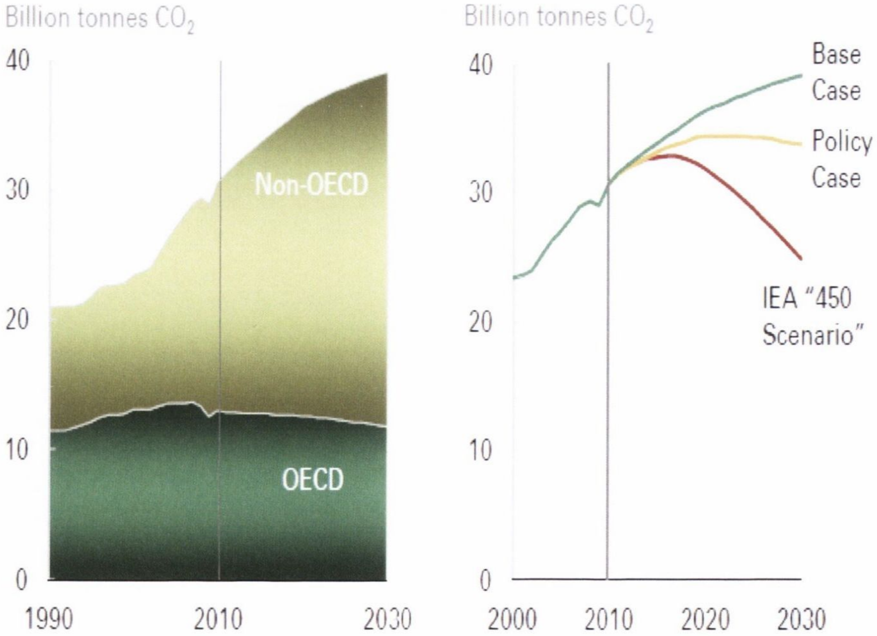


Figure 2.3 – Global CO_2 from energy use and '450 Scenario' [28]

From an environmental impact point of view this is challenging in that under both the Kyoto Protocol [32] and the '450 Scenario' [33] binding emissions targets are being enforced which incur penalties if breached.

From a business perspective, since energy supply is heavily fossil fuel dependant, the pricing of the raw materials used to generate energy for example coal, oil and natural gas also have a direct impact on business performance with high prices impacting industry competitiveness [34]. It is this high price scenario which the world currently finds itself in and expects to be in going forward, as shown in figure 2.4.

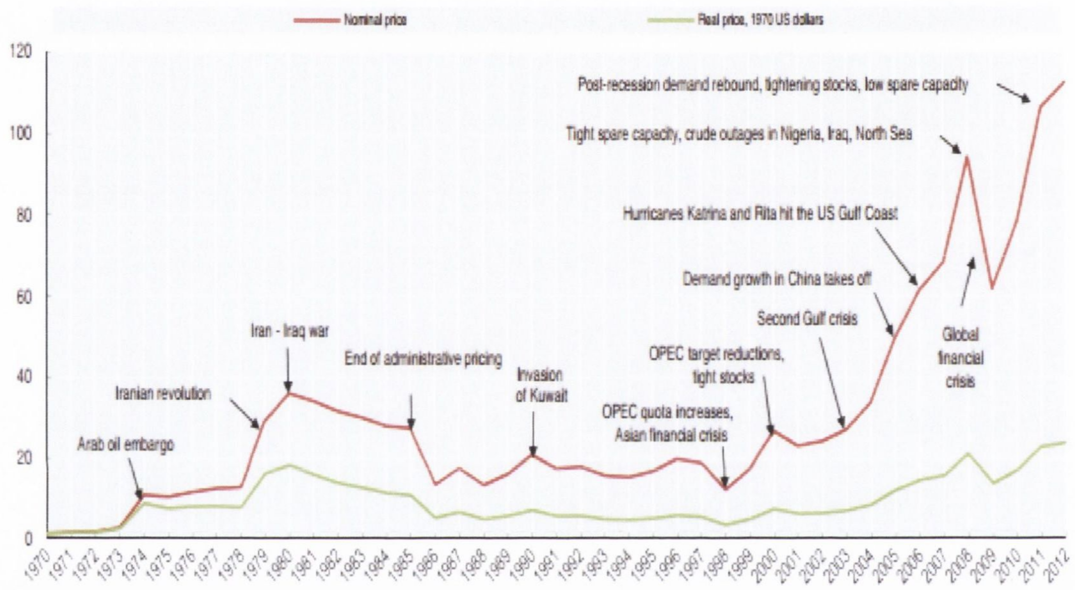


Figure 2.4 – Historical Crude Oil Prices ($/Barrel) [34]

These concerns do not change when looked at from either a regional or an individual country perspective within the OECD. Taking Ireland as an example, recent government based analysis have highlighted similar challenges from an energy perspective for the Irish economy in terms of energy outlook and emissions challenges [35]. However, in an Irish context, this translates into a more challenging business environment in terms of energy pricing compared to the EU average, as shown in figure 2.5. This is primarily due to the heavy dependency on external supply.

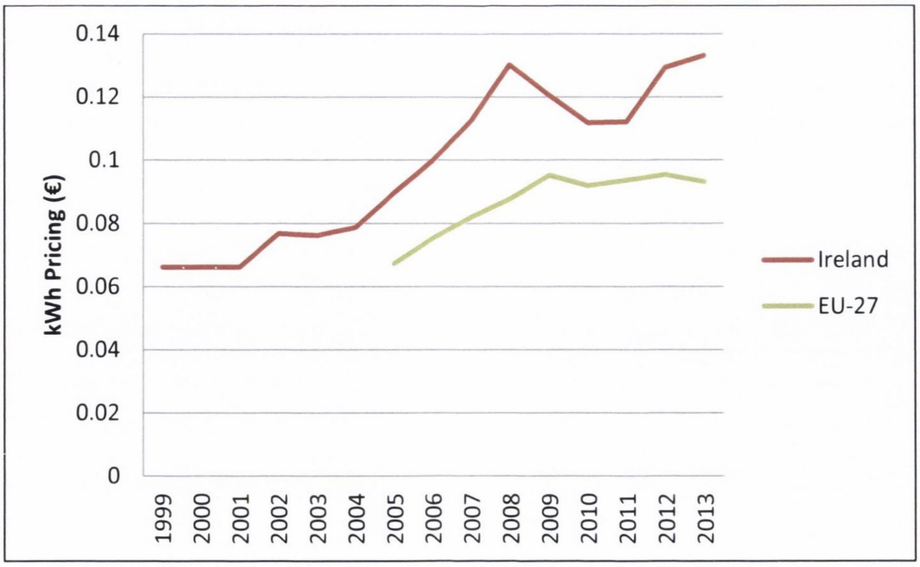


Fig. 2.5 - Comparison of historical Industrial kWh pricing for Ireland vs. EU 27 [36]

It does highlight for economies such as Ireland that in this 'high oil price' business environment any energy efficiencies or energy efficient technology installation that can be achieved will have a quicker return on investment, as highlighted by the analysis undertaken by McKinsey & Co for the Sustainable Energy Authority of Ireland [37]. This supports the view that 'energy use and output are tightly coupled with energy availability playing a key role in enabling growth' as proposed by Stern [38]. This has implications not only for small economies such as Ireland but also larger economies such as China [39] in terms of energy being a limiting factor to output growth.

As a result, from an industrial perspective, both globally and within regional economies companies which optimise natural resource use in line with the Brundtland commission's definition of sustainable development, to 'meet the needs of the present without compromising the ability of future generations to meet their own needs' [40] will move to a more sustainable manufacturing footing. This is favourable from an environmental and competitive perspective as it can only enhance competitiveness through manufacturing more energy efficiently.

This has been a motivational factor in the development of product life cycle knowledge and how design can be used to reduce the environmental impact of products [41, 42]. It has been developed beyond just design, to the entire life cycle, from production to distribution to usage and ultimately disposal [43]. This approach advocates a better use of life cycle knowledge to support a movement away from a limitless mass production and consequently mass waste settings to one where production volumes can be reduced and compensated for by enhanced quality, longer product lifetime and reuse options [44]. This development highlights the benefits associated with a more integrated approach which includes life cycle planning as part of the process in developing more sustainable practices [45] among manufacturing firms.

2.2 Sustainable manufacturing

A competitive and more sustainable manufacturing capability within organisations can facilitate improvements to the environmental impact of industry. As proposed by Jovane et al [46] where he argues that industry needs to focus on improving the competitive advantages of products by using knowledge based improvements to product sustainability. The challenge of delivering new, more sustainable service delivery or manufacturing performance requires not only a deep understanding of product life cycle analysis to set direction but also adaptable and learning factories [47] which are capable of continuous improvement.

The monitoring and control of factories through measurement and the development of more integrated metrics, in particular cost which energy is currently factored into by organisations is becoming more prevalent [48] as industries strive to understand new opportunities for improvement. Improvement should be seen as a key indicator which reflects a factory or organisations ability to evolve and innovate as suggested by Boer et al [49]. Facilitating this improvement in monitoring and innovation, automation is seen as a key driver in developing a competitive and sustainable manufacturing industry [50]. It is with an increased integration of automation and control in manufacturing that products manufactured can incorporate increasing complexity in line with customer expectations. Within the healthcare industry [51], this has been supported through adaptable and intelligent factory settings. It is through this recognition of the need to adapt that flexibility and changeability will be delivered within all types of manufacturing organisations [52].

Through this automated approach, an overall infrastructure can be developed to monitor and ultimately model energy performance within factory settings for example energy flows. Current energy management tools provide a high level overview of energy consumption within manufacturing systems which present challenges to breakdown energy consumption among process, workstations and production zone settings [53]. This is particularly true with respect to legacy factories as highlighted by Aughney et al [54]. If energy monitoring is not considered at the initial stages of design, the level of automation required is generally not in place and must be retrospectively installed. This can be cost prohibitive or at the very least an infrastructural challenge. This reflects historical factory facility priorities being placed on improving service, building extra manufacturing capacity for operations and increasing output performance rather than focusing on energy efficiencies [55]. A consequence of this approach is factories can often be oversized and consume significantly more energy than required. Figure 2.6 highlights an example of where over sizing can occur where 12 ISO class 5 clean rooms were audited for clean room air change rates. The variation in air change rates for the same cleanliness level highlights the optimisation opportunity available on many energy intensive factory parameters in spite of conventional wisdom.

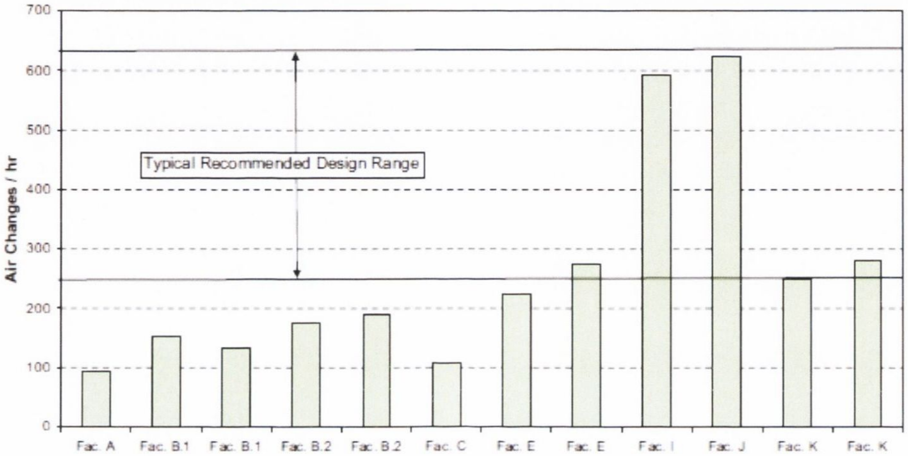


Figure 2.6 – Air rate variation for the same cleanliness specification [55]

Consequentially, early consideration of energy monitoring even at a high level, can lead to significant economic impacts on building and facility management. This can be reflected in terms of cost improvements such as economic optimisation, energy reduction through fuel optimisation and reduced environmental impact through pollutant optimisation improvements [56] as suggested by Andreassi et al.

This work to improve the understanding of energy consumption within factory settings should be facilitated as it enhances an overall understanding of life cycle management. In particular life cycle costing would benefit as a more thorough understanding of the real cost of manufacturing and would enhance the overall understanding of the impact of manufacturing within the life cycle. This view has been highlighted by Westkämper et al [30], as shown in Figure 2.7 who argues for more cost characterisation beyond the concept and design stages of Life Cycle Management (LCM). As energy and resource input into manufacturing is significant this increased focus will allow a more detailed understanding of the true cost of products, from concept to reuse.

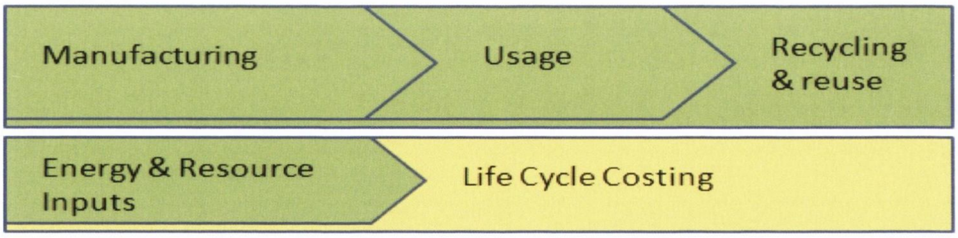


Figure 2.7 – Where further costing analysis is needed within life cycle costings adopted from Westkämper et al [30]

This would compliment work already being undertaken to understand the embodied energy of products throughout their lifecycle. Simulation work to model all relevant energy flows of factories to identify and select improvement measures for example batching, supply chain optimisation or energy delivery has been demonstrated by Herrmann et al [57]. An additional impact of using simulation for design improvements has been to develop an integrated approach linking building design and sustainable processes to ensure optimisation at the earliest opportunity as shown by Levers et al [58]. A further benefit of this approach is to understand the effects of globalisation. It has shown how manufacturing location and associated logistics can significantly impact a products embodied energy [59]. For a modern economy such as Britain's, imports have effectively doubled its carbon foot print from 11 tCO_2 to 21 tCO_2 per person highlighting the impact of manufacturing location [60]. This supports the concerns highlighted by I.T. Herrmann et al [61] that there can be a 10 fold difference between embedded and avoided emissions depending of the region used to manufacture compared to the region the product is sold. Through this understanding, indicators can be developed which identify environmental performance indicators for all the stages within a products lifecycle [62] and as a result, identify critical design parameters which can lead to an improvement in or the identification of optimal lifetime [63] of products.

2.3 Sustainability in discrete manufacturing process chains

Over the lifetime of a piece of discrete manufacturing equipment, the capital cost is generally less than 20% of its total cost of operation with the majority of the cost being maintenance and energy consumption. Simulation work completed by Herrmann et al [20] has highlighted the influence of production management on energy consumption. These points highlight an evolving realisation that within factory settings: the production discipline within these factory settings can have a significant influence on overall energy consumption. This conclusion is in broad agreement with subsequent work completed by Herrmann et al [64] in highlighting the 'significant influence on costs within the use phase depending on the use pattern' in terms of reliability and energy consumption within factories. Reflecting a business need to gain maximum benefit from an asset base to offset against fixed costs. This highlights an opportunity to research factory energy consumption in a greater level of detail than is normally considered. A further reinforcement of this position has been made by Duflou et al [65] who postulated 'compared to the material consumption, the energy and resource consumption and related environmental impact, of the manufacturing stage of products is not negligible as often assumed in LCA studies'. Despiesse et al [66] further support this view of understanding in more detail the impact of manufacturing. He suggests by 'focusing on the factory, it is necessary to capture the energy and material networks that link the manufacturing systems components, namely production, facility and production systems'. This reflects an ongoing need for further comprehension of the manufacturing impact on sustainable manufacturing.

The challenge in understanding manufacturing energy and resource consumption performance at a deeper level requires an ability to understand production equipment. This is supported by Herrmann et al [67] who have argued for a deeper understanding of single processes and interdependencies within process chains to support prediction of consumption patterns. Energy consumption within manufacturing process chains requires a deep understanding of individual equipment configurations. In particular overall system and internal system component function as well as other potential influences such as environmental conditions like temperature, supply voltage and current or humidity [68] and how it is utilised within the targeted equipment. It is a requirement for users to understand possible optimisation measures, opportunities to influence user behaviour or equipment modifications. All of these considerations will support identifying an optimal energy profile while allowing a production machine to perform its primary function. The goal is to ensure functionality with optimal energy consumption. This approach is of fundamental importance because energy is only one consideration within a production environment, as shown in Figure 2.8.

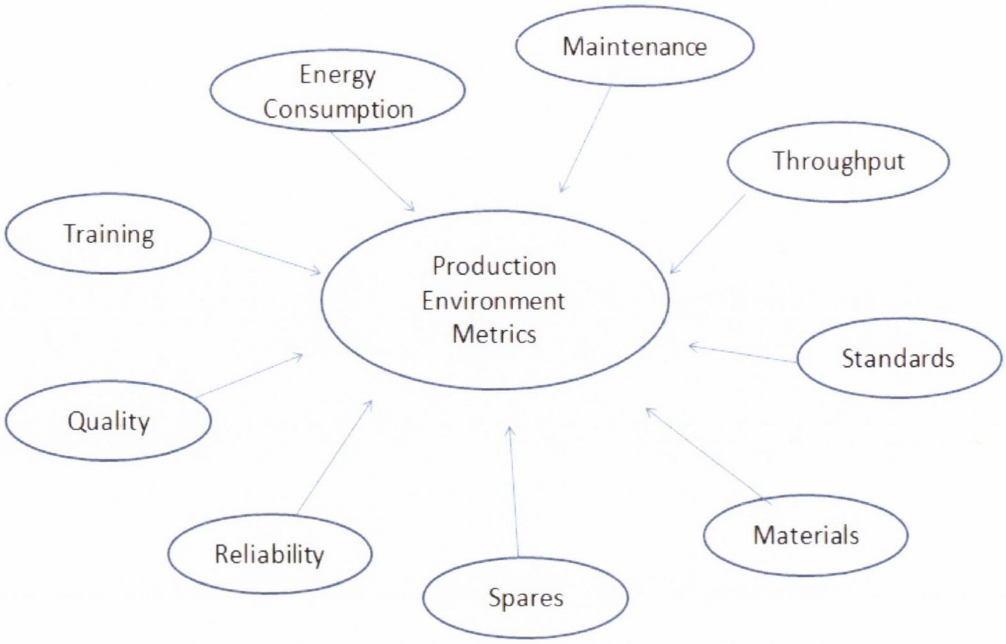


Figure 2.8 – Energy optimisation and other operational metrics, adopted from Bardouille et al [69]

There is evidence that a more detailed understanding of how energy is consumed in production equipment performance is taking place, most notably through modes of operation for example running, idle, productive and non-productive states as highlighted by Devoldere et al [70]. This work has highlighted the potential for energy consumption reduction for non-production modes. It is noted that there can exist a relatively small difference observed in energy consumption between productive or value added states and non productive or non-value added manufacturing states in discrete production equipment. The relevance and opportunity of this approach to manufacturing based companies has been highlighted by Gutowski et al [16], as shown in figure 2.9. This correlation not only shows the electricity consumption needs by different industry equipment types but also highlights a challenge to manufacturing based industries in terms of product complexity. Gutowski's contribution has highlighted a potential link between product complexity and higher energy consumption within manufacturing production equipment within these environments. This can potentially impact on business cost performance depending on the product portfolio being developed due to the energy inputs required for manufacturing facilities.

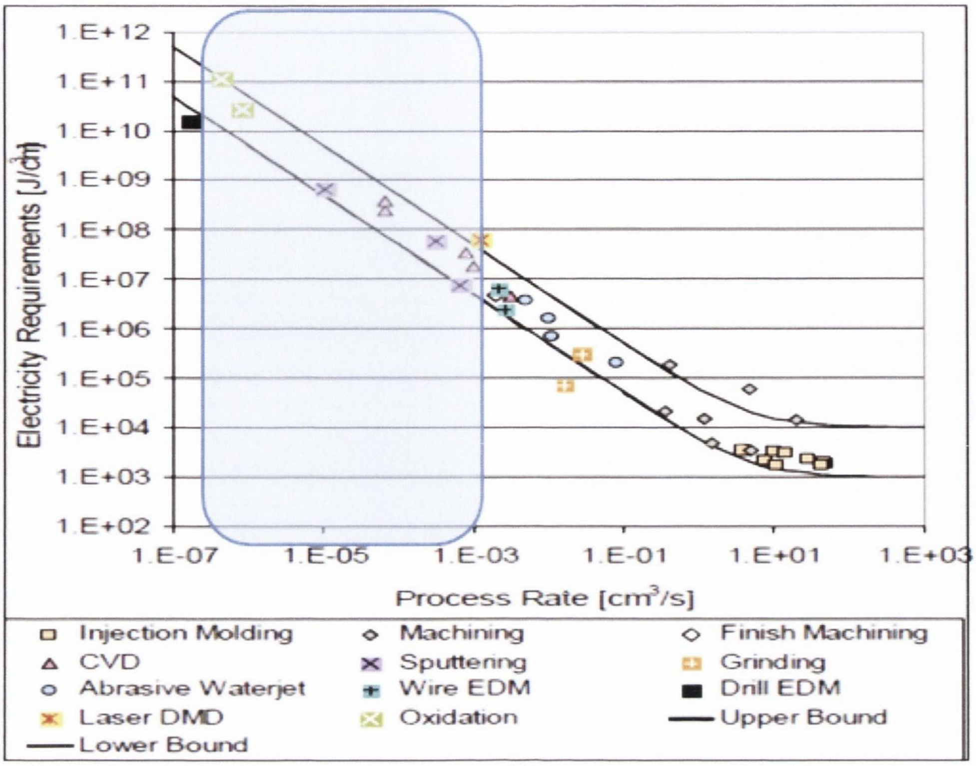


Figure 2.9 – Electricity consumption for various manufacturing processes as a function of process rate adopted from Gutowski et al [16]

2.4 Industry sectors and energy focus

It can be seen from figure 2.9 that a significant number of the individual production systems sampled for the Gutowski study were in the semiconductor industry. The semiconductor fabrication process can account for up to 80% of the CO_2 emissions related to the supply chain and production of a chip [71]. This highlights where significant opportunity for potential energy efficiency improvements may lie. It also reflects a growing trend in product complexity which has led to a 47% increase in electricity use in the semiconductor industry in the United States alone [72] from 8.37 billion kWh in 1995 to 12.31 billion kWh in 2005. The International SEMATECH Manufacturing Initiative (ISMI) [73] has been a key driver for the industry to understand its contribution to climate change and take proactive measures to reduce its overall production costs through leading industry wide activities. Part of this program has focused on understanding energy consumption in semiconductor facilities, as shown in Figure 2.10. The organisation has driven the development of standards in energy data collection [74, 75]. This has resulted in the industry accepted standard SEMI S23 being adopted by both semiconductor manufacturers and Original Equipment Manufacturers

(OEM). This standard supports overall energy conservation within semiconductor manufacturing through guidelines on how to approach measurement, continuous improvement and awareness of energy for SEMATECH members [76, 77]. The organisation advocates and supports energy use characterisation within member companies to identify appropriate utility reduction projects across all utilities consumed within the industry, through characterisation of both utility consumption at production level such as ultra-pure water, power, gas and equipment utilisation levels for example running and idle states [78-85].

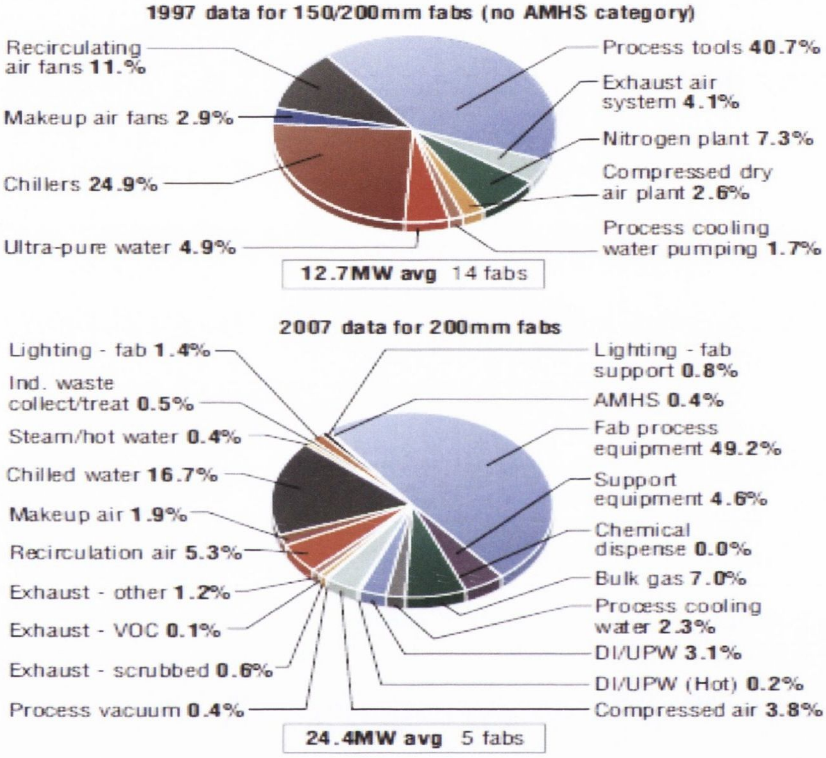


Figure 2.10 – Energy use by system based on fab wide characterisation studies in 1997 and 2007 [86]

The significance of process equipment utility consumption becomes apparent in that energy consumption can vary from 40% to 50% of the total power used by an IC manufacturing fabrication facility. This has led to process equipment energy consumption studies to determine power allocations on a process tool and process tool component level, as shown in figure 2.11. This has shown that up to 70% to 90% of equipment power is used for heating and vacuum pumps, depending on the application. It was observed that consumption levels did not significantly change during idle and processing operating modes. Although this has driven equipment suppliers to investigate reductions in energy consumption during idle states, it has been limited due to the potential process and production impact concerns.

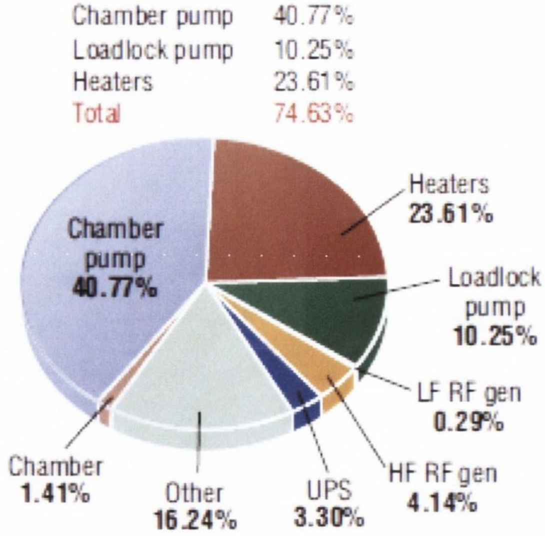


Figure 2.11 – Process equipment energy use at a component level [86]

This is leading to the development of environmentally benign manufacturing strategies, particularly in both Japan and Europe [87]. This view point is allowing companies to highlight the environmental advantages of their products and processes, allowing them to potentially enhance their competitive position within the market through highlighting how the energy characterisation of their business operations is allowing them to reduce the impact of their businesses.

2.5 Lean methods

The application of lean methodologies to support this understanding is also becoming evident. Historically, these methodologies have been used extensively within industries to improve productivity and supply chain logistics. Their widespread use within industry reflects their applicability to many types of problems: optimal sizing of systems with respect to the customer [88], the impact of value stream mapping in understanding value in terms of the customer [89] and Toyota's 'Just in Time' concept of delivering exactly what the production line needs when it is needed [90]. Building on these methods, energy value stream mapping has facilitated measurement and reduction of CO_2 emissions in manufacturing [91] with energy orientated simulation being applied to understand application opportunities [57]. This has allowed characterision of manufacturing operations with the view to reducing energy consumption within their manufacturing process chains. An example of energy measurements for machining operations is shown in figure 2.12. This highlights, as shown with the previous semiconductor example, the significant use of energy when the machine is idling. It also highlights the relatively small percentage difference that can potentially exist between a running and idle state on production equipment.

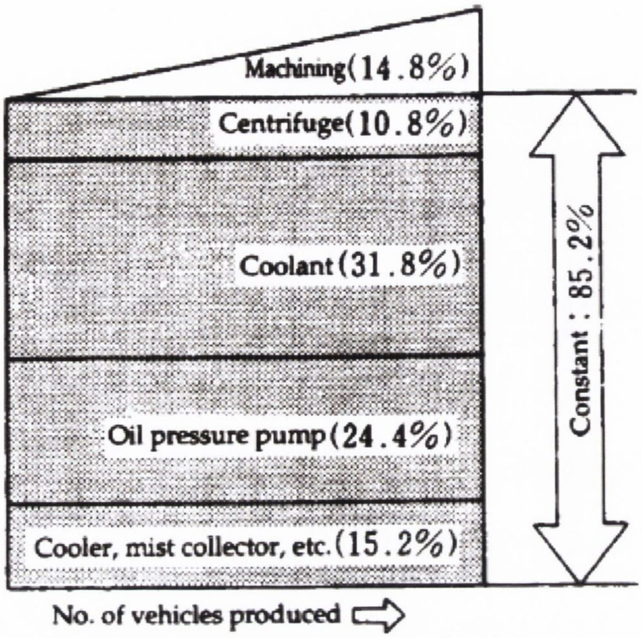
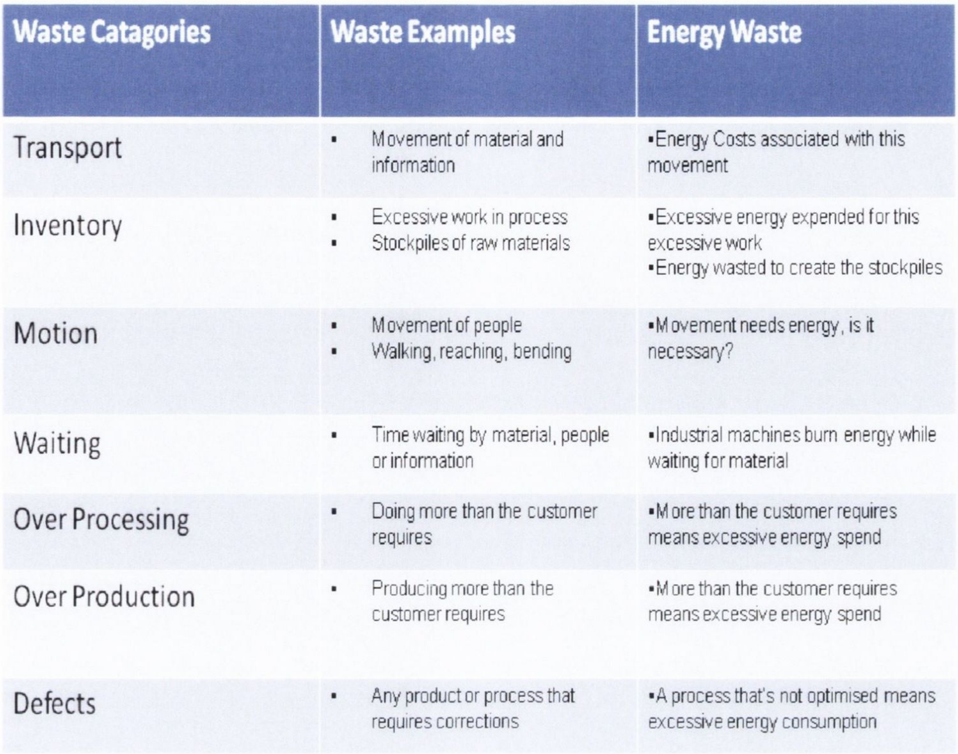


Figure 2.12 – Energy use for machining [16]

There have been ongoing efforts at government department level to encourage the proliferation of lean techniques to improve energy efficiencies within industrial settings [92]. Within these programs, the workforce is encouraged to put an energy perspective on lean categories [93] using techniques such as kanban implementation and Value Stream Mapping (VSM). Both of which are proven tools used to enhance both Overall Equipment Effectiveness (OEE) and supply chain management. This approach can be used in support of identifying significant energy users in ISO 16001/50001 preparation work and factory based energy efficiency programs [94, 95]. The intent of industry practitioners using a lean methodology is to actively engage their workforce in identifying waste opportunities and solutions and ensuring participation as highlighted in figure 2.13. The utilisation of lean methodologies has also been demonstrated in monitoring overall factory level energy performance and identifying non-value added activities. This has been highlighted by Kissock et al who demonstrated using a lean energy analysis methodology to statistically analyse plant energy data can highlight improvement opportunities of up to 11% [96]. With the lean approach supporting environmental improvements at a production cell level [97] as well as supply chain improvements [98].



Waste Catagories	Waste Examples	Energy Waste
Transport	- Movement of material and information	•Energy Costs associated with this movement
Inventory	- Excessive work in process - Stockpiles of raw materials	•Excessive energy expended for this excessive work •Energy wasted to create the stockpiles
Motion	- Movement of people - Walking, reaching, bending	•Movement needs energy, is it necessary?
Waiting	- Time waiting by material, people or information	•Industrial machines burn energy while waiting for material
Over Processing	- Doing more than the customer requires	•More than the customer requires means excessive energy spend
Over Production	- Producing more than the customer requires	•More than the customer requires means excessive energy spend
Defects	- Any product or process that requires corrections	•A process that's not optimised means excessive energy consumption

Figure 2.13 – TIMWOOD model adopted in support of energy reduction [88]

In summary, energy efficiency investigations are evolving within a factory context to investigating production environments, manufacturing process chains and characterising energy consumption based on productive states. This is challenging factories to realistically assess their metering strategies and capabilities, as highlighted by Kara et al [22] who have outlined a structured metering approach at a unit process level. To further develop on this approach, it will be necessary to engage sections of the workforce who have expert knowledge of production equipment behaviour and performance. Steinhilper et al [18] have shown that combining these approaches in a formal decision support structure can deliver a framework which allows energy optimisation opportunities to be identified with manufacturing environments.

2.6 Workforce involvement in decision making

Managing energy is still a relatively young discipline and many companies can find it difficult to develop meaningful metrics. This is primarily because energy consumption is a function of load and can be product dependant within manufacturing environments. However, employee engagement in improving energy efficiency can have an immediate impact, of up to 10%, as shown in Figure 2.14 [99]. The closer this engagement happens with actual manufacturing personnel within organisations, the greater the potential. This approach recognises the collective knowledge and experience available on the factory floor and the detailed knowledge obtained over time which can be utilised for improvements [90].

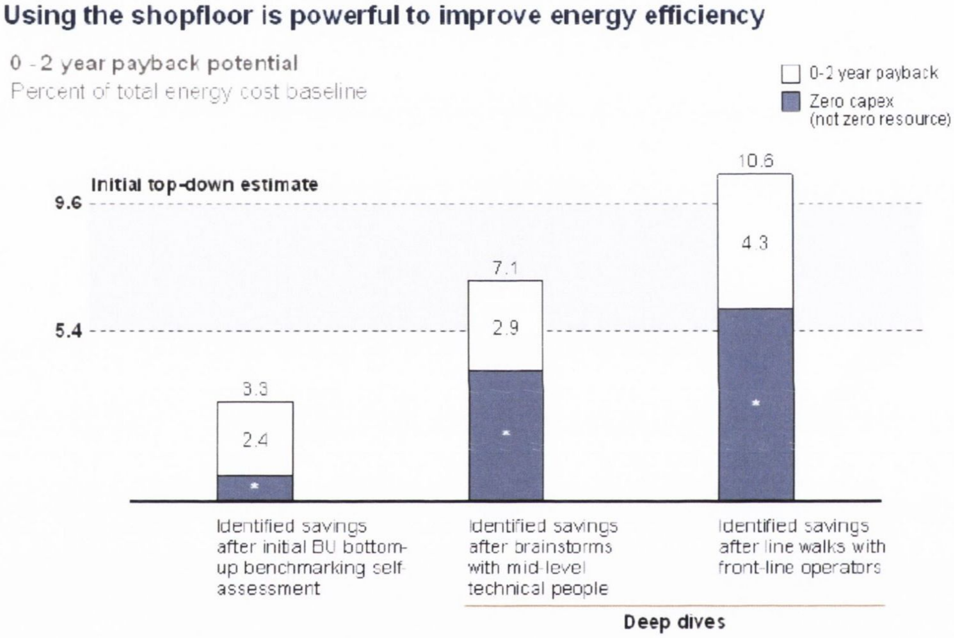


Figure 2.14 – Percentage impact of engaging personnel at various levels within an organisation [99]

This is recognition of their experience and a team based approach that is used within industrial environments for operational improvement. Lean tools such as the hoshin kanri or policy deployment process [89] are widely adapted to various levels across many lean focused industries where employee feedback is actively sought by management with respect to predefined priorities or identifying priorities. This use of employee input can also be facilitated through the Quality Function Deployment (QFD) technique which matches customer and technical requirements to design priorities, as shown in Figure 2.15. Employee knowledge of manufacturing processes and tools can be leveraged to identify improvements to support energy efficiencies. Through their experience, the QFD matrix can be used to capture operational and tool requirements ensuring workforce knowledge is captured. This data can then be used to correlate against the technical requirements needed for energy reduction. It is an effective tool in capturing downstream customer and design requirements [100, 101]. Value Stream Mapping, when extended into energy performance understanding, can be developed into an extended energy value stream which using workforce interaction provides a systematic approach to finding and evaluating measures to reduce energy and CO_2 emissions [91].

These approaches are effective at inputting improvements such as productivity or design improvements as an attribute into an organisation. These processes take advantage of a workers ability to apply a judgement based on their experience and make a subsequent decision. This ability to apply judgement and decide on priorities reflects Saaty's belief that 'decision-making by structuring our thoughts and by asking the right questions to deepen and broaden our insights so we do it consciously, carefully and clearly. Decision making requires prioritisation' [102].

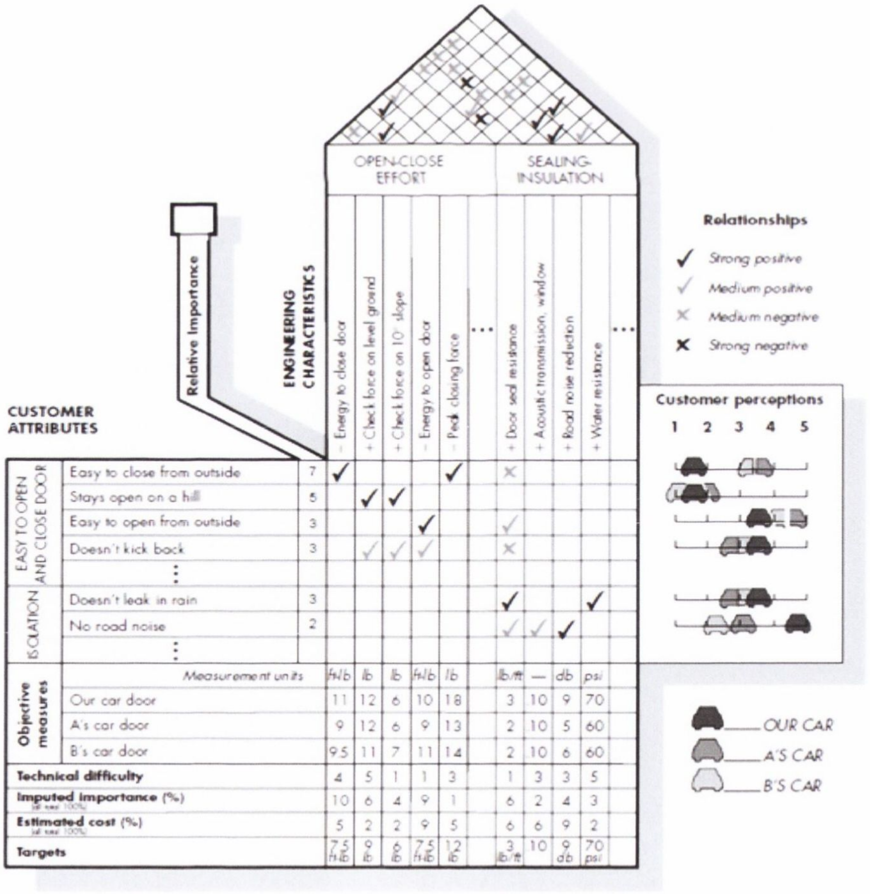


Figure 2.15 – Example highlighting the QFD approach [103]

Workforce judgment and decision making ability has application within production environments where multiple priorities exist. It is this basis that facilitates the use of an Analytical Hierarchy Process (AHP) where a problem is structured as a hierarchy, broken down and aggregating the solutions of all the sub problems into a conclusion, graphically shown in figure 2.16. The approach used [104] focuses on the goal of solving the problem through the creation of a problem statement for example a production tool based energy change. It relies on the workforce involved knowing enough about the problem that requires a solution to develop a complete structure of relations and influences. Workforce input into criteria and sub criteria identification can allow at a tool level the identification of success criteria which must be met while improving tool energy efficiency for example equivalency in availability, quality and cost KPI's. It requires the workforce having enough knowledge and experience or access to others who do, to assess the priority of influence and dominance (importance, preference or likelihood to the goal as appropriate) among the relations within the structure. Workforce input can then be utilised to provide solutions or alternatives to improving tool energy efficiency performance.

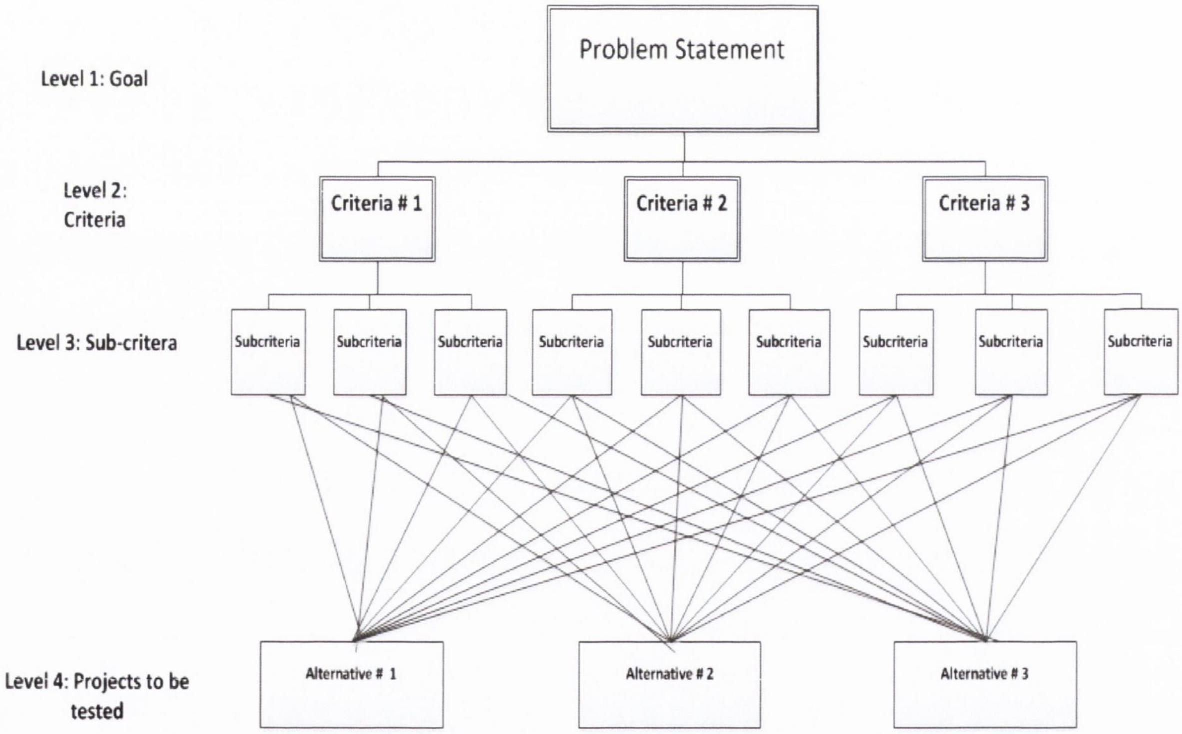


Figure 2.16 – Hierarchy structure used to breakdown a problem statement into criteria adopted from Saaty [104]

Finally it allows compromise where some differences of opinion or data may develop on how to resolve the problem statement. This highlights where differing views and data can be used to obtain a solution agreeable to different areas or business units within factories who value known process indicators differently.

The principles which guide problem solving using AHP are decomposition, comparative or pair wise judgements and synthesis of priorities [105]. Decomposition involves structuring a problem with the elements or criteria in a level being independent from those in succeeding elements. In using comparative judgements, pair wise comparisons of the relative importance of elements within a given level with respect to a shared criterion or property in the level above. This gives rise to a matrix of judgements and its corresponding principle eigenvector, a shown in equation 2. These judgements are paired in a judgement matrix A. Saaty highlights the benefit of this approach using actual knowledge about real world issues [106] using pair wise comparisons:

$$Aw=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ n \end{bmatrix}=cw \qquad (2)$$

Where $A = (a_{ij})$ an n x n judgement matrix

c = a proportionality constant

This homogeneous system of linear equations $Aw=cw$ has a solution w if c is the principle eigen value of A, or the characteristic value of the matrix A.

The approach has been widely applied in both a business and academic context where judgement and priority decisions are commonplace, particularly in multicriteria environments. Once there is more than one criteria to meet, conflict can occur as one has to trade between two optimal decisions [107]. The AHP process can be directly taught in its basic form [108] and used for typical strategic or business system level decisions such as resource allocation and vendor selection [109]. For example, it has been applied to power plant management to optimise heat rate and NO_x emissions [110] and the development of recycling strategies [111] for electronic equipment. It has also been used to identify the appropriate delivery method for construction projects: design-bid-build, design-build or construction-management-at-risk [112] where third party involvement is a business practice. SETAC [113] have also recognised the benefit of using a hierarchic approach such as AHP in characterising large systems such as those which are encountered in LCA. This approach also finds application in more tactical problem statements such as factory floor problems where boundaries may not be sharply defined. It has been used as the basis for directly manipulating the linguistic terms that maintenance staff use when making judgements when performing Failure Mode, Effects and Critical Analysis (FMECA) to evaluate different options for maintenance [114]. From a software perspective, it has been demonstrated to add value in monitoring software quality attributes in relation to users and purchasers [115] with respect to what they as customers value.

A crucial factor in engaging the appropriate sections of a work force is firstly engaging with management. The management structure that exists within manufacturing companies is the primary vehicle used within organisations to engage workforces in factory programs and one of three traditional approaches used by industry to deliver energy savings through energy efficiency. The remaining two being technology implementation and regulation or policy adherence [116]. Management also have the benefit of being able to engage in industry or regional learning networks to understand energy efficiency successes and failures in other facilities [117] to provide learning's. Management also have a significant influence on the behaviour of workforces and can ensure the development of appropriate workforce behaviour modification. For example, the introduction of enhanced metering within a factory setting is not sufficient to alter energy behaviour, it must be accompanied by awareness raising and alternate activities [118].

Leveraging this management influence, workforce knowledge can be utilised in decision making in terms of understanding risk factors and mitigation actions required when implementing projects, again due to the in-depth knowledge of a workforce. This experience has application in a wide variety of industrial settings such as the development of cloud computing solutions [119] to ensure proper execution and management of job files. Utilising workforce knowledge to identify risk factors has also been demonstrated to improve supply chain performance [120]. The construction industry have developed on risk factor identification by utilising an AHP structure and prioritise a large number of risks [121] and the development of a life cycle framework to manage project risk on an ongoing basis [122]. A unique feature of workforce experience in identifying risk factors is the ability to identify interdependencies, mutual influences and cause-to-effect models [123]. In terms of applying this structure to a machine or system, Klein et al [124] have documented how a risk assessment can be completed based upon decomposition of the system into a hierarchy of functionally defined assessment areas. Risk evaluation and factor identification, although key to improving project success rates do not, in general include return on investment considerations [125].

2.7 Leading initiatives and ongoing projects

The increasing economic impact associated with climate change and the growing argument for carbon tax levies on energy users [126] is leading to a growing momentum and direction towards the concept of sustainable development. Therefore, it can be concluded that organisations which recognise, value and support innovative approaches such as sustainable development will ultimately improve their competitiveness. The Intergovernmental Panel on Climate Change (IPCC) published its 3rd assessment on climate change in 2001 which had highlighted potential levies and subsequent mitigation policies as strategies to address climate change and is expected to lead to structural changes in manufacturing, including price increases and loss of output [127]. This loss of output may be a consequence of industry potentially being required to lower emissions through increasing service from existing raw materials. However this development is unlikely to be immediately profitable from a business point of view unless companies and industries in this situation have other revenue streams to offset against this scenario, as highlighted by Allwood et al [128]. In 2007, the IPCC working group highlighted one of the key mitigation technologies and practices projected to be commercialised before 2030 as being advanced energy efficiency, in particular more efficient end use electrical equipment [129].

In support of the IPCC's target reductions on green house gas emissions, there has been an increasing European focus on energy efficiencies as part of the regions approach to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 [130]. This has been translated into a European energy efficiency plan which highlights avenues that will be potentially pursued in addition to the existing policies of emissions trading schemes and industrial emissions directives. These new avenues will focus on legal instruments that would regulate improving energy efficiencies through ecodesign or custom made equipment being addressed through standards [131]. Specifically, a number of EU directives are focused on developing a framework for improved ecodesign (2005/32/EC), end-use energy efficiency and energy services (2006/32/EC) [132]. This is a consequence of the EU stressing 'the need to increase energy efficiency in the EU so as to achieve the objective of saving 20% of the EU's energy consumption compared to projections for 2020' [133]. This direction is in parallel with meeting its commitments on greenhouse gas emissions and renewable energy usage, as shown in Figure 2.17. In light of this increased focus, government agencies are increasing supports for energy efficient design initiatives. In Ireland, the SEAI has utilised the LCA approach to highlight the criticality of design and its influence on product lifetime. Using this approach, energy efficiency design improvements have been delivered under SEAI sponsorship across various manufacturing system environments in Ireland. These highlighted with minimal cost (0.2-1% of total project costs) energy efficient design considerations would yield a payback of 6 months to 1 year [14].

The EU parliament committee on industry, research and energy has stated in amendments to upcoming energy efficiency directives that 'it would be preferable for the 20% energy efficiency target to be achieved as a result of the cumulative implementation of specific national and European measures, on the basis of clear and enforceable national targets, promoting energy efficiency in different fields. However if that approach does not succeed, it would be necessary to reinforce the policy framework by adding a system of binding targets' [134].

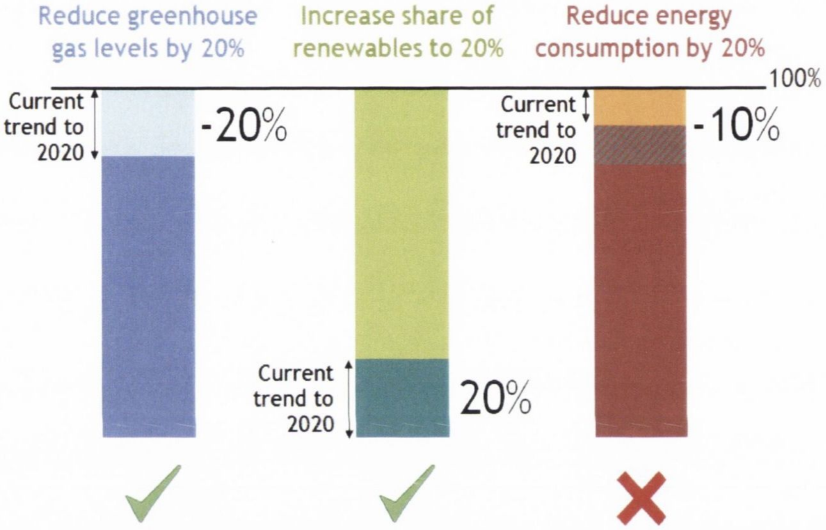


Figure 2.17 – EU scorecard for meeting all 3 '20-20-20' goals by 2020 [135]

This increased political momentum is a result of a growing concern that currently the EU is on track to achieving only half of the objective of saving 20% of its primary energy consumption by 2020 [136], as shown in figure 2.17. As a consequence, specific legal performance requirements will be required as part of an overall package to reduce energy consumption. Energy efficiency legislation is being considered as a result, as shown in figure 2.18.

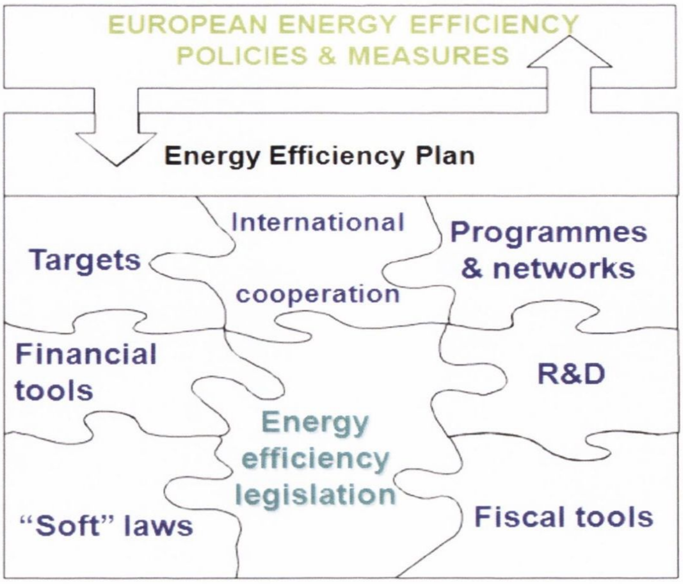


Figure 2.18 - EU Integrated approach to Energy Reduction [135]

With this perspective in mind, improving energy efficiency performance within factory settings is a proactive and favourable approach for organisations with manufacturing facilities within the European region. A thorough understanding of energy management models, information infrastructure and processes will be required to respond to future energy efficiency challenges [137]. This need is starting to take shape within the policies of the EU through research funding and initiatives, specifically on the development of smart adaptable energy aware factories. The European Factories of the Future Association (EFFRA), an industry driven association [138] 'developing a radically new paradigm for cost-effective, highly productive, energy-efficient and sustainable production systems'. Research that is currently being funded under the FP7 frame work includes the 'Factories of the Future' stream, specifically project: FoF-ICT-2011.7.1 [139]. Within this program a number of research strands are supporting energy efficiency improvements within factory settings. These involve industrial and academic collaboration. KAP - *Knowledge* of past performance *Awareness* of the present state, enabling the *Prediction* of future outcomes - which is focused on production performance standards to allow cost effective resource use [140] and PLANTCockpit which is developing a central environment for monitoring and controlling factory environments [141]. These projects not only recognise the need for enhanced monitoring of energy and resource consumption in discrete manufacturing settings but the need to consider appropriate human factors to ensure effective responses within factories [142, 143]. The visualisation tools developed from these projects and from other sources promoting energy awareness in factories [144] will support organisations to monitor energy performance dynamically. This will enhance specific roles already in existence such as energy management and energy aware factory floor resources to influence organisational behaviour towards more sustainable operations [145].

From the evidence emerging in the literature, a more detailed understanding of production equipment energy consumption and performance would complement the growing body of work developing in manufacturing environments and factory settings [9, 10]. This demonstrates how impactful a systematic and data driven approach which supports discrete manufacturing energy characterisation can be. This approach has the flexibility to use either representative data such as a screening approach or a more in-depth level of analysis to understand energy consumption. It also highlights the opportunity to develop a standard on how to approach and understand environmental impacts at a machine level and input the data collected into mainstream LCI methodologies. This presents a further opportunity for collaboration between industry and academia in the area of energy efficiency. This movement into 'end use' characterisation from a manufacturing perspective [11] which is focusing on all utility consumption categories within manufacturing and production tool settings. Research is required to deliver a more detailed understanding of how energy is used within these discrete settings, in particular understanding end use conversion devices based on the potential highlighted by Allwood et al [146]. The potential of energy efficient improvements has developed into the creation of Energy Performance Contracts (EPC) between an energy user and the provider of an energy efficiency improvement measure, which is verified and monitored during the term of a contract [147]. EPC is now seen as a means to achieve standards such as ISO 50001. The ongoing development of a smart grid environment within the EU is also linked to improvements in energy efficiencies. With the increased understanding of factory performance that comes with energy efficiency understanding, the impact of production strategies on factory energy demand has given rise to Demand Side Management (DSM) being seen as a new area of energy efficiency improvement [148].

2.8 An industrial perspective on LCA

An example of how environmental considerations have influenced industry is the development of closed materials loops extending the view of raw material supply chains. This has been carried out on a formal basis by recycling raw materials from end of life products back into internal supply lines, as shown in figure 2.19. This approach has a cost benefit as well as an environmental benefit. The opportunity for reuse and in particular the leadership shown by Europe has been acknowledged within the international business community. This has been highlighted in the United States by the CEO of Universal Lubricants who recently stated 'true sustainability isn't just about a final product, but includes the way that product is made and is used throughout its entire life cycle. The re-refining industry is growing in the US because its energy and environmental advantages coupled with product durability make it a ripe area for investment. Catching up to our European counterparts, both in terms of absolute production and consumption numbers, is a priority for the public and private sectors' [149].

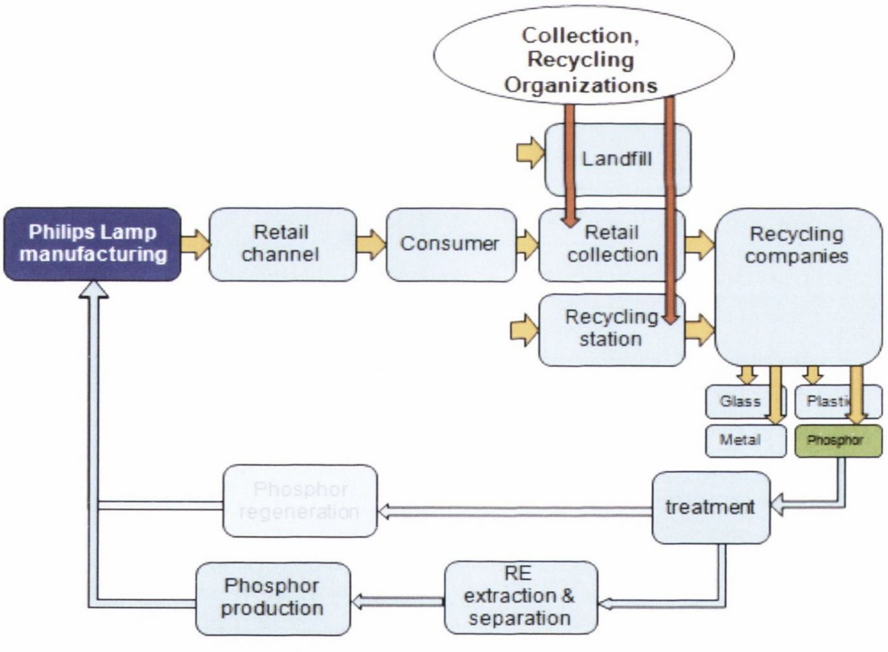


Figure 2.19 - Recycling flow used by Philips for raw material reuse [150]

In effect, manufacturing does not have to rely exclusively on increasing mass production to increase revenue. As customers see value in products with lower environmental impact through better design, longer lifespan and more effective reuse, more optimum production levels can be achieved. This 'post mass production paradigm' viewpoint has the potential to effectively decouple economic growth which businesses depend on for revenue growth from material and energy consumption used when manufacturing products. As assembly processes are a significant percentage of added value within the manufacturing sector [151] this highlights a significant opportunity for decoupling energy consumption and volume based manufacturing businesses. From this, a conclusion can be drawn: industries which focus on a more effective use of raw materials through improved design of products and focus on energy efficiencies within their manufacturing operations will enhance their competitiveness, environmental impact and branding. As Alting et al [152] have stated 'when it comes to the role of the manufacturing industry in ensuring sustainable development, the message is simple: it has to greatly reduce the use of raw materials and the impact on the external environment, while preserving or improving the functionality of the products'. This challenge, if addressed by manufacturing based industries, can be seen as both a competitive and environmental advantage. This has been advocated by Nakamura el al [153], arguing that environmental value to business can be classified into 4 areas: cost reduction, avoidance of risks, improvement of service quality and improvement of customers image. Many industries and corporations have taken this literally, with corporate environmental objectives being publically communicated. An example of what this means from an individual company point of view is demonstrated by ABB who committed 'to have quantifiable, visible and communicated environmental goals and programs ready for all core products and at the same time integrated into the strategies of all business areas' [154] as shown in figure 2.20 which utilises life cycle thinking to inform direction [155].

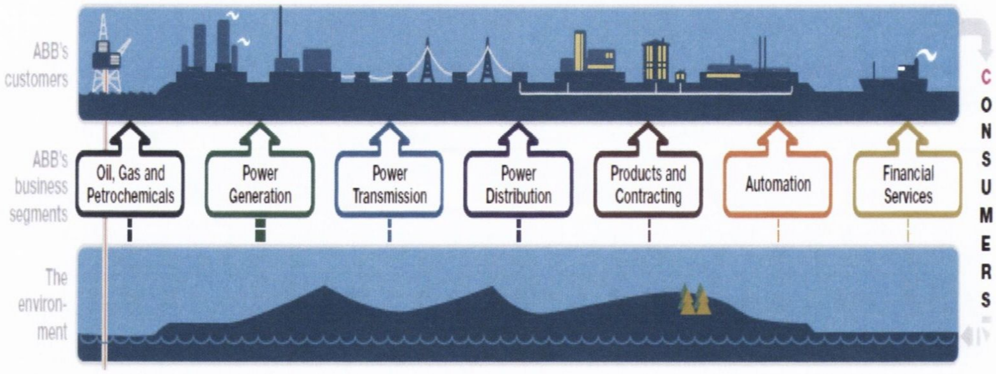


Figure 2.20 – Outline of all ABB's targeted business segments covering the entire energy chain

A further example of how LCA has been used within an industry to support an environmentally considered approach has been GlaxoSmithKline's environmental sustainability strategy. This program has set the ambitious target of having a carbon neutral value chain by 2050 [156]. The corporate statements made by ABB and GSK put an obligation on these organisations to characterise their operations, transport and product development from a carbon and energy input point of view to identify opportunities for improvement.

Corporations have taken this viewpoint further through developing new business opportunities through the use of LCM within their business objectives. General Electric have developed new products and services with reduced environmental impacts marketed under their 'Ecomagination' strategy [157] which offers environmentally considered services and products. This environmental awareness is also supported by collective groupings of companies. The E8 organisation, an international group of electricity companies from the group of G8 countries is an example of this, where 8 of the world's largest energy companies collaborate on issues impacting their core business such as sustainable development and climate change [158]. Similarly this collaborative approach is also evident within the United States where 100 of the largest electric power producers annually benchmark their environmental performance based on generation, plant performance and emissions data. This has allowed a capability within this sector to assess environmentally focused programs across this industry such as transitioning to lower emission based fuels and pollution prevention programs. From 1990 to 2010, this has led to a 68% reduction in SO_2 and NO_X emissions primarily driven through switching from coal fired generation stations to natural gas. Despite this however, in the same period CO_2 emissions have increased by 24%, primarily driven by economic growth [159].

The increasing focus on environmental impacts has resulted in the development of demand side management technologies to support energy savings and minimise environmental impacts. This is leading utility service providers and distributers to put an increased focus on developing more flexible electrical distribution systems to control loads and generation [160]. This has led to service offerings being provided where flexible energy users who can reduce their load during peak grid demand periods can reduce their environmental impact and obtain a financial reimbursement [161]. Although this does put the obligation on potential industrial customers to understand their energy utilisation at a deeper level and are they capable of obtaining value from this service by being able to partially reduce their load demands.

2.9 Introduction to LCA

Manufacturing is an important contributor to an industrial society through the creation of products and processes which generate wealth, services and employment [21]. Historically manufacturing companies have been driven by the need to meet customer's expectations through the manufacture of products which have been defined by the market need and which meet all required legislation. The manufacturing process can however impact the environment through pollution or natural resource depletion [21] and can result in negative consequences for the environment. To compound this, worldwide energy generation is heavily dependent on natural resources [162]. As energy is a key enabler in facilitating manufacturing operations, there is a realisation that energy consumption within manufacturing processes needs to be characterised [13] to improve manufacturing sustainability in support of a reduction in the demand for natural resources. These challenges are pushing manufacturing strategically towards a more sustainable manufacturing platform where the consumption of natural resources needs to be considered and reduced. This is leading to the development of more sustainable products, processes and services that comply not only with economic, societal needs and constraints but additionally also consider environmental needs and constraints [46].

As a methodology, Life Cycle Analysis (LCA) and Management (LCM) considers the product life cycle as a whole and works to optimise the interaction of product design, manufacturing and life cycle activities while protecting resources [30] as shown in figure 2.21. The development of structured approaches and methodologies to characterise and quantify energy and resource consumption within manufacturing settings will lead to an enhancement of LCA. It is with this characterisation that improvement opportunities will be identified within manufacturing process chains. Specifically in identifying retrospective improvement upgrades to existing manufacturing equipment or in identifying enhancement opportunities to be included in future designs.

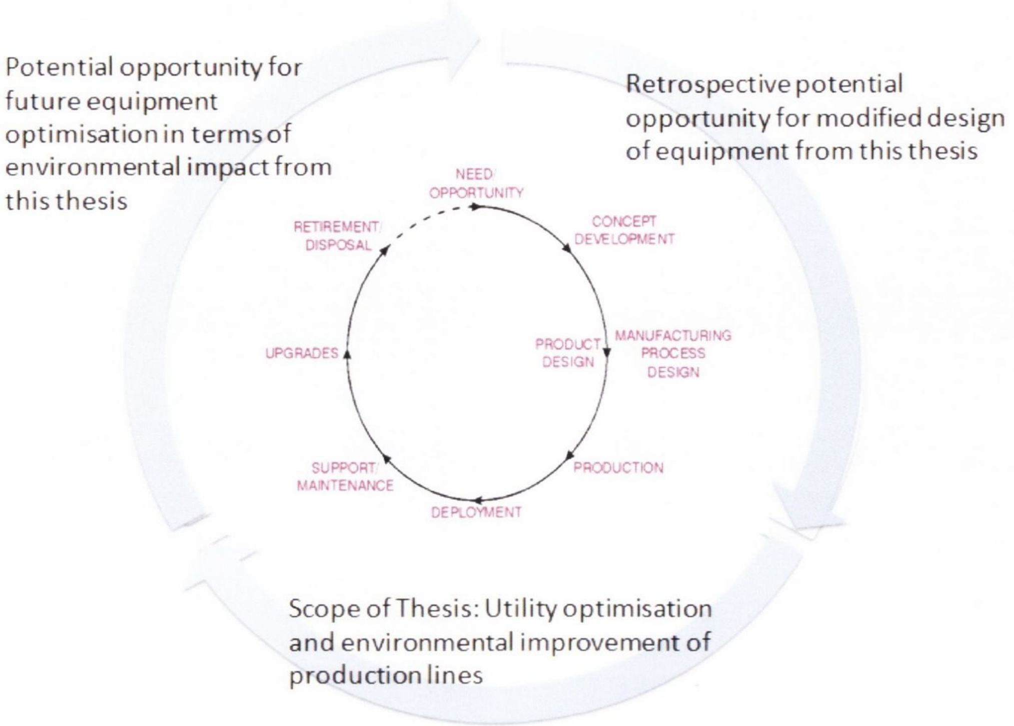


Figure 2.21 – Life Cycle Management phases adapted from Westkämper [163] overlaid with optimisation of utility consumption within manufacturing process chains highlighting benefit to the product life cycle

Using the holistic approach demonstrated by LCA, improvements in the understanding of energy consumption within manufacturing industries have become a key focus point because of the potential impacts on the environment [164]. This approach has driven the development of a more ecological and qualitative understanding of the cycle between raw materials, production, product use and recycling of manufactured products to include energy consumption within this cycle as Erkman [165] suggested in a historical view on industrial ecology 'the goal is first to understand how the industrial system works, how it is regulated, and its interaction with the biosphere: then, on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function'.

This has led to the realisation that energy efficiency or improved energy productivity will enhance future manufacturing competitive capabilities. Energy efficiency can be defined as the ratio of productivity delivered to the energy consumed [166]. This view has only gained further urgency with the steady increase in energy prices [36] and its immediate impact on manufacturing competitiveness. With this economic challenge comes opportunity. By focusing on improving energy efficiency within manufacturing environments, industry can support the holistic approach advocated by LCM in developing approaches to improve energy efficiency at a factory level and subsequently enhance the overall understanding of manufacturing within the overall life cycle of products. This dual approach is reflected in the collaborative environment that is demonstrated between the industrial and academic fields in developing a standard or benchmark approach to characterising and improving the understanding of industrial impacts to the environment.

2.10 Standards in environmental management

Environmental policy aims at supporting industry in the transition to sustainable production and consumption while meeting required legislation requirements. This is taking place in different ways and at different levels. Businesses strive to achieve this through continuously improving the environmental performance of their products in balance with socio-economic needs while supporting environmental protection and preventing pollution [167]. The integrated assessment of environmental impacts from the cradle to grave approach used in the LCA methodology, working to understand environmental impacts [168] has been an academic - industrial focus through the development of a holistic view on the overall environmental impact of products [8, 169]. This dual approach has allowed an evolution of the methods and indicators used in environmental impact assessments which is leading to a more rigorous approach in understanding the environmental impacts of products.
The Society for Environmental Toxicology and Chemistry (SETAC) [170] was the first international organisation (1989) to recognise the potential of LCA and the need for developing a standard scientific basis for conducting LCA [171]. By holistically analysing the cradle to grave environmental impact of products, the initial SETAC workshops focused on understanding a technical model for LCA [172] which became the accepted code of practice, easily recognisable to the modern LCA practitioner [173]:

- **Goal definition and scoping:** defining the purpose and objectives of the study, product identification or process, end use of study and key assumptions
- **Inventory analysis:** Identification and quantification of raw materials and energy inputs within the boundaries of the study
- **Impact assessment:** Qualitative and quantitative characterisation and valuation of impacts to ecosystems, human health and natural resources
- **Improvement assessment:** Identification, interpretation and evaluation of opportunities to achieve improvements

This structured approach was further developed on by focusing on impact assessments on human/ecological health and resource depletion initially through a 3-phase framework: classification, characterisation and valuation [174, 175].

A joint collaboration between the United Nations Environment Program (UNEP) and SETAC was established in the 1990's to further improve a best practice approach to establishing databases for lifecycle inventory analysis and environmental impacts with regular workshops on improving global guidance for the creation, management, dissemination of datasets for LCA, informally known as the 'Shonan Guidance Principles' [170, 175]. This guidance works to:

- Serve as the basis for improved dataset exchangeability and links for databases worldwide
- Increase the credibility of existing LCA data and data accessibility
- Complement other initiatives particularly where more prescriptive guidance has been developed

The emphasis was on dataset development and access to databases as there was already focus on methodology and conducting LCA's defined through the International Organisation for Standardisation (ISO) as shown on figure 2.22 [167] .

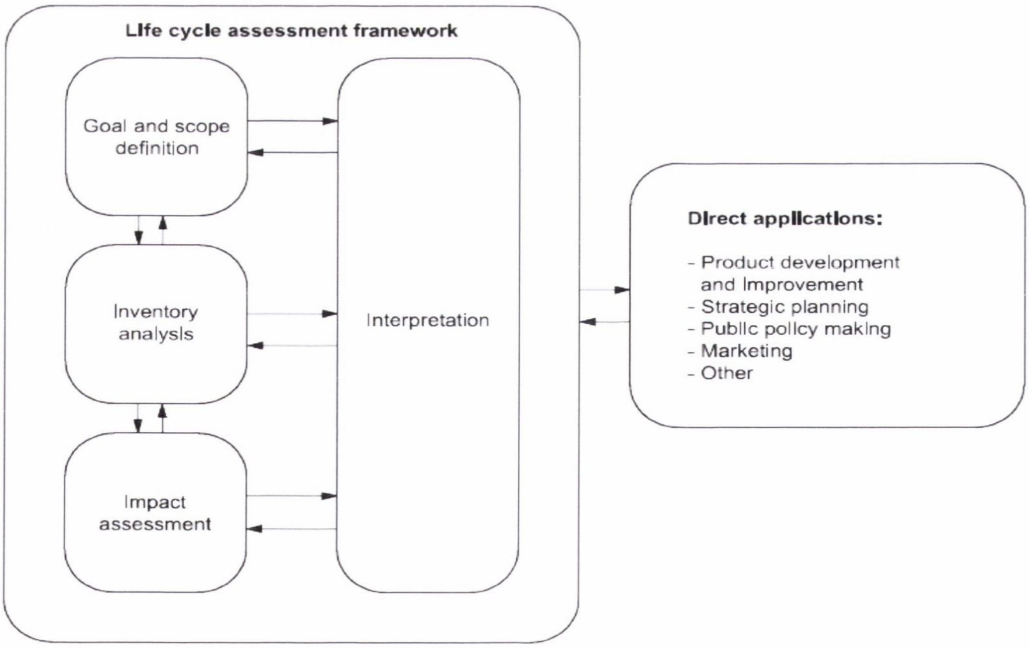


Figure 2.22 – Methodological frame work of LCA [8]

In order to support business organisations to achieve and demonstrate improved environmental performance by controlling the impacts of their products, services and business activities, the ISO standard 14001 [167] was developed. The benefits seen by industry [176] include:

- The standards are designed to promote sustainable development
- Companies operating in a global market place are seeking to harmonise energy management systems
- The development of a proactive approach to the environment
- Businesses would prefer to regulate internally rather than rely on external supervision
- Builds on the approach used for the successful and widely used ISO 9001 quality management series [177]

This is based on the 'plan-do-check-act' (PDCA) methodology [178] widely used as a project management tool. This approach reflects the fact that many organisations manage their operations through a 'system level approach' of which the PDCA methodology is a proven tool. The ISO series has benefited significantly from the impactful work undertaken to develop improvements in the overall LCA methodology.

This has resulted in a significant subset of the ISO 14001 series being dedicated to outlining an LCA centred standard [8, 179-182] to support businesses in their work to improve the environmental impact of their products, as shown in figure 2.23.

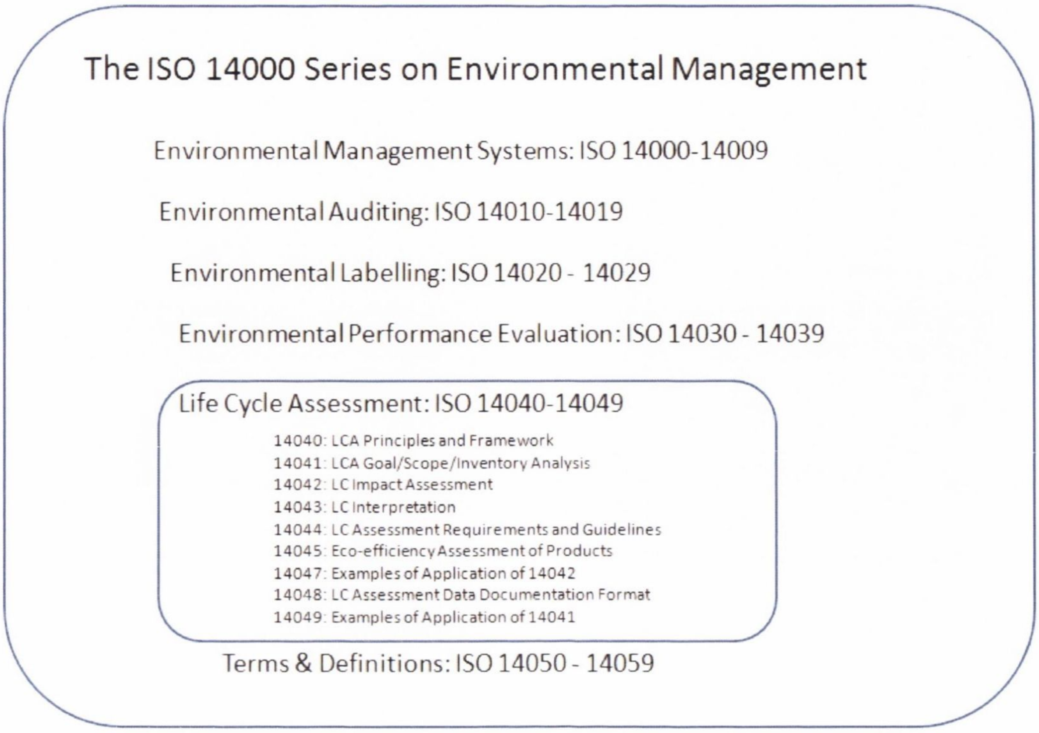


Figure 2.23 – LCA influence on ISO standards adapted from the international organisation for standardisation [167]

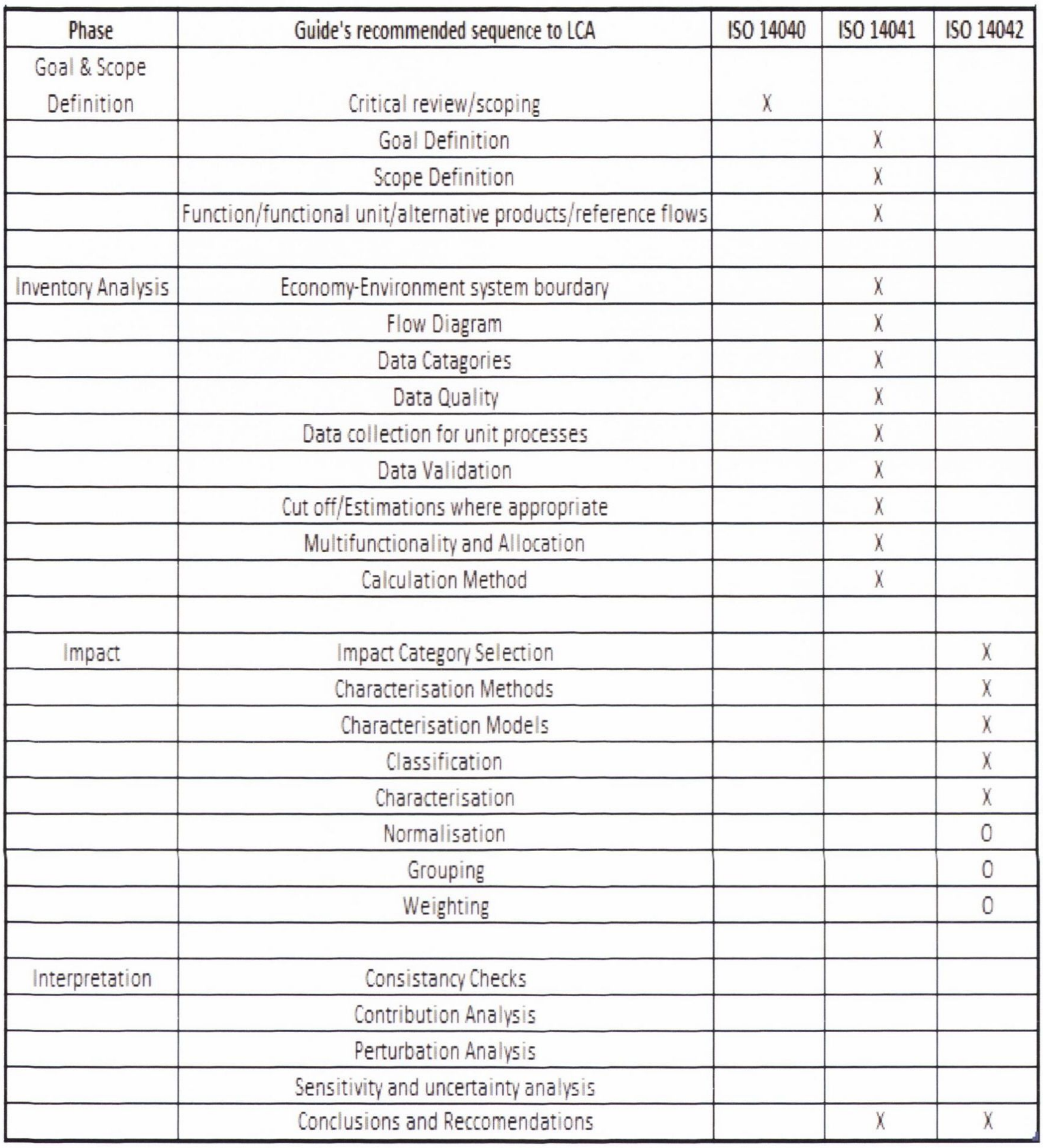
The success of this approach has been built on by the International Organisation for Standardisation and others to deliver for more specific energy orientated standards, for example the EN 16001 & ISO 50001 Energy Management Systems [183, 184]. This has driven organisations to concentrate more on the delivery of verifiable improvements in their significant energy user performance. This is an improvement on initial focus, which was on the development of an organisational and metering capability to monitor energy performance.

From the early 1990's, international businesses have adopted the ISO 14XXX series of standards. There are, however a number of challenges to this series which can impact the type of results achieved:

- The standards apply to processes and systems used to produce products rather than the products specifically
- Despite industry participation, the ISO standards are a product of a nongovernmental organisation and as a result the standards are voluntary
- Businesses view the standards as self-regulatory, which may or may not tie in with their legal environmental obligations

- The standards allow businesses to identify their significant energy users and develop improvement plans which can have varying degrees of impact with respect to a products life cycle
- The impact or improved results can be heavily influenced by the understanding of the individual or organisation driving the standard
- The ISO standards do give enough guidance on how to perform a Life Cycle Assessment and literature exists to support [185], however significant experience is required to support, in particular understanding the impact of environmental issues raised [180]

Despite this, these challenges have highlighted improvement opportunities to build on. In particular, the development of a more detailed or prescriptive approach to LCA in order to improve the standard of information available. The 'Handbook on Life Cycle Assessment: Operational Guide to the ISO standards' [168] was an important step highlighting these opportunities. Within this guide the author, Guinee argues for a more prescriptive step by step approach to the 4 main phases previously documented by both the SETAC and ISO organisations. Within each of the phases, Guinee suggests a defined sequence of steps without omission. Each phase is to be supported by a mixture of skill sets: LCA clients, stakeholders, LCA researchers and a critical reviewer with the emphasis on a data orientated, consensus approach. Although the guide broadly agrees with the ISO 14001 series of standards on LCA, a significant emphasis is put on step sequence and data integrity beyond ISO, namely the inclusion of normalisation, grouping and weighting of data within the impact assessment phase as shown in figure 2.24 as well as arguing for a standard data format to collect data – the SPLOD format [186]. A summary of the impact categories that can be collected are highlighted in figure 2.25.



Phase	Guide's recommended sequence to LCA	ISO 14040	ISO 14041	ISO 14042
Goal & Scope Definition	Critical review/scoping	X		
	Goal Definition		X	
	Scope Definition		X	
	Function/functional unit/alternative products/reference flows		X	
Inventory Analysis	Economy-Environment system bourdary		X	
	Flow Diagram		X	
	Data Catagories		X	
	Data Quality		X	
	Data collection for unit processes		X	
	Data Validation		X	
	Cut off/Estimations where appropriate		X	
	Multifunctionality and Allocation		X	
	Calculation Method		X	
Impact	Impact Category Selection			X
	Characterisation Methods			X
	Characterisation Models			X
	Classification			X
	Characterisation			X
	Normalisation			0
	Grouping			0
	Weighting			0
Interpretation	Consistancy Checks			
	Contribution Analysis			
	Perturbation Analysis			
	Sensitivity and uncertainty analysis			
	Conclusions and Reccomendations		X	X

Figure 2.24 – Data collection requirements adopted from Guinee's sequence [168]

The industrial benefit of the structured LCA approach to understanding the environmental impact of business products, processes and services from cradle to grave has been to allow a more detailed understanding of cost benefits to different environmental options for example cost versus impact optimisation [187, 188]. This has developed into a tool to allow companies to make informed decisions regarding the environmental impact of their products through the ability to model different change scenarios. There is evidence that this approach is supporting studies on the impact of precision to a products life cycle where Helu et al [189] demonstrated through an automotive case study the precision requirements of parts and the anticipated environmental impacts. This provides an effective tool to allow manufacturing organisations to easily assess benefits against cost. However, the biggest impact of LCA has been the opportunity to use the LCA tool to improve product design with respect to environmental impact by allowing effective analysis to be performed with respect to product design options and manufacturing technology selection [190-193] in support of environmentally informed design decisions or identifying where product adaption is more appropriate to redesign [194]. This understanding of impact can benefit companies further by modelling the performance of products and the probability of environmental penalties through allowing a manufacturer to assess the risk of a product not fulfilling any relevant environmental legislation early in the design process [195].

2.11 Metrics in LCA

A critical development within the evolution of LCA has been the expansion of Life Cycle Impact Assessment (LCIA) methods. This has been developed with the aim of matching Life Cycle Inventory (LCI) data to corresponding environmental impacts [196]. Subsequently, this has also had the positive knock on effect of highlighting opportunity to use this development to allow companies to cost more effectively and accurately their internal manufacturing operations and product portfolios and the subsequent environmental impacts using LCIA as a basis for measurement [69].

Using the direction outlined within ISO 14042 [180], LCI results can be classified into impact categories relevant to the study in question as shown in figure 2.25. By identifying 'stressors', conditions that may lead to human or ecological health impairment [113], this can support the categorisation of environmental loading and resource consumption within the LCI phase into stressor groups. These stressor groups can then be assessed by impact. The number of impact categories has risen with the development of LCA, as shown in figure 2.25. It is this approach that has led to the development of several methodologies which model impact assessments against impact categories. However, the applicability of these categories is dependent on the studies being performed and the availability of data [197]. The methodologies used in LCIA are based on two modelling approaches: midpoint or endpoint impact assessment. Midpoints are considered to be links within the cause-effect chain of the environmental mechanism prior to the end points, from which indicators can be derived to reflect the relative importance of emissions. It is a point between the stressor and the end point for example ozone depletion or global warming potentials. Endpoints are those physical elements, deemed a concern to society or the LCA user, that occur at an end point level in the cause-effect chain i.e. human health impacts in terms of disability adjusted life years – DALYs [197, 198].

Impact Catagories	**Detail**
Abiotic Resources	Nonliving natural resources ie Energy
Boitic Resources	Living natural resources ie Rainforests
Land Use	Consequences of human land use
	Land competition: Loss of land as a resource
	Loss of biodiversity: Effects on biodiversity
Loss of Life Support Function	Impact of biotic harvesting or land use
Dessication	Environmental problems caused by water shortages
Climate Change	Impact of human emissions on the atmosphere
Stratospheric Ozone Depletion	Ozone changes and affects on human health, natural & manmade environment, natural resources
Human Toxicity	Human health impact of toxic substances
Eco Toxicity	Natural environment impact of toxic substances
Freshwater aquatic ecotoxicity	Impacts on freshwater ecosystems
Marine aquatic ecotoxicity	Impacts on marine ecosystems
Terrestial Ecotoxicity	Impacts on terrestial ecosystems
Freshwater sediment ecotoxicity	Impacts on the sediment of freshwater ecosystems
Marine sediment ecotoxicity	Impacts on the sediment of seawater ecosystems
Photo Oxidant Formation	Formation of reactive chemical compounds by sunlight reacting with air pollutants
Acidification	Formation of acidifying pollutants
Eutrophication	Impact of excess level of macronutriants
Waste Heat	Expelled heat, unused at a local level
Odour	Above a certain emission level
Maloderous	Airbourne odour
Maloderous Water	Water bourne odour
Noise	Above certain limits
Ionising Radiation	Release of radioactive substances, exposure
Casualities	Accidents

Figure 2.25 – Sample of impact categories based on SETAC [174] and CML2002 [168] guidelines.

The fundamental difference between the two approaches is that midpoint assessment methods have a predictive or problem orientated approach compared to the damage orientated approach of end point assessments [199]. For the customer or LCA users point of view, if there is confidence in the model being used then factors can be calculated to reflect the relative importance of an emission, then a midpoint methodology is preferable. If analysis of trade offs and aggregation across impact categories is required then end point analysis is preferable. A sample of methodologies, as shown in figure 2.26, highlights the variety of options available to the LCA practitioner.

Methodologies	**Development by**	**Quantitative Method of Assessment**
Eco-indicator 95	Pre (Holland)	Mid-Point
Eco-indicator 99	Pre (Holland)	End-Point
CML2002	Institute of Environmental Sciences (CML) - University of Leiden (Holland)	Mid-Point
EPS2000	Chalmers Unversity of Technology (Sweden)	End-Point
IMPACT2002+	Swiss Federal Institute	Mid-Point
LIME	National Institute of Advanced Industrial Science & Technology (Japan)	Mid-Point/End-Point
ReCiPe	Pre (Holland)	Mid-Point/End-Point
EDIP97/2003	Environmental Design of Industrial Products (Denmark)	Mid-Point
TRACI	US EPA	Mid-Point

Figure 2.26 – Sample of methodologies available based on midpoint/end point analysis adopted from [7, 168, 196, 199-202]

Due to the extensive work completed on midpoint and end point characterisation, the user now has the option to use a combination of midpoint and end point when selecting methodologies and software. An example of this is highlighted in figure 2.27, showing a methodology where both midpoint and endpoints are used to model damage/impacts.

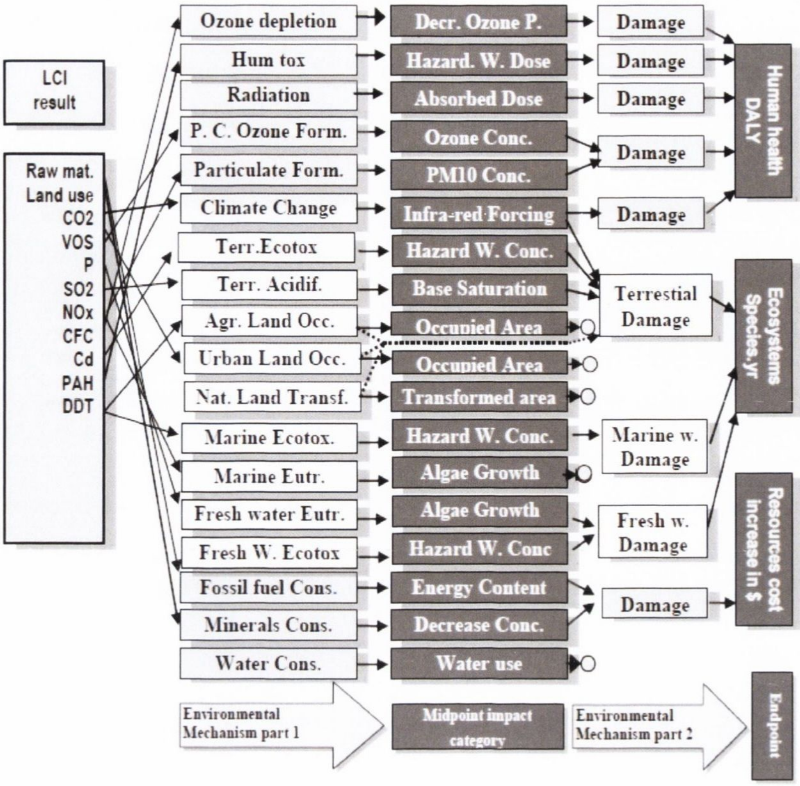
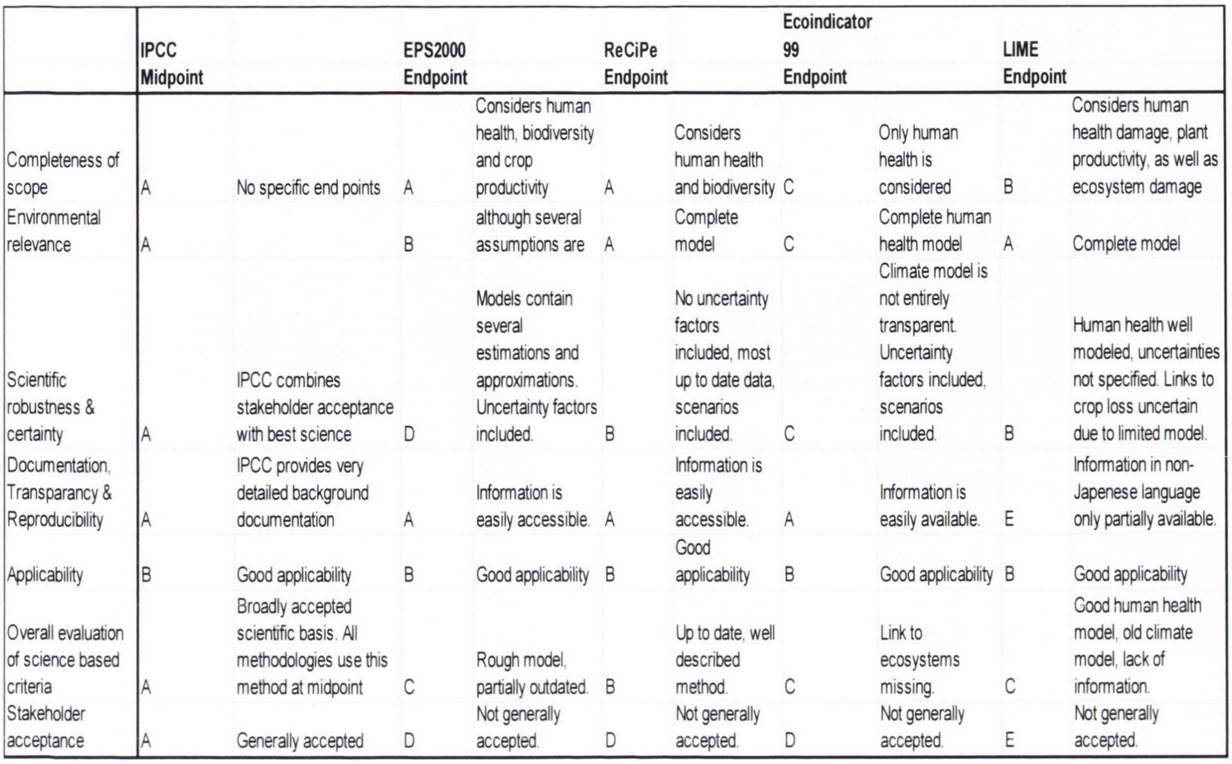


Figure 2.27 – Midpoint/Endpoint relationship with LCI used in ReCiPe2008 highlighting use of Midpoint/Endpoint indicators within the hierarchy [200]

2.12 Further development of a standard

Neither the ISO 1404X standards, nor the LCA methodologies should be viewed as separate efforts. Both demonstrate different approaches to improving environmental performance. ISO supports the use of a standard or structured approach to LCA, although it is up to the discretion of the organisation on how to use this approach resulting in varying degrees of success. This is performed under the ISO 14001 environmental standard, as shown in figure 2.23, which highlights the extent to which LCA has influenced the ISO 14001 series, in particular the 14040 – 14049 series. The more prescriptive and quantified techniques involved in LCA methodologies developed by LCA practitioners deliver a more analytical approach but are time consuming due to the types of detail needed and require a high degree of skill to utilise. Ultimately though, both industry and LCA practitioners are working to improve environmental impact by targeting the significant environmental aspects relating to products and manufacturing [8] through the compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle. The challenge going forward is to further enhance harmonisation between both the industrially supported ISO and the more detailed LCA approaches in light of an increased understanding of the effects of globalisation on the carbon footprints of industrial products [61]. This is particularly relevant as finished products are moved globally to various markets. Manufacturing has become more modular with partially manufactured products being moved to different geographies for final assembly/processing and as a consequence can impact the type of LCA methodology used [203] and pose further data collection challenges. In terms of LCIA, this is challenging to quantify with increasing subdivision and system expansion being required [204] to support the allocation of environmental burden of products manufactured in various geographies. The defining of LCA boundaries becomes not only more important as a result but more difficult in terms of a global supply chain as larger system studies contain more uncertainties in both data availability and in assumptions [205]. This is resulting in a distinction being made between attribution and consequential life cycle analysis [206]. With the attribution approach working to understand the environmentally relevant physical flows to and from a life cycle and its subsystems. While the consequential approach works to understand change within a life cycle with respect to the environmentally physical flows and changes.

The increasing amount of methodologies, as shown in figure 2.28, can pose a problem to the LCA practitioner, due to different outputs and conclusions as shown by Jolliet et al [196] and Dreyer et al [199]. Although the ISO 14041-3 series have helped minimise this impact through the development of standardisation of approaches to defining how these studies should be completed. In parallel with this, there are ongoing efforts through SETAC to support harmonising different aspects of the methodology for life cycle assessment [207]. The SETAC direction is supporting an enhancement of existing standards through the improvement of data exchange, dealing with hierarchies and overlaps, understanding how to interface between existing LCA software tools. The ultimate goal of this effort is to reduce the variability that exists and interpretation challenges resulting through multiple available tools with appropriate background data and procedures to deal with uncertainty.



	IPCC Midpoint		EPS2000 Endpoint		ReCiPe Endpoint		Ecoindicator 99 Endpoint		LIME Endpoint	
Completeness of scope	A	No specific end points	A	Considers human health, biodiversity and crop productivity	A	Considers human health and biodiversity	C	Only human health is considered	B	Considers human health damage, plant productivity, as well as ecosystem damage
Environmental relevance	A		B	although several assumptions are	A	Complete model	C	Complete human health model	A	Complete model
Scientific robustness & certainty	A	IPCC combines stakeholder acceptance with best science	D	Models contain several estimations and approximations. Uncertainty factors included.	B	No uncertainty factors included, most up to date data, scenarios included.	C	Climate model is not entirely transparent. Uncertainty factors included, scenarios included.	B	Human health well modeled, uncertainties not specified. Links to crop loss uncertain due to limited model.
Documentation, Transparancy & Reproducibility	A	IPCC provides very detailed background documentation	A	Information is easily accessible.	A	Information is easily accessible.	A	Information is easily available.	E	Information in non-Japenese language only partially available.
Applicability	B	Good applicability	B	Good applicability	B	Good applicability	B	Good applicability	B	Good applicability
Overall evaluation of science based criteria	A	Broadly accepted scientific basis. All methodologies use this method at midpoint	C	Rough model, partially outdated.	B	Up to date, well described method.	C	Link to ecosystems missing.	C	Good human health model, old climate model, lack of information.
Stakeholder acceptance	A	Generally accepted	D	Not generally accepted.	D	Not generally accepted.	D	Not generally accepted.	E	Not generally accepted.

Figure 2.28 - Summary of the evaluation of 5 models that assess climate change [208]

The purpose of Life Cycle Impact Assessment is to provide additional information to support assessing the results from inventory analysis to better understand its environmental significance. By defining the functional unit of a product [209], describing the primary functions fulfilled by a product system and linking this data with economic data has the potential to enhance industrial willingness to support and develop LCA analysis, particularly with Input-Output analysis. To date the approach uses average data [169] and there is a risk to missing significant parts of environmental interventions in LCI analysis [210]. Through comprehending the cost input during inventory analysis, further development can include a generic weighting based on monetary measures [211]. This will allow industry to factor manufacturing costs into new/modified designs. This will ensure environmental improvements can be financially assessed with respect to manufacture costs of improved products. An indication of movement in this direction is highlighted by the development of a weighting set based on a ‘willingness-to-pay’ for environmental performance [212].

2.13 Summary and context

The need to comprehend how energy is consumed has driven a need for structured approaches to be developed to understand and characterise energy use. This has been recognised through the collaboration of differing disciplines within both academic and industrial environments. This is supporting the ongoing development of sustainable manufacturing approaches through the creation of standards which can guide users on understanding and targeting appropriate energy consumption improvements. This development has been undertaken in two parallel strands through both LCA supporting an empirical approach and the energy and environmental ISO series orientated towards organisational change.

Through LCA this structured approach allows an understanding of the environmental impacts associated with all stages of a products life from raw material extraction and processing, manufacture, use and recycling. This empirical approach has allowed the quantification of impacts using midpoint indicators reflecting the relative importance of emissions or end point indicators reflecting physical attributes of societal concern. Leveraging this approach, LCA practitioners can model the impact of more environmentally considered products and designs. This data driven approach has allowed further metrics to be included in LCA evaluations such as the addition of cost data facilitating informed economic impact into future design changes. This approach however comes with the burden of expertise requirements. The scalability of the approach has also resulted in various LCA based methodologies giving rise to potential issues in data variability, exchange and interpretation between systems. The International Organisation for Standardisation has provided through the ISO 14001/50001 series of standards which emphasise the identification, measurement and verifiable improvement of environmental and energy consumption performance. Although the series is not as prescriptive or quantified as the LCA approach. The ISO series has gained widespread adoption in commercial and industrial settings with widespread adoption within manufacturing based organisations. This allows a focus within factory settings without a need comprehend the complete life cycle. As with LCA, ongoing improvement within the ISO 50001 series has resulted in the current development of the 50004 standard to further support a more effective adoption of energy management.

Both approaches were born out of a growing need for sustainability resulting from population expansion, increasing raw material, energy demands and pricing. Further challenges have compounded this need with increasing globalisation and sector/regional emission limits which add to the urgency of adoption in addition to closer academic and industrial collaboration to improve these approaches. There is evidence of this adoption within commercial organisations with the implementation of recycling strategies within supply chains, more effective use of raw materials and corporate social responsibility objectives being published. These not only lend themselves to a more sustainable approach but also contribute to more competitive performance. From a factory perspective this approach is visible through ongoing monitoring and targeting of performance, energy gap analysis as well as the adoption of energy efficiency strategies. Through these initiatives, the significance of production systems within factories is becoming more apparent with more detailed analysis being undertaken highlighting the impact of energy use within cost of ownership as well as use pattern. In addition, as production systems become more complex and discrete equipment increase in complexity, further process interdependency characterisation is being advocated to identify improvements. Many industries are pursuing this with the development of sector wide responses such as standards development, carbon neutral value chains and environmentally benign manufacturing. In a European context legislation is obliging organisations to adopt environmental considerations in their products and services through improved design, energy efficiency and end use focus.

From the literature review completed, methodologies can be seen to have a positive impact in supporting the characterisation of the environmental impact of products as highlighted through LCA as well as aiding organisations in supporting energy management as shown by the ISO standards. Both examples also highlight the versatility of using a methodology based approach in terms of leveraging different capabilities such as the expertise needed for LCA or the organisational support of the ISO series. Within this context, an opportunity arises to develop a methodology which supports developing a deeper understanding of energy use and the potential impacts to support energy based change in considering consequences to operational compliance. The methodology should be prescriptive enough to support organisational adoption but not requiring the burden of expertese LCA brings while allowing a detailed understanding of the consequences of energy based change which the ISO series currently does not support. In considering this research gap, a contribution can be made to support the ongoing work to reduce the resource intensity of the production of goods and services in the support of affluence (*T*) as shown previously in equation 1.

3 Lean energy methodology

3.1 Introduction

This chapter describes the energy analysis methodology with its theme being structure and verification. It builds on the lean based DMAIC methodology [89] and information systems available in factories. To assist the user, the methodology flow breaks down into a series of sub flows which in turn use and input-output template for data gathering requirements.
Guidelines and standards have been developed through international and national bodies to support companies in structuring themselves to address energy improvements [184, 213, 214]. These standards however only outline a direction on which companies should structure themselves to support energy work and do not give any specific direction on how to improve energy performance. Recent advances giving direction on how to support characterisation of manufacturing systems have been outlined by both Duflou et al [65], Kellens et al [9, 10] and Kara et al [22]. These advances support the characterisation of energy consumption within discrete manufacturing process chains. Within factory environments, management and staff are constantly 'dealing simultaneously with a sizable number of factors which are interrelated' [215]. It is this organised complexity that the management of energy and resources within manufacturing environments must consider as shown in figure 2.8 as energy consumption is just one of many operational metrics managed when dealing with change. This challenge can also be compounded by insufficient or unsuited metering to support energy improvements.

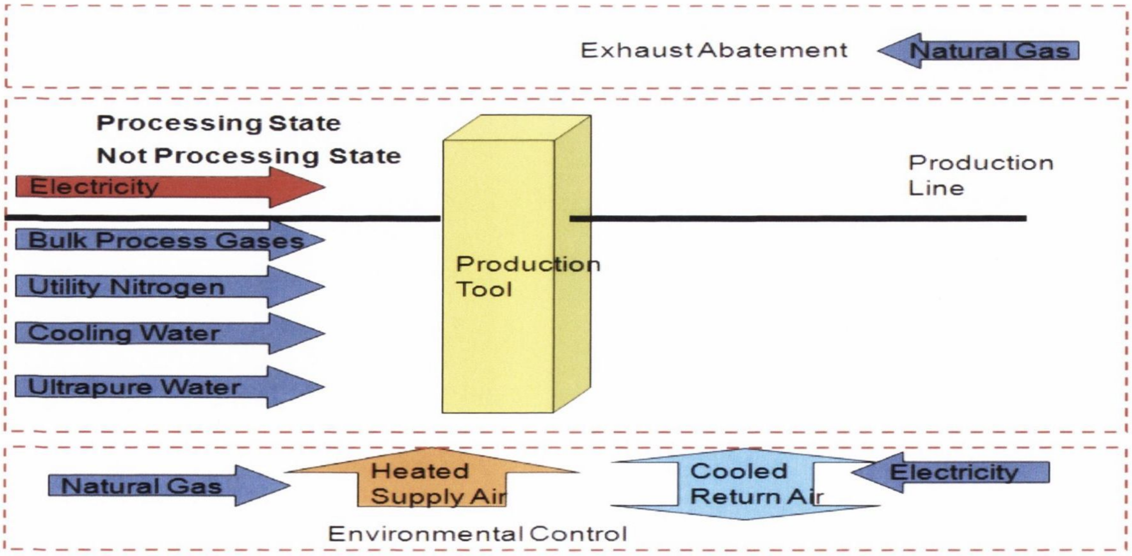


Figure 3.1 – Schematic of energy and resource inputs within an industrial environment

Figure 3.1 highlights the technical complexity that can exist at a process tool level in terms of energy inputs. It can be seen from this figure the range of process inputs that directly feed into the production tool example as well as the tools interaction with the controlled environment in which it is placed. This can lead to an inability to support energy based improvements or to characterise consumption due to the range of input categories, differing manufacturing states and their subsequent energy behaviours.

In order to comprehend this complexity an approach was developed which builds on the contributions made by Kara [62], Duflou [23] and Herrmann [67] and allows the combining of a number of elements within a factories organisation to support factory based characterisation of production systems and improvement paths. The methodology is designed to be used by organisations with a lean focus for example who have used lean to reduce costs using 'value add' and 'non value add' definitions of activities to identify waste. In addition it is developed with organisations in mind that have used the ISO 50001 structure and require a more prescriptive and analytical approach to evaluate energy based change projects. The methodology is outlined in figure 3.2. The theme through the approach is structure and verification with the flow outlined breaking down into a series of subtasks or sub flows as shown in figure 3.3 allowing a consumption characteristic to be developed guiding the user through the sequential phases. By following the approach an organisation can identify gaps in information sources which if closed will improve an organisations capability to reduce energy consumption.

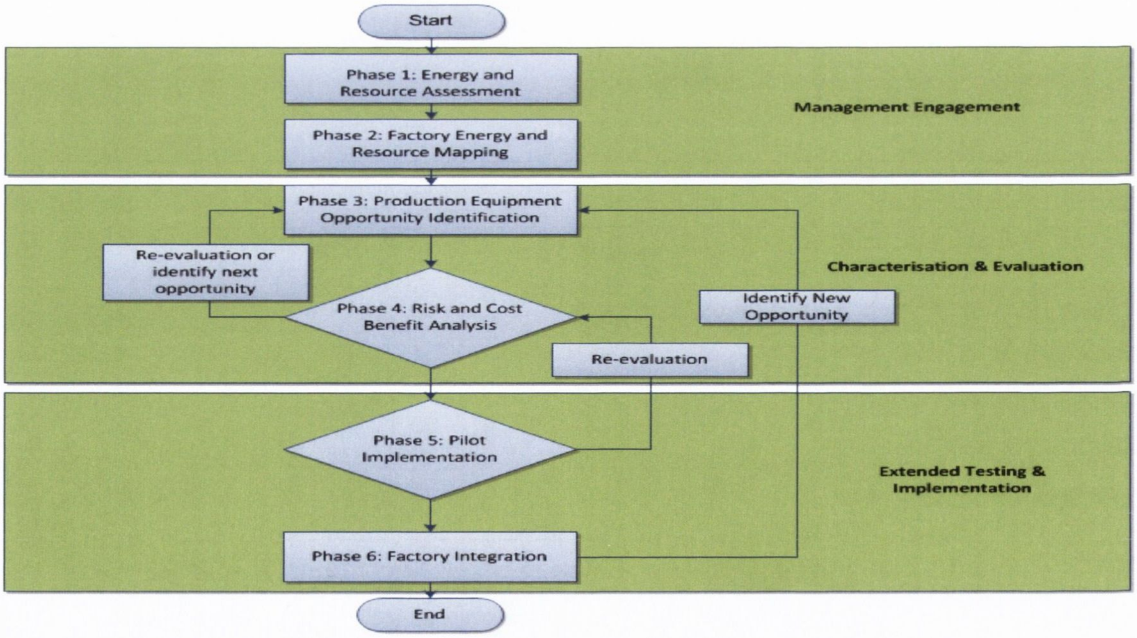


Figure 3.2 – Overview of lean energy methodology

It builds on a culture of continuous improvement and the DMAIC methodology utilised within lean organisations, focusing on using measurement data, understanding the cost benefit of improvements identified and the risk factors associated to those improvements. It uses human factor knowledge throughout all the phases to understand and deliver improvement opportunities through kaizen and workshop exercises. Throughout the process all energy data is converted into cost based consumption. This is to ensure factory users can continuously compare consumption and opportunity identified to other parameters with the factory environment for prioritisation, for example other cost saving initiatives such as throughput or maintenance improvements.

The initial two phases engage management to ensure energy consumption is put into an appropriate perspective for example in terms of cost performance. As management are responsible for strategy and human resources, this also ensures management can facilitate further work through the use of appropriate skill sets for example operations and maintenance. Through this sponsorship, energy characterisation and improvement opportunities can be evaluated to identify suitable improvements for more in-depth scrutiny through extended experimentation and implementation testing. Phases three and four utilise these factory floor resources to complete appropriate tool based measurements and historical reviews of factory information systems to support experimentation in phase four. Based on these learnings, longer term testing and implementation plans can be derived for phases five and six which will involve both operational and maintenance resources to implement but also management for pilot ratification.

Within each individual phase, a sequential series of steps have been outlined to allow the overall objectives of each phase to be delivered. To support these objectives, an 'input/output' template was developed for each step to define what 'input' requirements are needed for each step to process, in order to obtain the required output. The template is shown in figure 3.3. Appendix 1 contains the full input/output requirements by step for each phase documenting the hard and soft data required, how this data is to be used and the expected outputs needed to proceed to the next step within each phase.

Step	**Input**	**Model**	**Output**
	What information is needed 'The Questions' 'Certain Information'	What is the process the input goes through to get the output	The output of the process

Figure 3.3 – I/O template

3.2 Phase 1: Energy and resource assessment

The purpose of phase 1 is to formally identify and collate the energy and resource categories consumed within the factory of study. In many factory settings and in particular industrially large settings these categories are the responsibility of multiple departments or individuals and as a result can be managed individually and separately. The performance and accountability of these categories may not reside with site factory management as a result and can be managed through a central resource based in a different geography.

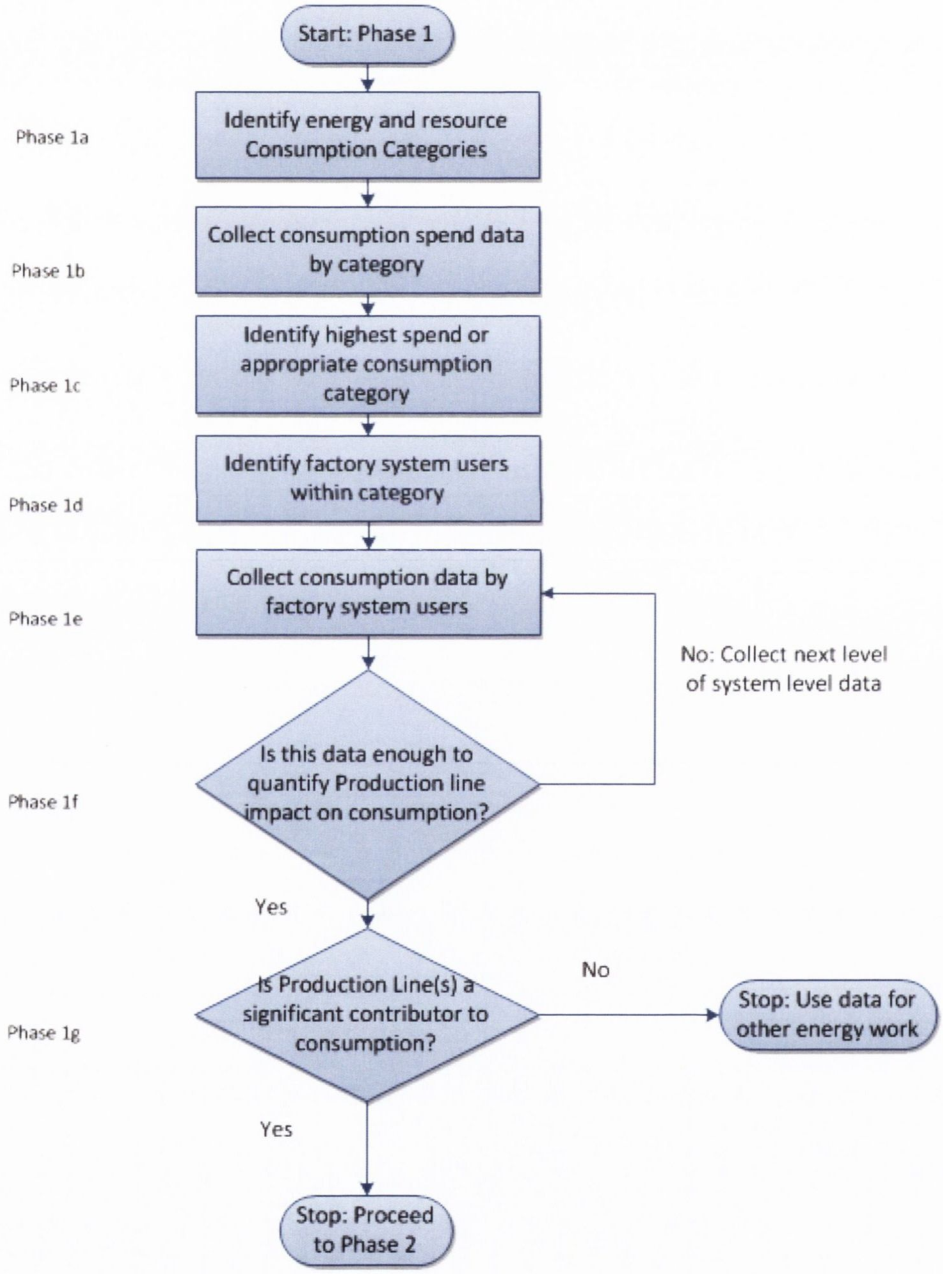


Figure 3.4 – Phase 1: Energy and resource assessment

By engaging in phase 1, a baseline of consumption is recorded which can be used to engage factory support. This data will be used to drive a sense of urgency needed to facilitate organisational change. It supports the assembly of appropriate skills to support further characterisation and improvement efforts as argued by Kotter in his assessment of 'Why Transformation Efforts Fail' [216] where he cites management engagement and empowerment to act as key to change initiatives. To be successful in driving this urgency in excess of 75% of management need to be convinced by this data for support to be gathered for subsequent phases within an organisation. This exercise is also important to provide the data needed to create an organisational vision for future energy performance. The outline of the requirements for an energy and resource assessment is documented in figure 3.4. This involves identifying the appropriate energy and resource categories:

$$E_g,\ E_r \dots\ E_n$$

Or

$$R_g,\ R_r \dots R_n.$$

Where:

E_g, $E_r \dots$ E_n = Energy from grid, renewables, other categories

R_g, $R_r \dots R_n$. = Resources from grid, renewables, other categories

Energy consumption will be measured in kWh, natural gas in kWh, ultra pure water in m^3, chilled/process water in kWh and air flow in cubic foot per meter. The category consumption history is then converted into cost data. A system level map is generated of users of the targeted energy and resource categories:

$$S_1,\ S_2,\ S_3\ \dots\ S_n.$$

Where $S_1 \dots$ S_n are the system level consumers within a factory.

Phase 1 formally assesses the identification of the highest energy or resource consuming systems and in particular allows the review of how influential the production environment is within factory consumption. This evaluation ensures the documentation and reporting of factory energy and resource performance to site management. Each step within phase 1 formally requires documented inputs to be collected to support the process requirements of each step. This process allows specific outputs to be obtained by step which support the execution of the proceeding operation. For example in Figure 3.5, the initial operation: step 1a for Phase 1 is outlined documenting the requirements to perform this step, in terms of soft and hard data. The complete documentation needs by phase and individual steps are documented in appendix 1. This phase focuses on creating the link between factory utility consumption and overall factory cost. Understanding the energy cost drivers, allows an organisation to directly compare this cost with other cost categories within the organisation. This in turn ensures projects are prioritised based on cost benefit to an organisation.

This phase also defines the boundaries around any potential energy improvement projects. It allows clarification of the appropriate energy category to be worked. This phase can support the creation of scope for projects and define for example where the energy project starts and ends. This also allows the identification of customers of the energy category which in turn allows the appropriate skill sets to be identified within the organisations workforce to support appropriate energy improvement projects. By addressing these areas, energy improvement opportunities can be given the appropriate level of scrutiny and support by site management, who ultimately allocate resourcing and budget support.

	Input	Model	Output
1a	Identify source of information: • Utility Bills • Finance Groups • Facility Management • Vendor or Service Management • Building Metering •Automated Reporting Systems	• Document Energy and Resource catagories, $E_{TOT} = E_g + E_r \ldots E_n$ E_{TOT} = total energy inputs E_g = power from grid E_r = power from renewables $R_{TOT} = R_g + R_r \ldots R_n$ R_{TOT} = total resource inputs R_g = resources from grid R_r = resources from renewables	• Listing of Energy and Resource catagories for factory • Gaps in factory level data collection or reporting Capability Identified

Figure 3.5 – Phase1a I/O requirements

3.3 Phase 2: Factory energy and resource mapping

The purpose of phase 2 is to understand consumption behavior of targeted manufacturing chains. Within this phase an energy or resource category is selected for further analysis. This involves generating an overall map of how the selected energy category is utilised within the manufacturing process chain $(S_{prod\ line})$ being studied.

Within this mapping process: distribution and usage are detailed for the targeted manufacturing process chain, identifying all discrete manufacturing tools $(T_1, T_2, T_3 \ldots\ldots T_n)$. The process for phase 2 is outlined in figure 3.6. See appendix A1 for detail. The intent of this approach is to study and understand patterns of consumption but also to identify measurement data gaps. This will identify future measurement improvement project opportunities. Through this mapping phase the influence of production consumption and behavior will also become apparent in terms of significance. This phase allows a more detailed understanding of consumption and ultimately cost to be built allowing an understanding of next steps. Subsequent phases use this data to progress in terms of production consumption experimentation and energy reduction. A management review of this phase may also reveal no further progress into subsequent phases is warranted due to production consumption significance or other cost based priorities are more urgent.

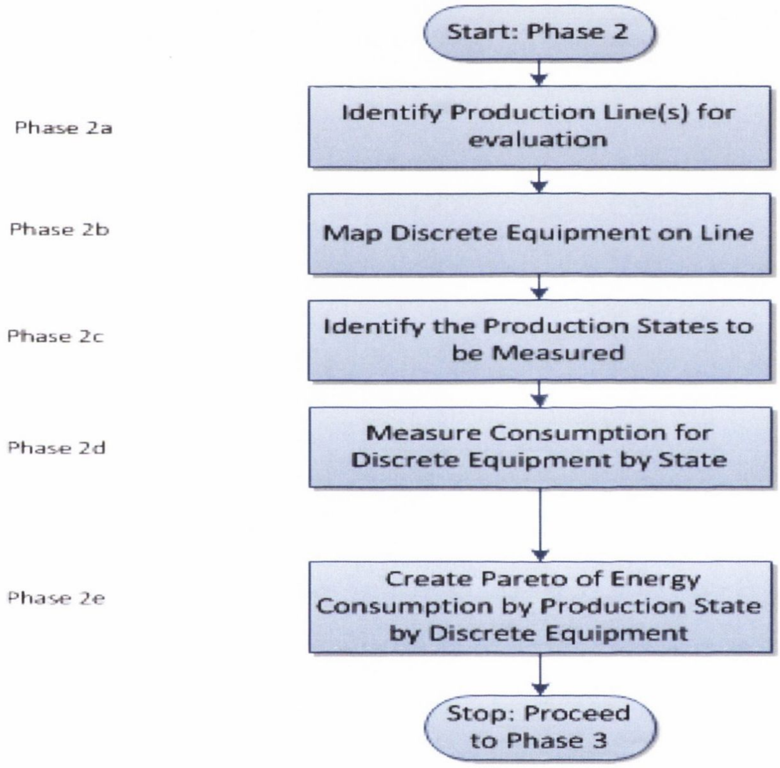


Figure 3.6 – Phase 2: Energy and resource mapping

As a result of this mapping exercise, energy consumption is recorded for all production equipment. This metering exercise is required to correlate production level consumption (*P*) to non production level consumption (*NP*). Any differences will highlight a potential relationship between manufacturing states and energy consumption within a manufacturing process chain, for example 'running' and 'idle' consumption for discrete production equipment. This will also help develop an understanding of the 'method of operation' of the identified production line and how it is managed and run based on normal production requirements. Time and energy studies can support this understanding of the impact of normal operations to any energy patterns highlighted. As previously stated, if measurement gaps within the production line are highlighted, once off measurements can be collected for the appropriate equipment by using handheld or appropriate metrology, e.g. fluke meters or flow meters. This can be done for all normal operation usage modes and is used to enhance the consumption picture of the production line being studied. Figure 3.7 highlights the consumption picture at a production line level, which will be generated from phase 2, for a given manufacturing state, energy consumption can be collected for the targeted production line.

	Input	**Model**	**Output**
2e	• $S_{prod\ line}$ or production line of interest S_x • $E_{prod\ line}$ or $R_{prod\ line}$ • Production State(s) for $T_1, T_2 \ldots T_n$	• For $E(T_{1..n}) = E_P + E_{NP}$	• For a given production state P or NP, $E_{prod\ line}$ pareto of $E(T_1)+E(T_2)+E(T_3)+\ldots+E(T_n)$ Where $E(T_1) = E_P + E_{NP}$

Figure 3.7 – Step 2e: Consumption calculation for manufacturing process chains

From this analysis, a distribution of energy consumption ($E_{prod\ line}$) can be created for the production line identified. This highlights production equipment which is energy intensive and may warrant future investigation - $E(T_1)$, $E(T_2)$,...,$E(T_n)$. This data can also be supplemented with a time study analysis to understand the potential opportunity that may exist from the amount of time equipment is operating within normal operation usage modes. This will highlight potential optimisation opportunities for specific productive (*P*) or non productive (*NP*) modes. The range of production modes monitored will vary depending on the industry or manufacturing site but productive modes include all value add modes which the manufacturing environment deem important to revenue for example: running production, quality tests or internal equipment testing to ensure functionality. Non productive modes will include all non value add modes which the manufacturing environment deem wasteful or wasteful but required for example idle time, down time or maintenance time.

This analysis forms the basis of a team based exercise where the data is presented to the production line workforces who operate the equipment and participated in phase 2. This allows input to be given by the workforce on the impact of operations, specifically overall equipment effectiveness metrics such as availability, performance efficiency and quality [217]. It also allows the workforce to give input on where to identify opportunity for energy reduction or efficiency opportunities.

3.4 Phase 3: Production equipment opportunity identification

The purpose of phase 3 is to identify and characterise energy consumption within a significant energy user within the targeted production system. From the previous phase it will be possible to identify discrete production equipment that are significant energy users within the identified production line(s) for example:

$$E(T_1),\ E(T_2),\dots,E(T_n).$$

These can be targeted for a deeper level of understanding of how the energy category is consumed for specified usage modes. This requires the development of equipment energy maps with principle components or modules identified ($c_{1\text{-}n}$). The process for Phase 3 is outlined in figure 3.8. The primary resources used for this phase are the maintenance and engineering disciplines that support production equipment operations. These resources will be responsible for tool and module metering as well as reviewing factory information systems.

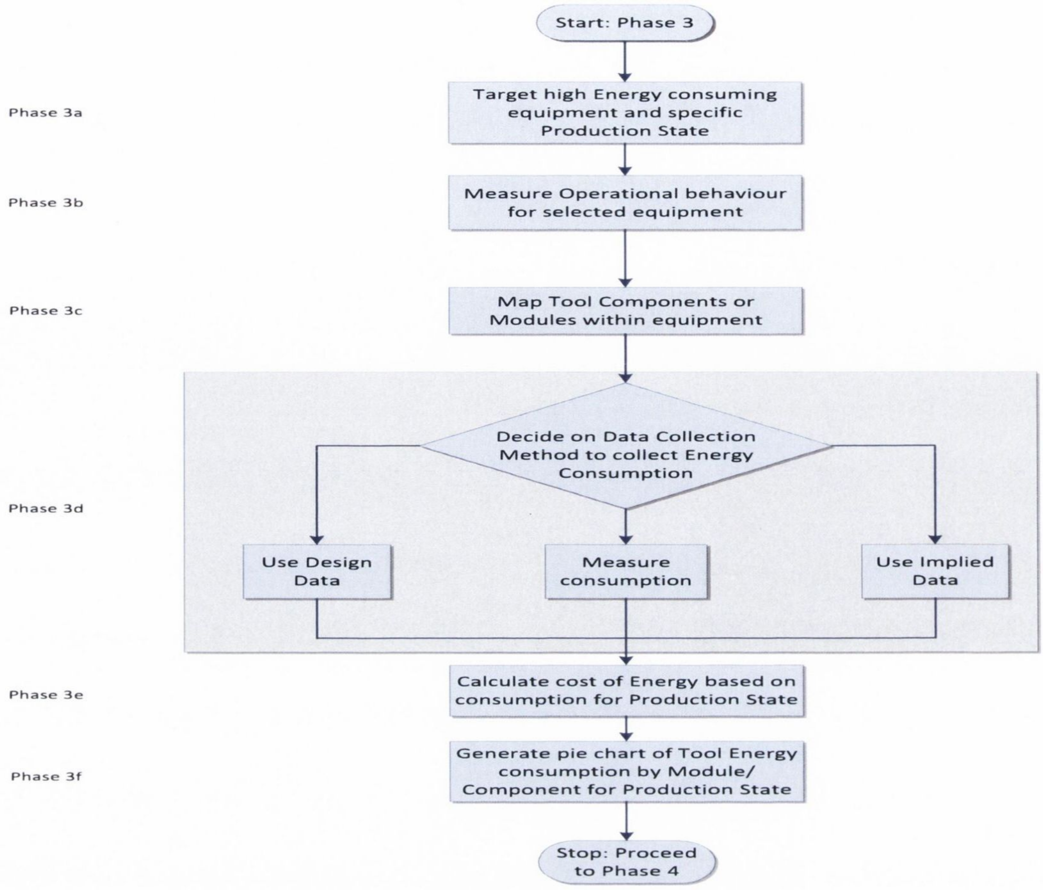


Figure 3.8 – Phase 3: Production equipment energy evaluation

This can be carried out through physically mapping out the significant energy users within the manufacturing process chain and metering (*m*) each component or module of interest. It can also be realised through using original equipment manufacturer (OEM) schematics to understand consumption if metering is not possible (*d*). A combination of both can also be used to imply (*i*) performance depending on the equipment capability for measurement. This allows a testing plan to be devised where each of the areas identified can be measured to build an understanding of how energy is consumed within the identified equipment:

$$E\ (T_1)_m$$

Where (*m*) is metered energy consumption (*E*) of a production tool T_1.

The result of this phase is a complete energy profile defined for particular usage mode(s) of operation (*P* or *NP*) on identified discrete production equipment. The level of analysis within this phase also supports a more thorough understanding of how energy is used on targeted production equipment which allows a reference to be created. It is from this reference that workshop exercises are completed with operations, maintenance and engineering to understand what improvement opportunities are possible. This data gathering exercise forms the justification for subsequent progress. This is outlined in figure 3.9 where the input-output requirements are highlighted.

	Input	**Model**	**Output**
3f	• Process level map of equipment: $E(c_1),E(c_2),E(c_3),..,E(c_n)$ for state NP	• Create table of tool consumption by module where $E(T_1)_m= E(c_1)+E(c_2)+E(c_3)+....+E(c_n)$	• Breakdown of Production Equipment module costed consumption for $E(c_1),E(c_2),E(c_3),....,E(c_n)$

Figure 3.9 – Step 3f: Approach used to characterise equipment module based consumption

Upon completion of phase 3, a consumption characteristic can be generated for a factory which includes the impact of production systems for energy or another resource category. A significant end user of either the energy or resource category is understood in terms of tool and modular consumption behaviour. From this analysis, a factory can generate value, ultimately through 2 differing ways. Use the information to understand the total energy content per part, for both direct and indirect consumption in their factory setting. This challenges an organisation to develop and improve on baseline performance in line with their corporate objectives. Or to use the subsequent phases to be outlined to evaluate energy improvement opportunities on the significant energy users within manufacturing process chains.

3.5 Phase 4: Risk and cost benefit analysis

In chapter 2 workforce involvements in decision making was explored in terms capturing human factor experience of equipment and operational performance through using the analytical hierarchy process. It is through this process human experience can be leveraged to identify energy reduction opportunities and what equipment performance criteria must be considered when identifying potential reduction opportunities. However in order to understand what energy savings can potentially be realised it is necessary to comprehend the risks and potential impacts related to tool performance if energy based change is pursued as these concerns may have greater cost impacts than the energy changes being considered. Management support will be necessary to support this trade off. Phase 4 addresses this concern through formally evaluating cost based improvements against the risk of implementation. 3 areas are considered with respect to any improvements identified. These are:

- Risk to functionality of equipment with optimised energy behavior
- Formal evaluation of factory capability to manage project(s) optimising energy behavior on manufacturing process chains
- Cost benefit analysis of equipment with optimised energy behavior

To whom or what area within the organisation benefits from any improvements are identified to ensure their participation in any evaluations completed. From the point of view of discrete production equipment, the engagement of the workforce, both maintenance and operations are critical to all 3 areas of concern, due to their unique and specialised understanding of equipment performance as their level of understanding of performance goes beyond metrics. The previous phases, most notably phase 3, provide a detailed understanding of current equipment performance in terms of energy consumption through metering and data gathering. This acts as the baseline to reference any energy improvements against but also to provide a data based argument for further characterisation and experimentation. From a risk mitigation perspective, the data collected and the subsequent testing of opportunity is approached from 2 perspectives: from an equipment functionality perspective which is evaluated in phase 4 and impact to factory KPI perspective, which is evaluated later in phase 5. The success criteria used in both phase 4 functionality and 5 pilot evaluations is illustrated in figure 3.10. Using a hypothesis based testing approach, optimized tool performance as a result of an energy consumption adjustment on production equipment is evaluated against tool reference performance.

H_0: No difference in equipment performance resulting from implementing an energy opportunity

H_A: There is a difference in equipment performance resulting from implementing an energy opportunity. This difference could be either higher or lower performance.

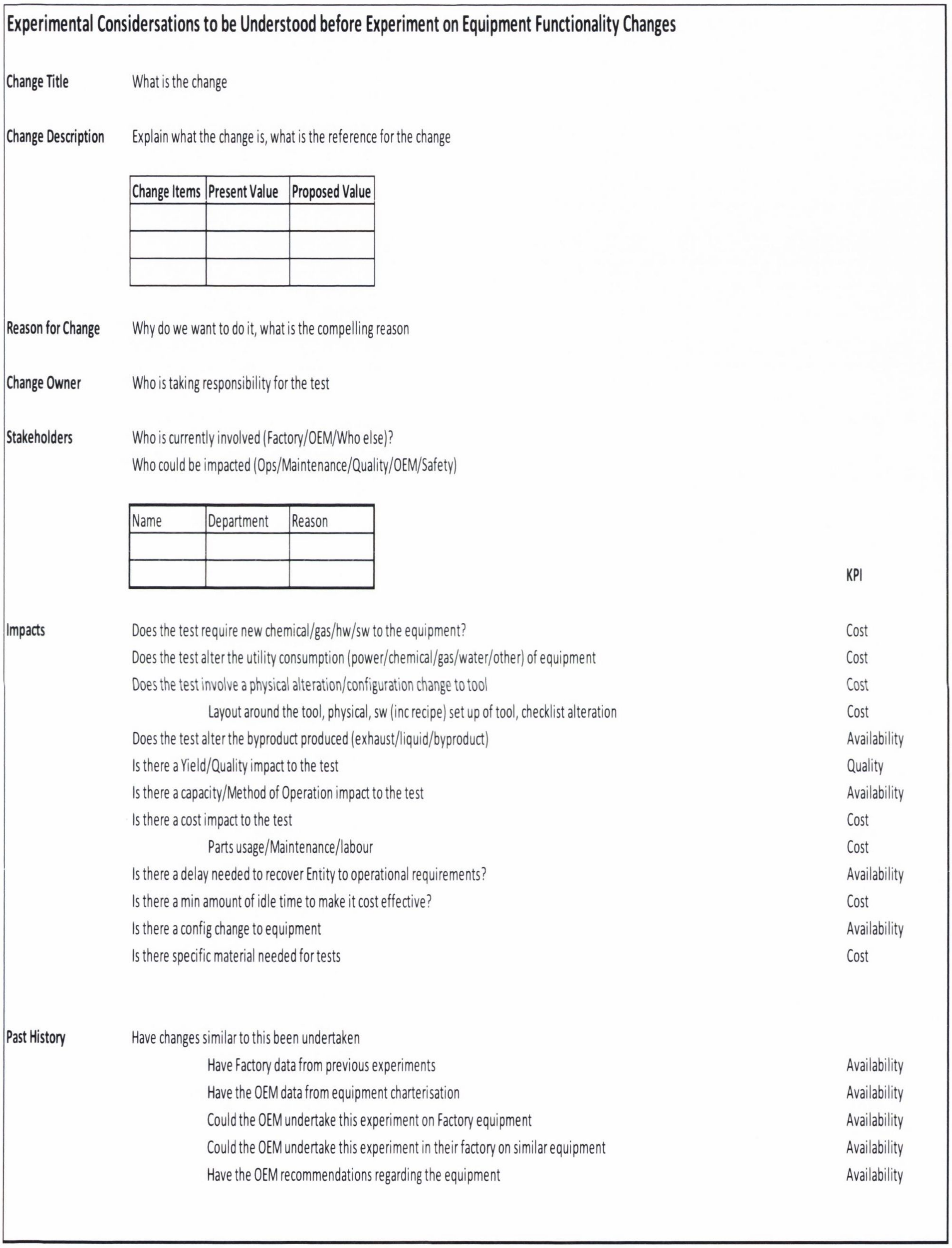
Using this approach, to avoid incorrectly rejecting an opportunity, tool functionality and related parameters are evaluated to understand if the opportunity should be selected for further analysis. By completing initial functionality evaluations and tests ensures the avoidance of incorrectly rejecting appropriate opportunities. It is with this approach that any testing undertaken in phase 4 is completed. To avoid incorrectly accepting a functionally valid opportunity as having long term KPI stability, a subsequent set of tests are performed in phase 5 to ensure no impact to targeted equipment performance over a specified time frame. This can be monitored by targeting appropriate factory metrics (KPI's) which equipment is managed to within the factory environment, for example availability, quality and cost. By evaluating over a longer period of time, a deeper level of understanding can be empirically and statistically obtained to ensure the appropriate level of understanding has been completed. It is with this approach that subsequent testing in phase 5 uses. As factory's are dynamic environments with multiple parameters or KPI's being managed at any given time, this subsequent testing provides the chance to ensure any potential gaps in the initial testing that may only become apparent over time are noted. This will ensure potential improvements or mitigation steps can be actioned early to ensure, if possible no opportunities are rejected incorrectly.

Decision	Null Hypothesis: True	Null Hypothesis: False
Reject H0	Incorrect decision	Correct decision
Accept H0	Correct decision	Incorrect decision

Figure 3.10 – Equipment evaluation approach used to test energy opportunities

3.5.1 Functionality of equipment with optimised energy behaviour

By engaging the appropriate workforce: equipment maintenance, operations and engineering in brainstorming energy improvements on targeted production systems, their unique perspective can be utilised to identify improvements. This unique perspective comes from their knowledge of equipment behavior through preventative maintenance (PM), good manufacturing practices (GMP) and constant engagement with equipment based tasks. This level of experience in performing equipment based tasks ensures a thorough knowledge of what targeted equipment is functionally capable of. Manufacturing process equipment is historically optimised for functionality and repeatability with respect to production output. As a result, optimised energy performance can be overlooked as a core requirement in production system set up. It is necessary to review all data collected to date with the process, from phases 1 to 3. This allows an understanding of the impact of equipment performance on energy behavior to be generated. In terms of comprehending is targeted production equipment capable of being optimised with respect to energy consumption, a number of considerations must be understood. These are the type of change being evaluated, stakeholders involved, potential impacts or consequences that may arise and critically past history or experiments that may have been undertaken. Figure 3.11 details a formal review procedure to capture all relevant considerations.



Experimental Considersations to be Understood before Experiment on Equipment Functionality Changes

Change Title What is the change

Change Description Explain what the change is, what is the reference for the change

Change Items	Present Value	Proposed Value

Reason for Change Why do we want to do it, what is the compelling reason

Change Owner Who is taking responsibility for the test

Stakeholders Who is currently involved (Factory/OEM/Who else)?
Who could be impacted (Ops/Maintenance/Quality/OEM/Safety)

Name	Department	Reason

		KPI
Impacts	Does the test require new chemical/gas/hw/sw to the equipment?	Cost
	Does the test alter the utility consumption (power/chemical/gas/water/other) of equipment	Cost
	Does the test involve a physical alteration/configuration change to tool	Cost
	Layout around the tool, physical, sw (inc recipe) set up of tool, checklist alteration	Cost
	Does the test alter the byproduct produced (exhaust/liquid/byproduct)	Availability
	Is there a Yield/Quality impact to the test	Quality
	Is there a capacity/Method of Operation impact to the test	Availability
	Is there a cost impact to the test	Cost
	Parts usage/Maintenance/labour	Cost
	Is there a delay needed to recover Entity to operational requirements?	Availability
	Is there a min amount of idle time to make it cost effective?	Cost
	Is there a config change to equipment	Availability
	Is there specific material needed for tests	Cost
Past History	Have changes similar to this been undertaken	
	Have Factory data from previous experiments	Availability
	Have the OEM data from equipment charterisation	Availability
	Could the OEM undertake this experiment on Factory equipment	Availability
	Could the OEM undertake this experiment in their factory on similar equipment	Availability
	Have the OEM recommendations regarding the equipment	Availability

Figure 3.11 – Production equipment considerations for functionality testing

These considerations and consequent mitigation planning will support functionality evaluation, and specifically will support step 'phase 4Fc' of phase 4 as shown in figure 3.11. This template allows a formal template in which to engage maintenance and operations personnel, engineers and management. It ensures all groupings within the organisation that can be impacted by an energy based change are consulted. These groups will also have the required capabilities to support decision making due to their in-depth understanding of equipment, operations and factory performance. The template will act as an engagement tool to encourage personnel to think beyond day to day performance metrics to understand any potential contributing factors to their equipments performance. This level of understanding is required to ensure all variables which could affect tool functionality are identified and comprehended. This process will validate some opportunities as being feasible and potentially eliminate or delay some opportunities. Delays will be due to potential upgrades or improvements being required to support the energy improvement opportunity. Elimination of an opportunity would be due to a factory not being in a position to support certain opportunities such as excessive capital requirements or lack of suitability of production equipment to being upgraded. The identification of independent variables which can affect equipment performance will allow, under defined testing the opportunity to evaluate those opportunities in terms of potential issues that could arise. Early identification of these variables also provides an opportunity for mitigation planning. From this exercise a future state energy consumption profile can be generated:

$$E_f\,(T_1)_m$$

Where (m) is the metered future energy consumption (E_f) of a production tool T_1.

The opportunities which support this new optimised energy consumption profile can then be progressed in a subsequent step of this phase, which understands the risk to key performance indicators (KPI's) on which the production equipment is managed to. Figure 3.12 highlights the procedure to support functionality testing. The expected outcome of this process is to have identified opportunities that have been validated as functionally possible. This process considers equipment energy reduction in terms of a single module system or a multi-module system to accommodate a range of equipment configurations. These configurations can then be evaluated against a single constraint or multiple constraints depending on the complexity of the manufacturing environment involved.

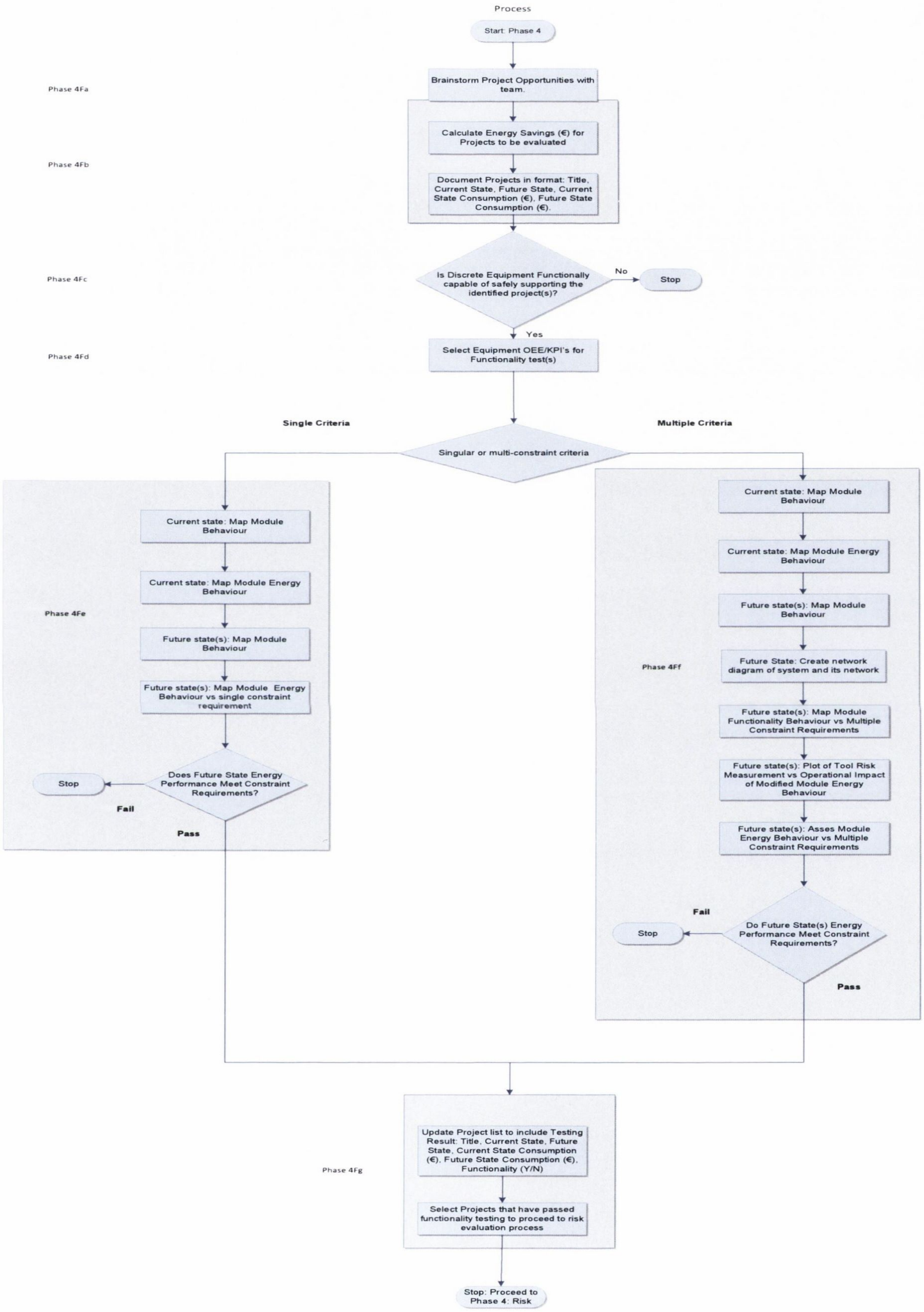


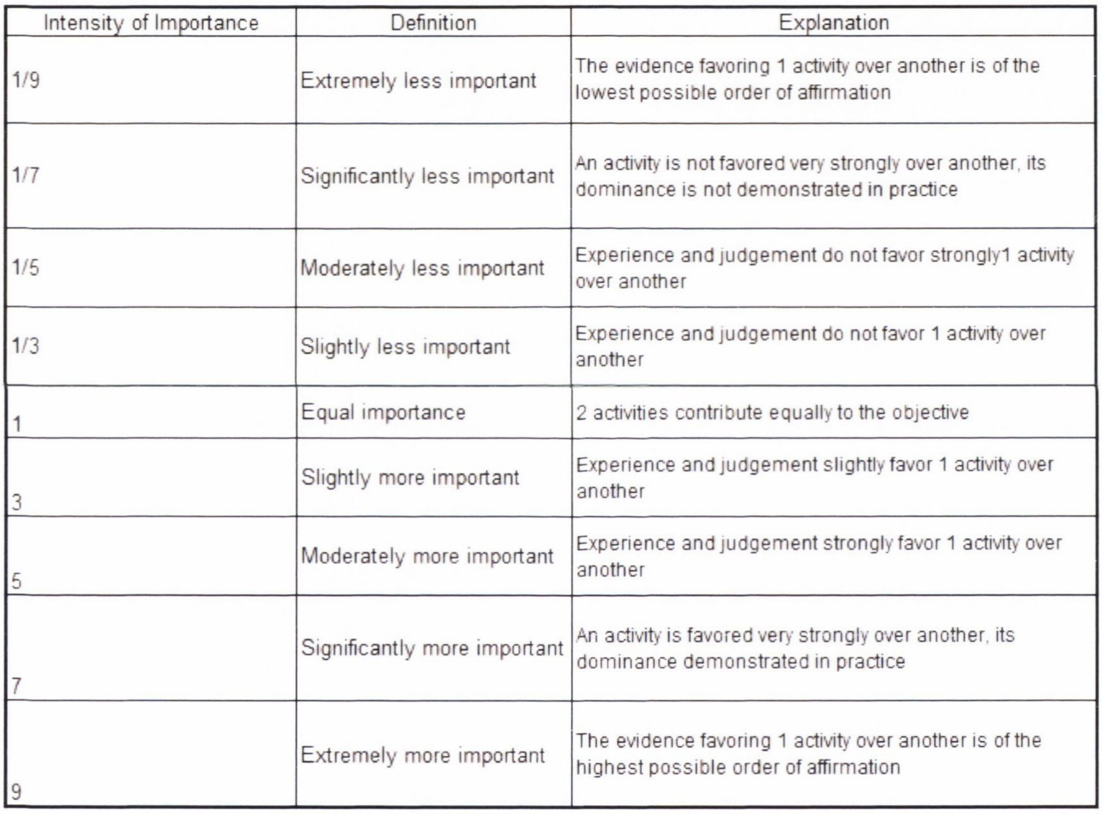
Figure 3.12 – Phase 4 Functionality: Functionality testing of equipment with optimised energy behavior

3.5.2 Formal evaluation of factory capability to manage project(s)

Due to the complexity of a modern factory structure and the output focus that drives factory based performance. Improvement activities must show equivalency to current compliance performance and standards before full implementation. It is as a result of this challenge that even modest or benign change can be rejected. The impression of risk or an uninformed opinion of what may happen can often push key decision makers to avoid change. Within factory structures, there are many departments that have distant or indirect relationships with the production line environment and as a result, measuring compliance versus factory output may be challenging. However for departments such as facility, energy and maintenance management, a different challenge arises due to the need of energy and utilities to support production line functionality and changes to utility delivery or usage may impact production performance greatly. The initial phases outlined are designed to allow an understanding of consumption through the use of equipment based personnel to collect the required data: operations, maintenance, engineering and equipment vendors. This requires factory management to facilitate this capability being developed. Through the costing of energy consumption in these initial phases, management has the justification to facilitate this ongoing development as this investment can lead to reduction opportunities. This capability also allows Key Performance Indicators (KPI's) and Overall Equipment Effectiveness (OEE) metrics which manufacturing process chains are managed to, to be understood. Figure 3.13 displays the overall flow required for this phase and how this capability and in-depth knowledge of equipment performance is leveraged. Initially factory priorities can be understood with respect to equipment performance. The performance metrics used are Availability (A_1), Quality (A_2) and Cost (A_3) as these are the most widely used KPI's on which to track equipment performance on a daily basis. Pair wise comparisons can be performed between A_1, A_2 and A_3 using the workforces experience of operations to assign an importance value. The scale used to assign a value is shown in table 1. See appendix 1 for detail relating to calculations. This will result in normalised or prioritisation values generated B_1, B_2 and B_3 as shown in equation 3.

$$\begin{array}{cc} & \begin{array}{ccc} A_1 & A_2 & A_3 \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ A_3 \end{array} & \begin{bmatrix} 1 & a_{12} & a_{13} \\ {}^{1}/_{a_{12}} & 1 & a_{23} \\ {}^{1}/_{a_{13}} & {}^{1}/_{a_{23}} & 1 \end{bmatrix} = \begin{array}{c} B_1 \\ B_2 \\ B_3 \end{array} \end{array} \qquad (3)$$

Due to the subjectivity that can arise when completing pairwise analysis and identifying the appropriate performance metrics it is necessary to complete this activity using a team based approach. By involving operations, maintenance, engineering and management in this activity and utilising factory information systems used to manage equipment performance, subjective interpretation and sensitivity to a particular parameter can be avoided. These values are a reflection of how production line personnel value metrics and as a result prioritise how they engage with equipment on a daily basis. It also allows personnel from outside the production environment to understand what KPI's need to be evaluated in any projects that may impact production line performance.



Intensity of Importance	Definition	Explanation
1/9	Extremely less important	The evidence favoring 1 activity over another is of the lowest possible order of affirmation
1/7	Significantly less important	An activity is not favored very strongly over another, its dominance is not demonstrated in practice
1/5	Moderately less important	Experience and judgement do not favor strongly1 activity over another
1/3	Slightly less important	Experience and judgement do not favor 1 activity over another
1	Equal importance	2 activities contribute equally to the objective
3	Slightly more important	Experience and judgement slightly favor 1 activity over another
5	Moderately more important	Experience and judgement strongly favor 1 activity over another
7	Significantly more important	An activity is favored very strongly over another, its dominance demonstrated in practice
9	Extremely more important	The evidence favoring 1 activity over another is of the highest possible order of affirmation

Table 1 – Importance scale for KPI prioritisation

Within each of these performance metrics A_1, A_2 and A_3, how these metrics monitor performance, what reason they were put in place and their capability to support the management of a production line can also vary depending on the requirements at time of creation. The reasoning behind the set up of the metrics may be lost due to changes in performance or changes in personnel. As a result, it is necessary to formally understand what value the individual performance metrics deliver in terms of the production line. This can be achieved by reviewing each KPI in terms of the following categories: likelihood (L), detectability (*D*) and severity (*S*). This understanding will facilitate to a more detailed level the ability of the individual performance metrics to manage energy based change. A team based FMEA exercise can be completed which allows failure modes to be identified with the production equipment identified for energy reduction. This team based exercise will allow a qualitative analysis of failures that can occur and be monitored by factory metrics for changes in occurrence during subsequent testing. By engaging maintenance and operations through their experience as previously undertaken, pair wise comparisons can be completed for the categories (*L*, *D*, *S*) outlined to understand an importance value (*I*) for each category within the factory performance metrics such that an importance or priority value can be assigned to each KPI in terms of *L*, *D* and *S*. For example the importance value (*I*) assigned by the workforce to the possibility of detecting a change (*L*) to the availability metric (A_1) is denoted as:

$$I_{A1}^{L}$$

A table of relevant importance values is shown in table 2. See appendix 1 for detail relating to calculations. For both Availability (A_1) and Cost (A_3) pair wise comparisons are only completed for Likelihood and Severity as historically these metrics are extensively tracked within production environments which results in highly detectable monitoring. Due to the high degree of variability that can occur in terms of Quality (A_2), detectability was included. As many factors can influence quality performance, many which may not be related to any potential energy change.

KPI	Likelihood (L)	Detectability (D)	Severity (S)
Availability (A_1)	I_{A1}^{L}		I_{A1}^{S}
Quality (A_2)	I_{A2}^{L}	I_{A2}^{D}	I_{A2}^{S}
Cost (A_3)	I_{A3}^{L}		I_{A3}^{S}

Table 2 –Prioritisation values by KPI

By ensuring these are monitored and understood a more effective analysis can be performed in subsequent phases. The interaction with the factory floor personnel up to this point has allowed their experience to support a formal review of a factory's priorities and what aspects of three core KPI's are seen as valuable to an organisation. This ensures from a management perspective a thorough understanding of a factories ability to engage in energy related projects within a production environment is understood before decision making. By using the projects selected from the output of the previous functionality evaluations, maintenance and operations experience can also be utilised to obtain an understanding of how successful these projects will be in terms of existing KPI's. A table of relevant values assigned through this experience is shown in table 3. See appendix 1 for detail relating to calculations. For projects identified for example Z_1 and Z_2, a value can be assigned by the maintenance, operations and engineering based on their experience and intimate understanding of factory metrics, to the possibility a change in performance of a KPI (A_1, A_2, A_3) in terms of likelihood (L), detectability (D) and severity (S) [218, 219]. For example a likelihood value (L) can be assigned by the workforce to the possibility of observing a change in the availability metric (A_1) if project Z_1 was implemented can be denoted as:

$$L_{A1}^{Z1}$$

KPI	Project	Likelihood (L)	Detectability (D)	Severity (S)
A_1	Z_1	L_{A1}^{Z1}		S_{A1}^{Z1}
	Z_2	L_{A1}^{Z2}		S_{A1}^{Z2}
A_2	Z_1	L_{A2}^{Z1}	D_{A2}^{Z1}	S_{A2}^{Z1}
	Z_2	L_{A2}^{Z2}	D_{A2}^{Z2}	S_{A2}^{Z2}
A_3	Z_1	L_{A3}^{Z1}		S_{A3}^{Z1}
	Z_2	L_{A3}^{Z2}		S_{A3}^{Z2}

Table 3 – Normalised prioritisation values by KPI

The values attributed are highlighted in table 4. The scoring values assigned reflect the workforces view on changes occurring to the KPI's in terms of Likelihood (L), Detectability (D) and Severity (S) as a result of an energy projects Z_1 and Z_2 being implemented.

Score	Detail	Likelihood/Detectability	Severity
1	Certain Fail	100% certainty	Major Impact
3	High Risk	>80% certainty	Significant Impact
5	Med Risk	≈50% certainty	Medium Impact
7	Low Risk	<30% certainty	Minor Impact
10	No Risk	Certain of no issue	No Impact

Table 4 – Scoring chart for project(s) by workforce

A capability score can then be calculated by project (Z_1), as shown in equation 4 which reflects a factory's ability to monitor and manage a change based on a company's priorities and capabilities.

$$Project\ Z_1 = \begin{bmatrix} B1\Big((L_{A1}^{Z1} \times I_{A1}^{L}) + (S_{A1}^{Z1} \times I_{A1}^{S})\Big) + \\ B2\,\Big((L_{A2}^{Z1} \times I_{A2}^{L}) + (D_{A2}^{Z1} \times I_{A2}^{D}) + (S_{A2}^{Z1} \times I_{A2}^{S})\Big) + \\ B3\Big((L_{A3}^{Z1} \times I_{A3}^{L}) + (S_{A3}^{Z1} \times I_{A3}^{S})\Big) \end{bmatrix} \tag{4}$$

The capability score is a function of the collective experience of the workforce team which have interacted with the process outlined. The individual scoring by project generated is individual to that project alone, with no relationship between the individual scores. The maximum scoring value obtainable is 10, which reflects a high degree of capability to manage an energy improvement change in a production line environment. The score itself does not gauge whether the energy improvement will positively improve the performance of the manufacturing process chain, in terms of KPI's. It reflects an appropriate level of ability within the organisation to support energy based change management in a production environment. Lower scores reflect potential gaps that may impact capability and highlight potential risks to the KPI's in terms of how capable an organisation is to manage a change with respect to energy projects and are they likely to cause an issue, would they be detected and if so how severely they potentially could impact production line KPI's. These issues and scoring will highlight gaps and improvement opportunities, that if resolved will improve the capability scoring for respective projects and an organisations capability to implement energy based change.

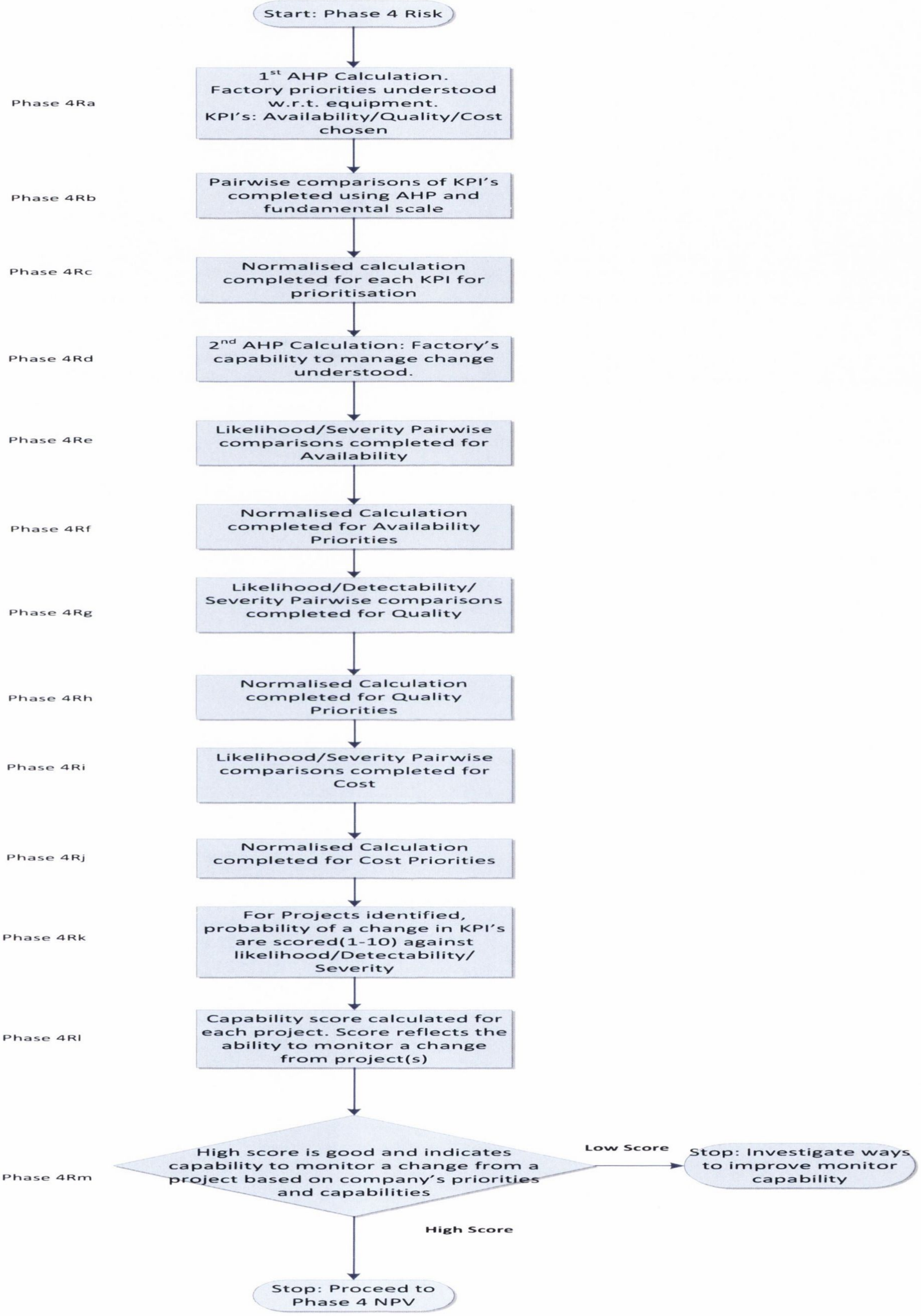


Figure 3.13 – Phase 4 Risk: Evaluation of capability to support energy based change

3.5.3 Net present value of equipment with optimised energy behavior

Factory's have multiple priorities, all of which must be managed regularly to ensure performance is met. The process outlined to date has identified energy based improvement opportunities that will improve performance and assess a factory's capability to manage. However, despite this improved understanding of a factory's ability to implement energy based projects, due to multiple and potentially conflicting priorities the project may not meet site requirements for implementation. To reduce this potential risk, it is necessary to compare the identified energy based projects to overall factory priorities in terms of cost of implementation. 2 scenarios will exist in terms of project implementation: equipment capability exists or capability modifications are required. The capability may exist on the equipments existing configuration to allow an energy project to be brought forward to phase 5. If the capability does not exist on the equipments existing configuration then an investment may be required to realise the energy improvements identified in previous phases. It will be the responsibility of management to approve the capital for these improvements and as a result the investment will need to be financially justified. See appendix 1 for detail relating to calculations to support this phase. By considering cost requirements, a practical understanding can be achieved which will allow the owner of the relevant projects to evaluate their projects with respect to costing impact on the organisation. This will support a more detailed review by financial resources within the organisation at a later stage in a factory's process. By utilising the Preinreich-Lucke theorem [220], the time value of money required for an investment can be used to appraise long term projects. This indicator allows cash flows, both incoming and outgoing from an investment to be evaluated. Each cash input/outflow as a result of an investment is discounted back to its Present Value (PV) and summed, such that the NPV is the sum of all terms as shown in equation 5.

$$NPV(i) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} \qquad (5)$$

Where

i = the discount rate or the rate of return what would be earned from the investment in the market with a similar risk

R_t= the net cash flow at time t

N = the total number of time periods (years)

By collecting the variables shown, an initial cost based assessment can be completed by the project owners to ensure relevance and importance when assessments are completed against other priorities and projects. A high level decision can then be made as outlined in table 5 on how relevant energy projects will measure on a cost basis relative to other factory priorities.

Value	Detail	Decision
NPV>0	Value Add Investment	Accept Project
NPV<0	Negative Value Investment	Reject Project
NPV=0	Neutral Investment Value	Project Adds no monetary Value. Use other company criteria to decide on success criteria

Table 5 – NPV decision criteria

Figure 3.14 highlights the procedure to support the evaluation of NPV by project. By performing this evaluation each project can be formally evaluated in terms of both an organisations capability to manage energy based change through their factory and include financially favorable projects in terms of quick investment recoupment. This is currently a critical requirement for legacy based factories in terms of continuous improvement and affordability.

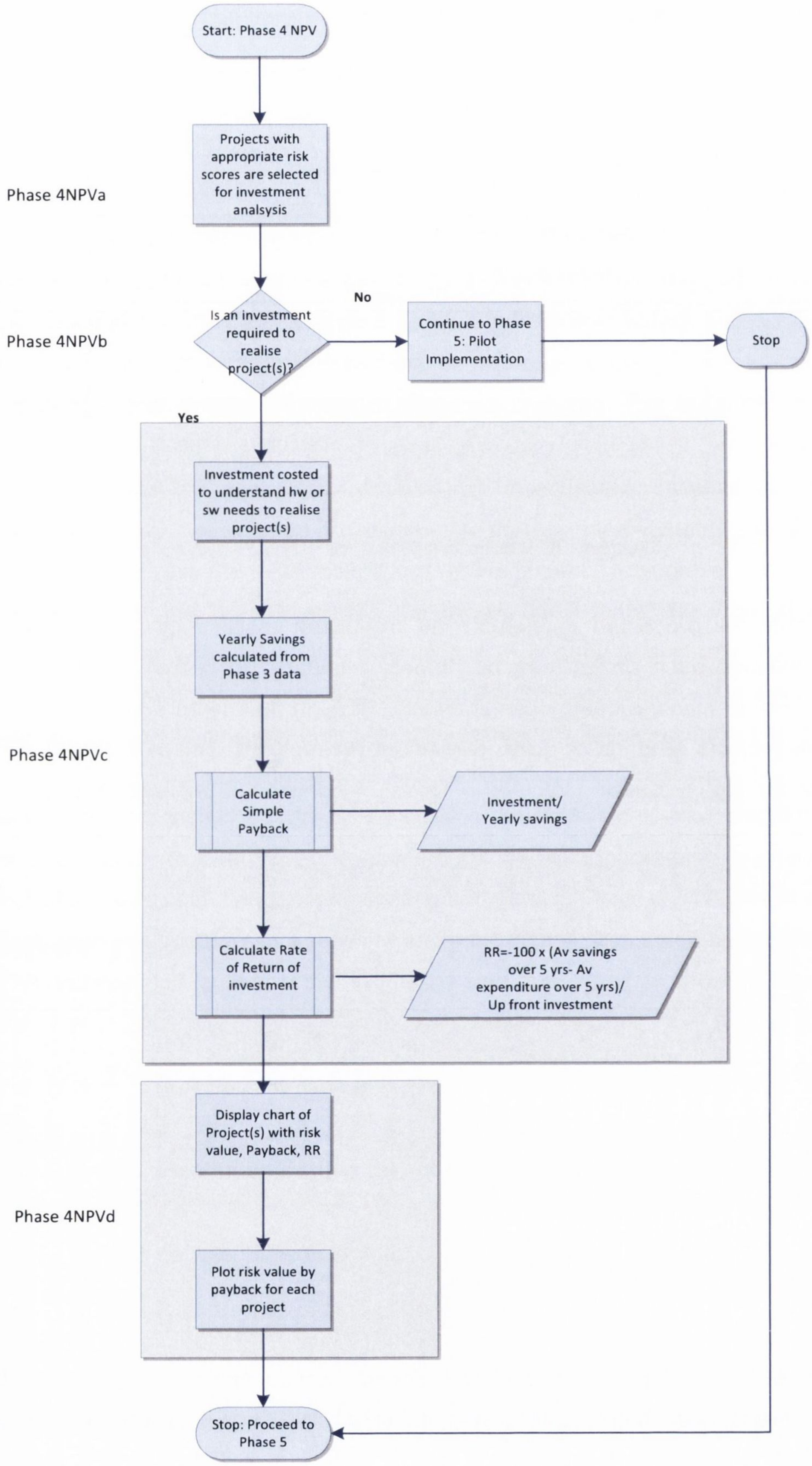
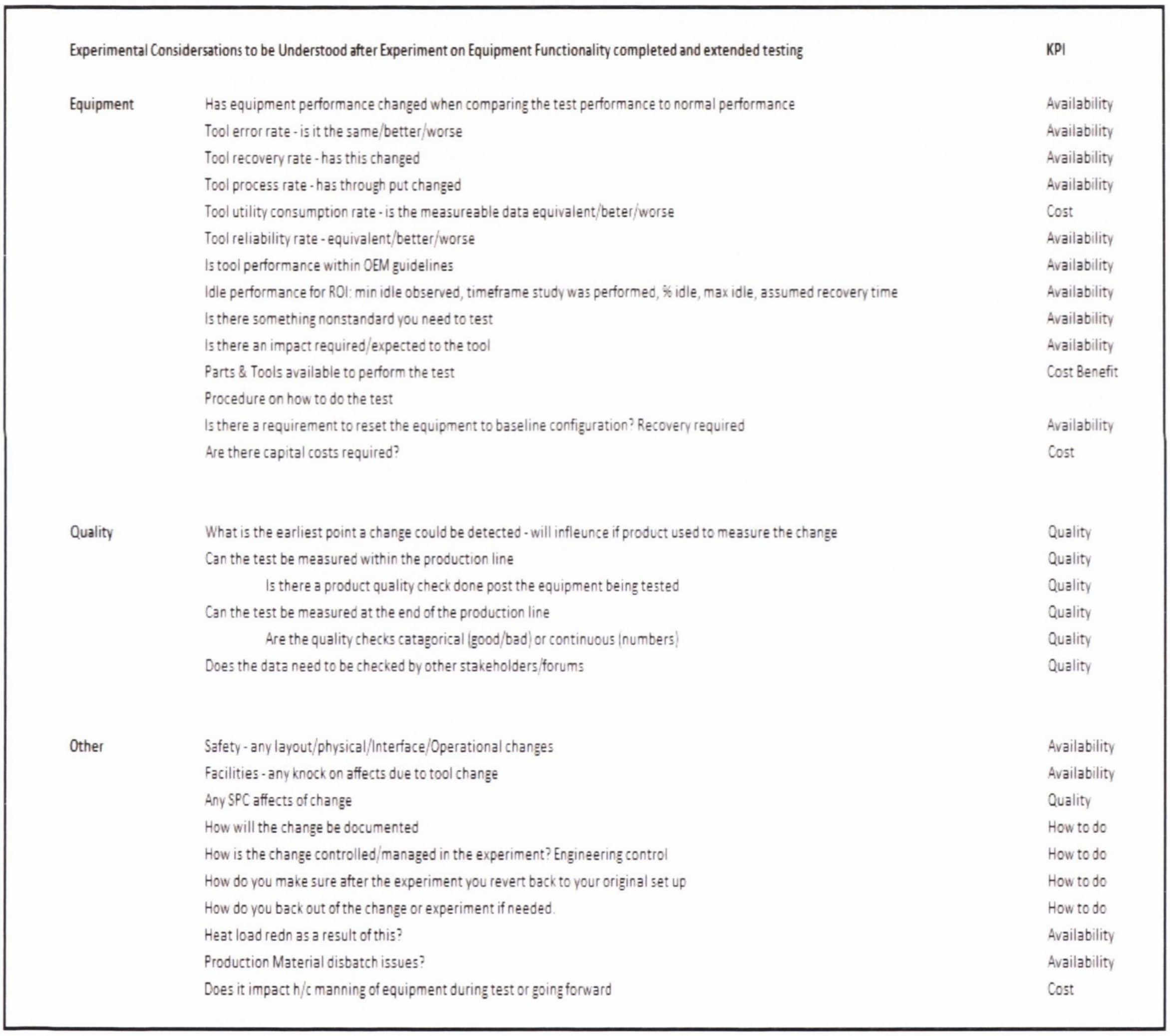


Figure 3.14 – Phase 4 NPV: Evaluation of financial viability of energy based change

3.6 Phase 5: Pilot implementation

In this phase high scoring projects with acceptable payback durations are evaluated. A team based approach using the experience of factory floor and management is again utilised to define an acceptable time duration under which the energy based projects are evaluated. The team membership will be more inclusive of management at this stage to formally engage both factory management, energy management as well as factory level owners of the KPI's being used to evaluate the selected projects over time. This will ensure as customers, expectations are met and continued support is given.



Experimental Considersations to be Understood after Experiment on Equipment Functionality completed and extended testing		**KPI**
Equipment	Has equipment performance changed when comparing the test performance to normal performance	Availability
	Tool error rate - is it the same/better/worse	Availability
	Tool recovery rate - has this changed	Availability
	Tool process rate - has through put changed	Availability
	Tool utility consumption rate - is the measureable data equivalent/beter/worse	Cost
	Tool reliability rate - equivalent/better/worse	Availability
	Is tool performance within OEM guidelines	Availability
	Idle performance for ROI: min idle observed, timeframe study was performed, % idle, max idle, assumed recovery time	Availability
	Is there something nonstandard you need to test	Availability
	Is there an impact required/expected to the tool	Availability
	Parts & Tools available to perform the test	Cost Benefit
	Procedure on how to do the test	
	Is there a requirement to reset the equipment to baseline configuration? Recovery required	Availability
	Are there capital costs required?	Cost
Quality	What is the earliest point a change could be detected - will infleunce if product used to measure the change	Quality
	Can the test be measured within the production line	Quality
	Is there a product quality check done post the equipment being tested	Quality
	Can the test be measured at the end of the production line	Quality
	Are the quality checks catagorical (good/bad) or continuous (numbers)	Quality
	Does the data need to be checked by other stakeholders/forums	Quality
Other	Safety - any layout/physical/Interface/Operational changes	Availability
	Facilities - any knock on affects due to tool change	Availability
	Any SPC affects of change	Quality
	How will the change be documented	How to do
	How is the change controlled/managed in the experiment? Engineering control	How to do
	How do you make sure after the experiment you revert back to your original set up	How to do
	How do you back out of the change or experiment if needed.	How to do
	Heat load redn as a result of this?	Availability
	Production Material disbatch issues?	Availability
	Does it impact h/c manning of equipment during test or going forward	Cost

Figure 3.15 – Phase 5 considerations to be evaluated

The team should be led by the engineering resources leading the energy investigations as engineering departments normally lead technical based initiatives within organisations and are proficient in understanding complex factory requirements. This ensures a broader range of factory considerations are reviewed compared to phase 4 where tool functionality and equipment behavior were primarily considered. The team created considers and identifies performance issues that potentially could occur over time to identify the types of metrics monitored in phase 5 under the overall categories used in calculating the capability scores in the previous phase. This ensures Availability (A_1), Quality (A_2) and Cost (A_3) continue to be evaluated and maintain a high level of consistency throughout the process. The areas to be considered are highlighted in Figure 3.15. However depending on the change being considered, a wider customer base may be required for example environmental engineering, vendor engineering or financial resources to verify specialist KPI's such factory emissions, equipment behavior or part consumption respectively.

Due to the potential impacts of energy based change in terms of production line material for example scrap rate or loss of product functionality, detection points and where detectability should be considered. Table 6 highlights the detection points within a factory that need to be considered in terms of identifying the appropriate monitoring point and type of KPI used to support Phase 5. This is based on ensuring detection of any potential changes within the organisation are detected as early as possible and will ensure dynamic and an appropriate level of monitoring within a manufacturing process chain.

Detectabilty	**Interpretation**
At tool	Preferable that test can be monitored at tool without testing on product
In production line	If product is needed, a min amount used and measured at the earliest point within the prod line
At end of production line	If detectability is at the end of the line, allocate a defined batch or statistically verifiable amount of product to evaluate
In the field	Engage downstream customers as part of evaluation

Table 6 – Detectability considerations of change being evaluated

The result of this interaction is a defined extended test plan with the appropriate KPI's that are production line based. The cross team evaluation will also highlight potential gaps in capability to support pilot evaluations which will support gap closure if needed. Figure 3.16 highlights the procedure to support pilot evaluation by project with appendix 1 detailing the requirements by step within the procedure.

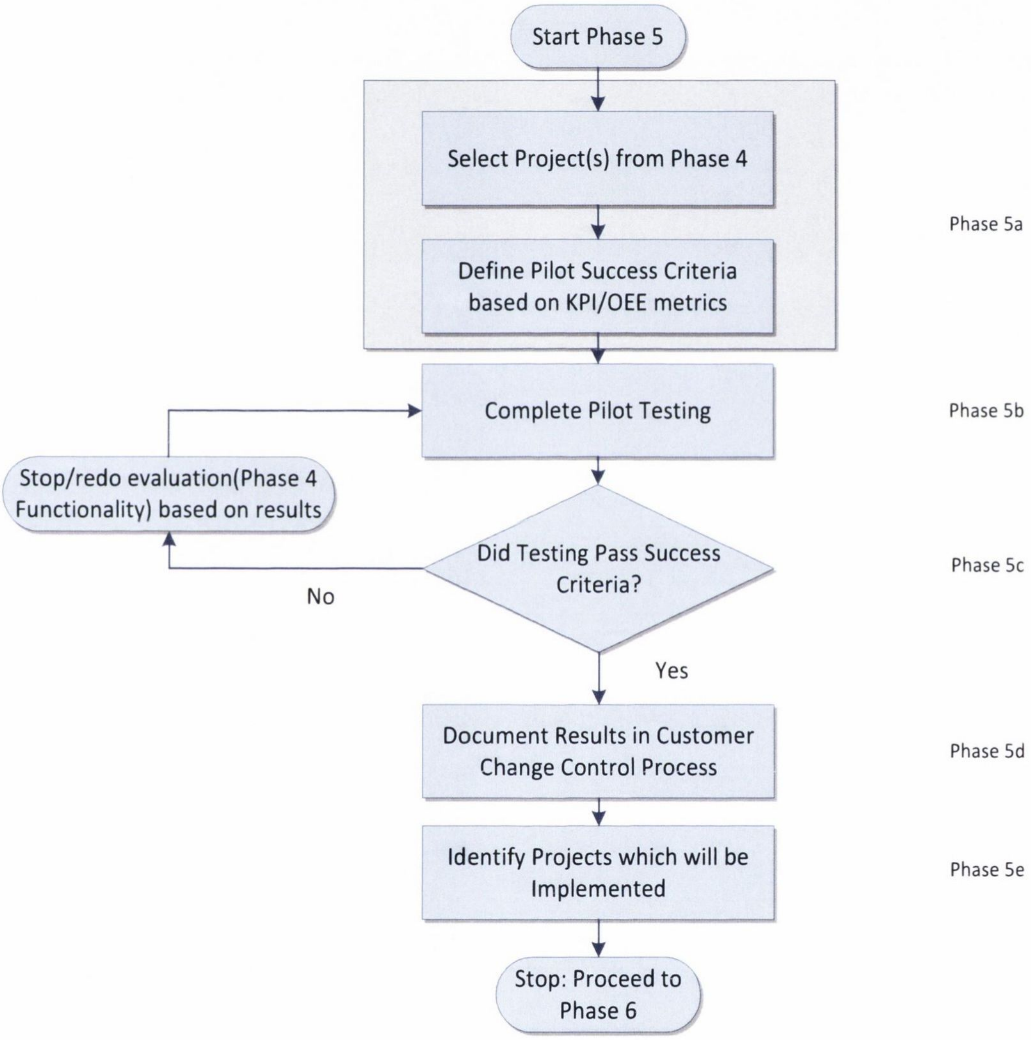


Figure 3.16 – Phase 5: Pilot evaluation

3.7 Phase 6: Factory integration

In this phase successful projects which have successfully completed two series of testing: equipment functionality testing from phase 4 and KPI testing from phase 5 can now be considered for factory integration. The process to date has also ensured the appropriate level of sponsorship and scrutiny from management. This ensures the appropriate level of prioritisation. This is particularly important in legacy factories with finite resources and potentially multiple priorities. The process worked can facilitate a factory's internal change control process or be used as an independent change control methodology. Figure 3.17 highlights the procedure to support a control solution by project with appendix 1 detailing the requirements by step within the procedure. The solution or control path decided on will depend on:

- the testing completed and adequacy
- the capability of production equipment targeted to be upgraded or modified both based on configuration and operationally
- budgetary considerations and costing of solutions

There will be three potential routes to solution implementation: automated, semi-automated and manual solutions. Ideally an automated solution will be pursued involving an optimisation of equipment through software or hardware modifications or adjustments. These will be realised as parameter adjustments, software revisions or hardware upgrades. Semi-automated solutions will involve modifications to equipments manufacturing enterprise system for example how it is controlled within the manufacturing process chain. This will involve managing the manufacturing states the equipment utilises in its existing shop floor environment to deliver optimised energy consumption. Reflecting the constraints which legacy factories work under, a third option of manual control may need to be investigated. This will involve modifications of documentation and training procedures such as manufacturing operations procedures (MOP's), good manufacturing practice (GMP) and response flow charts (RFC's) to ensure solution compliance. This detail can then be used to manage when the appropriate modifications to equipment can be scheduled. As previously undertaken, a team comprising of the appropriate skill sets can be utilised to identify the right solution path. This engagement will further ensure a successful control solution by allowing potential gaps in any implementation plans to be identified by the technical team.

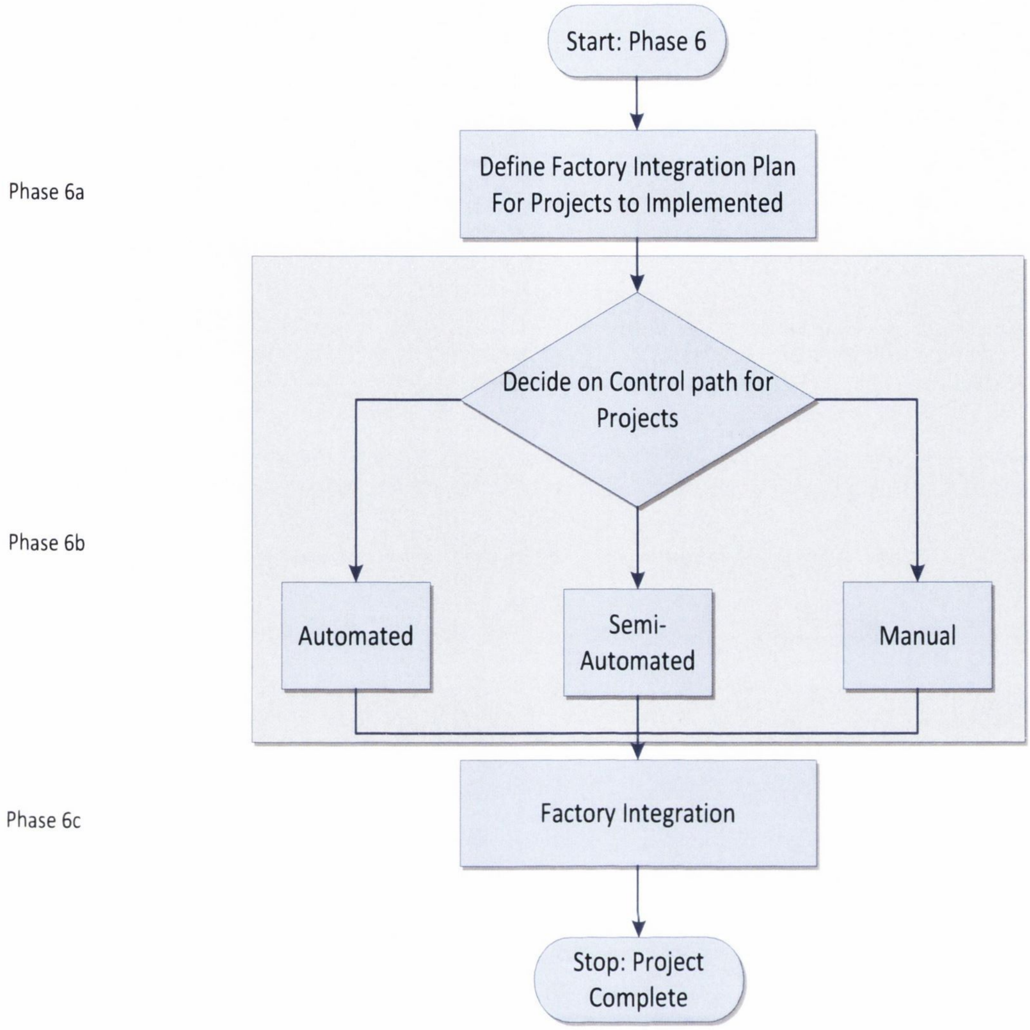


Figure 3.17 – Phase 6: Factory integration

3.8 Summary and concluding remarks

With an ongoing increase in industrial energy demand anticipated in Europe, energy efficiency will continue to be an important focus within industrial environments. The methodology outlined documents an approach to support the study and analysis of energy optimisation within complex manufacturing process chains. It focuses on generating an energy characteristic for complex discrete part manufacturing equipment and identifying optimisation opportunities based on targeting non value added process states. A structured problem solving approach is used to identify and evaluate risk factors associated with the implementation of improvements where qualitative workforce input is used to support the risk assessment. It also develops an assessment of an organizations capability to manage an energy improvement in order to minimize risk to core OEE metrics thereby ensuring opportunities are feasible and pragmatic. This supports a deeper understanding of energy use and potential operational impacts due to energy based change. It builds on a number of pillars as shown in figure 3.18.

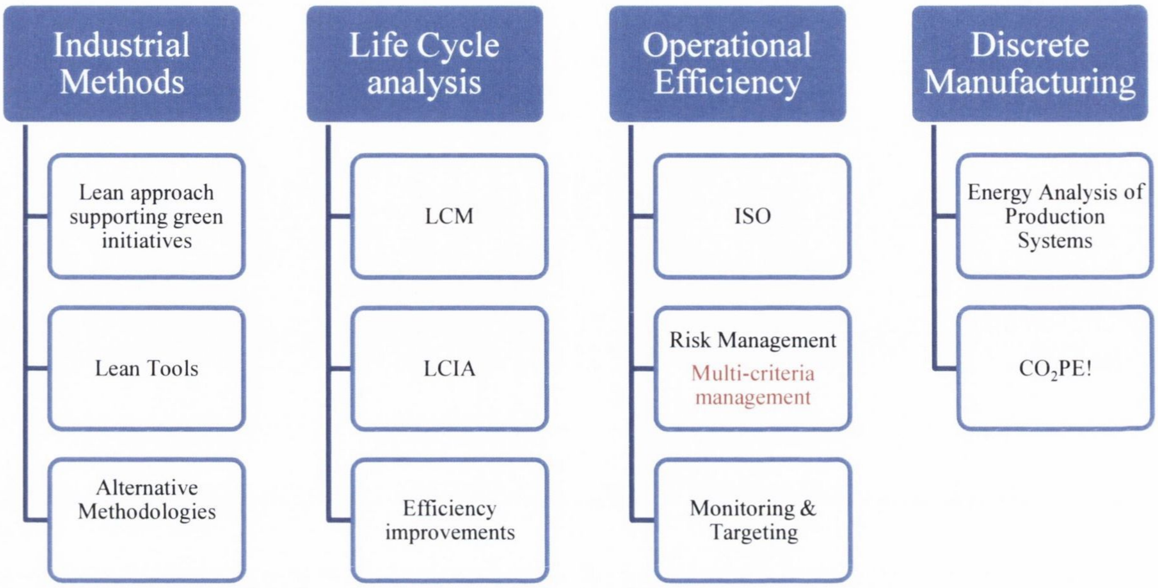


Figure 3.18 – Methodology pillars

From this review of the state of the art research an opportunity was identified to study the potential risks of energy efficiency improvements to production system performance and how the consideration of multiple criteria can mitigate operational impacts.

4 Use case application with single constraint criteria

4.1 Introduction

A survey of industrial energy and resource category usage and how they are utilised was completed for various manufacturing sectors within Ireland. The survey was developed by the manuscript author and a team of energy engineers within the industrial sites, a workshop was completed to identify and document the areas to be understood. See appendix A1.3 for the survey detail. The survey involved interviewing energy program owners within the respective sites as well as physical audits of all factory environments within the survey including more in-depth audits of each sites manufacturing production systems. The sectors which supported the survey were all discrete manufacturing environments and included ICT, bio-medical and pharmaceutical environments. The purpose of the survey was to obtain an understanding of the impact of manufacturing process chains and production systems in terms of consumption relative to the overall site energy budgets. Through the survey, a deeper understanding of industrial consumption categories and system level usage, for example production line, HVAC consumption was facilitated. In addition, the protocol outlined in A1.3 was developed to ensure a standardised approach was used to collecting data as different industrial environments use different approaches and definitions within their organisations, it was necessary to ensure this variation was mitigated.

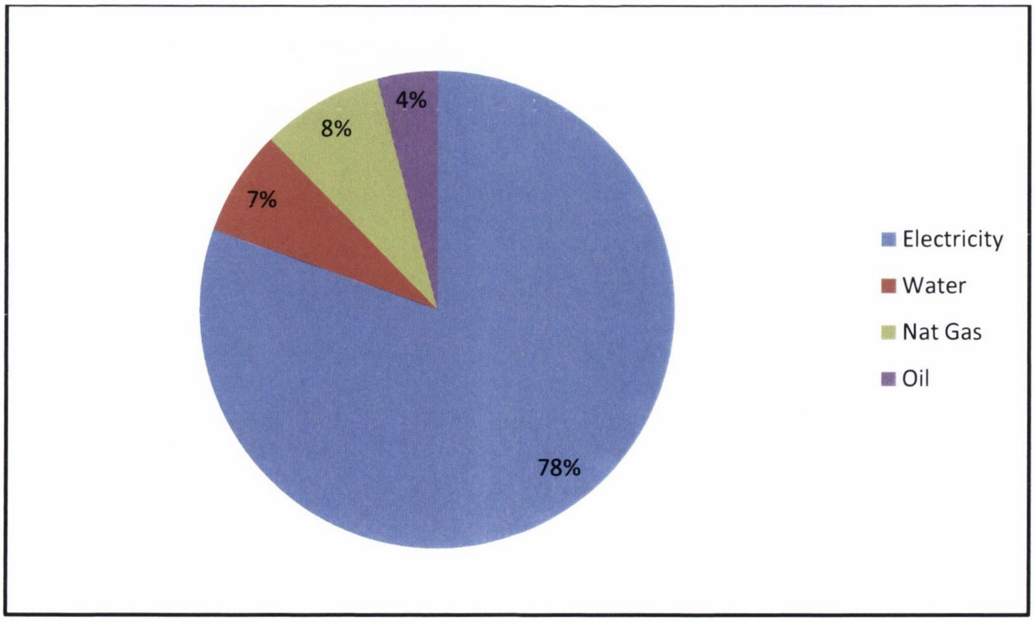


Figure 4.1 – Irish factory energy and resource categories

A further justification for the survey was as a consequence of an opportunity to reclassify consumption in terms of factory systems being identified. Historically, within an Irish setting, energy categorisation had been approached in terms of thermal and non-thermal process systems, as developed through the sustainable energy authority of Ireland [19]. The innovation for Irelands energy efficiency (i2e2) [221] technology centre, which consists of a consortium of manufacturing based companies facilitated the study to support this understanding of manufacturing process chain energy consumption impact. Figure 4.1 displays as a percentage by category, the total GWh budget spend across all five industrial sites surveyed consuming collectively 145GWh annually. In all organisations, kWh spend reduction was the primary motivation of the survey rather than CO_2 emissions reduction.

It can be seen that the survey highlighted the significance of electricity consumption to support operational activities. As a result, further analysis was completed through the survey to understand at a system level what the end use categories or system level consumers were, as shown in figure 4.2. It can be seen from the survey that this highlighted the significance of production equipment in terms of energy consumption.

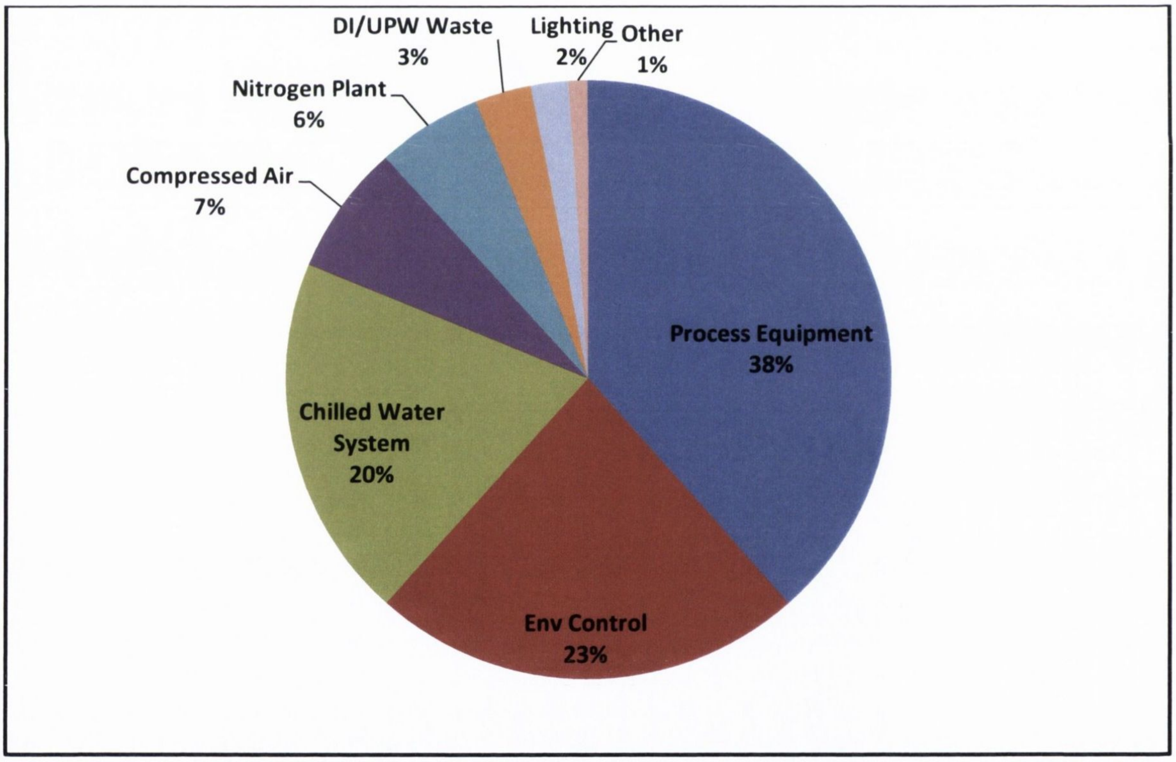


Figure 4.2 – System level end use categories

Production equipment was identified as discrete or individual manufacturing tools within the production environment utilised to add value to a product piece within a production environment. These individual manufacturing tools collectively were utilised within production systems or manufacturing process chains. Each manufacturing process chain studied was specific to its factory site and product needs. This highlighted an opportunity for further study in terms of developing a methodology to characterise energy consumption within manufacturing process chains. This was because within each process chain, individual process equipment was highly unique reflecting the specific functional requirements. As a result of this level of uniqueness and complexity, it was observed that optimisation by equipment type would potentially be required. This was because no single energy optimisation solution would be applicable across process chains rather a structured approach would be required to characterise and understand by process chain the significant energy users within each manufacturing process chain to identify the most impactful individual opportunities. Consequently, addressing this gap became a key target of the research outlined. Due to the significance of biomedical membership with the technology centre, a biomedical manufacturing facility which facilitated a case study within the survey completed was chosen to apply the methodology outlined previously in chapter three. Within this facility, there is an ongoing continuous improvement culture in terms of reducing environmental impact for example the adoption of ISO14001/50001 management systems and resource consumption reduction [222, 223]. As a result, the company was predisposed to evaluating further opportunities to improve its energy efficiency.

4.2 Case study: Biomedical facility

4.2.1 Phase 1: Energy and resource assessment

Phase 1 of the process is to formally identify and collate the energy and resource categories consumed within the factory of study. In many factory settings, these categories can be the responsibility of multiple departments or individuals and as a result can be managed individually or separately. The performance and accountability of these categories may not reside with site factory management and may be managed through a central resource based in a different geography: this phase identifies the appropriate category for further analysis. For the case study, three years worth of kWh consumption was analysed averaging 16 GWh annual consumption, highlighting the significance of electricity consumption to the site, as shown in figure 4.3. KWh consumption was the primary area of concern, rather than CO_2 emissions due to it being a direct cost to the organisation.

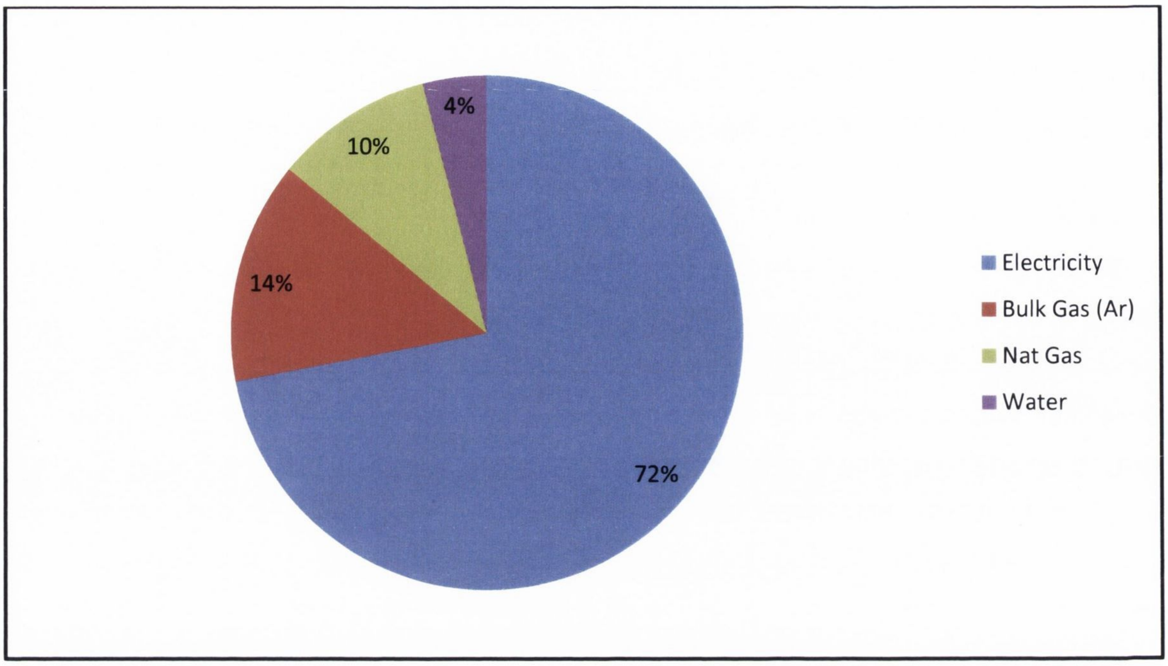


Figure 4.3 – Biomedical site energy & resource categories

It can be seen that electricity is the majority kWh consumer over the time period. The study referenced the fifteen distribution boards that service the factory through the site building management system. This highlighted the areas of significant energy use within the factory from a systems point of view, as shown in figure 4.4.

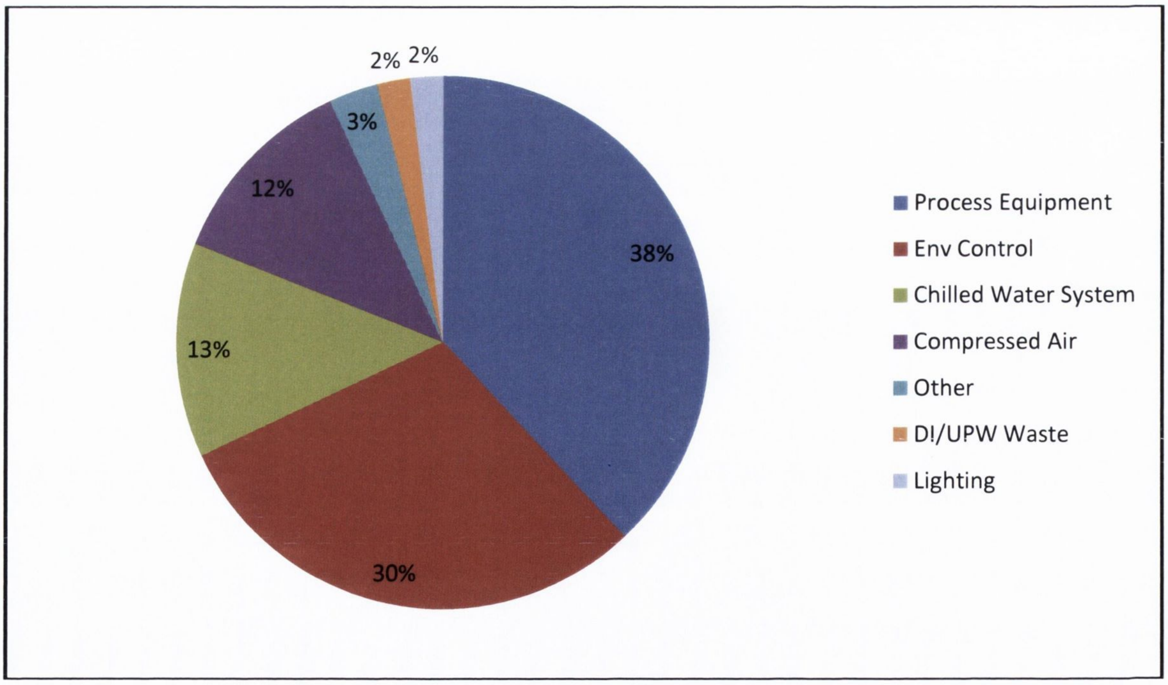


Figure 4.4 – Electrical consumption by system end user

It can be seen that process equipment was the most significant electricity consumption category within the factory. The process equipment category summarised the 5 manufacturing process chains used within the site. Environmental control included both dust extraction and HVAC systems. Further analysis was completed through a physical audit of all energy consumers within each production system. One year's worth of consumption data from the building management system was used to understand the consumption history of the individual production systems or value streams in the overall production category. This amounted to 6.4 GWh. This is shown in Figure 4.5 highlighting the foundry/raw material preparation value stream as being the most significant energy user within the production environment.

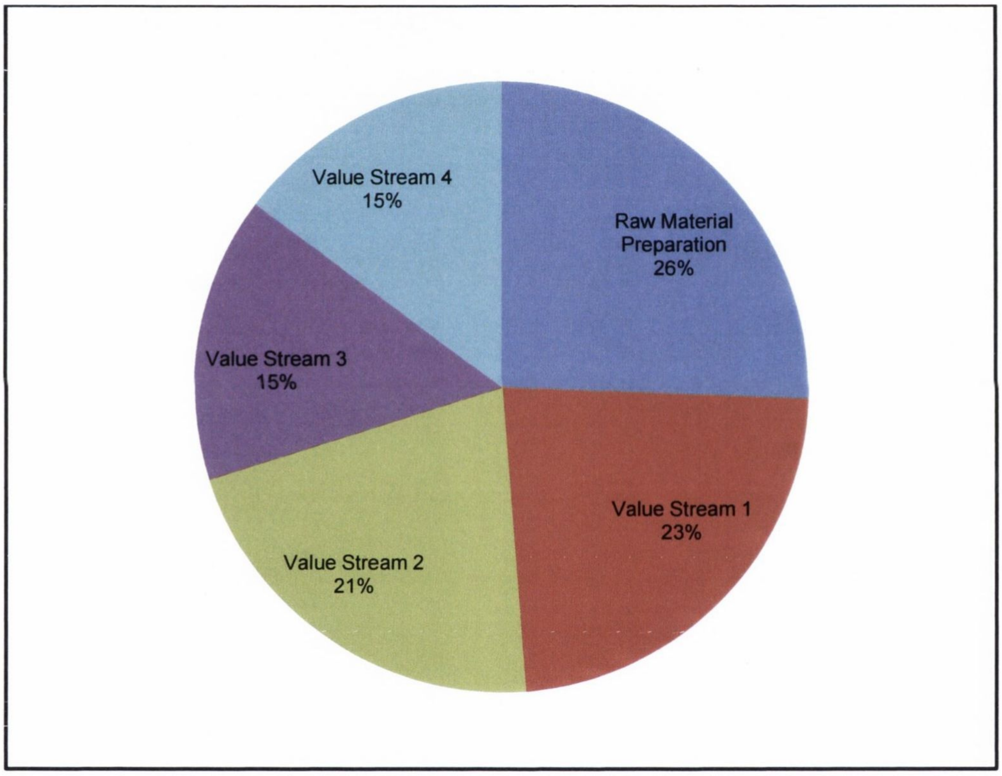


Figure 4.5 – Electrical consumption by value stream

Due to the significance of production systems in terms of energy consumption, an analysis was completed to understand how factory consumption compared to production schedules across the factory over the same one year time period. It was noted that the primary driver of the production schedule studied was to ensure product availability in the first half of the year. This resulted in a higher level of utilisation of the foundry value stream in the front end of the process. It can be seen in figure 4.6 that this highlighted a potential influence on energy consumption in terms of foundry utilisation.

In conclusion, phase 1 identified electricity as the most significant energy and resource category for a more detailed study. This resulted in identifying process equipment as being the most significant energy consumption category in terms of factory systems. This was reinforced by analysing production schedules and foundry utilisation history and led to a more detailed analysis of foundry energy behaviour in phase 2.

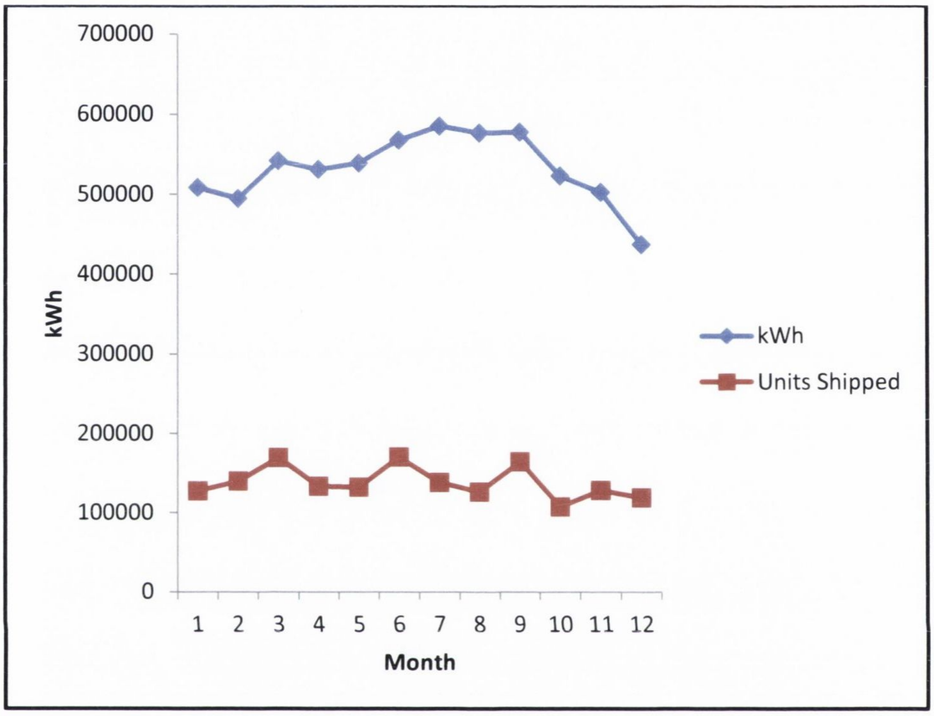


Figure 4.6 – Factory electrical consumption and production schedule

4.2.2 Phase 2: Factory energy and resource mapping

As a result of phase 1, it was decided to complete an energy behaviour analysis of the foundry value stream to understand the presence of significant energy users within this manufacturing process chain. This became the main objective of phase 2: to understand electricity consumption behavior of a targeted manufacturing chain for manufacturing activity. This involved generating an overall map of how energy is consumed within the manufacturing process chain ($S_{foundry}$). Within this mapping process: distribution and usage were detailed for the targeted manufacturing process chain, identifying all discrete manufacturing tools ($T_{Boilerclave}, T_{Pour\ Furnace}, T_{Coating\ Furnace}, \ldots, T_{Ultrasonic\ Bath}$). Figure 4.7 highlights this breakdown for the significant energy users within the foundry using energy value stream analysis to evaluate energetic performance [224]. The entire process chain was broken down into three segments due to the volume of equipment involved, as shown in figure 4.8. This included quantifying energy consumption for 2 manufacturing states: production and idle, for all 99 discrete tools within the foundry area. A Fluke 1735 power logger was used at a sample rate of 10.24 kHz with a 1 second time resolution to study tool energy behavior.

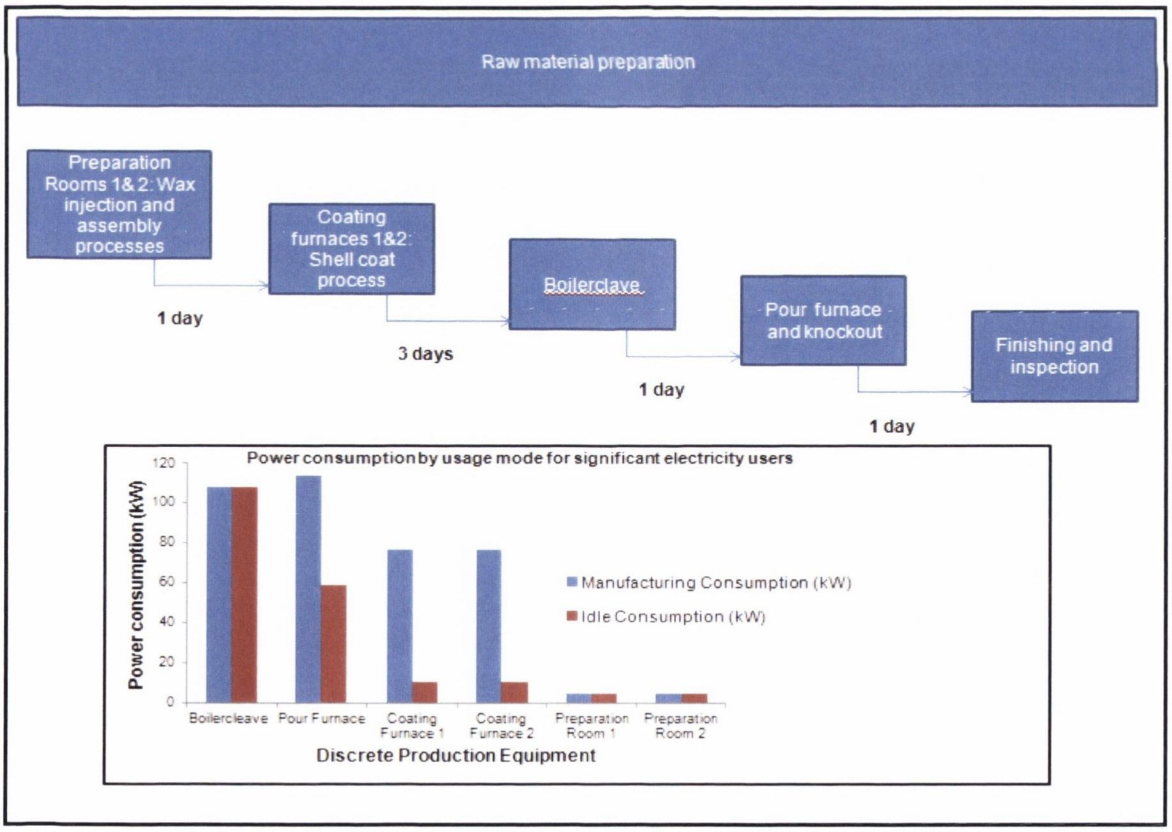
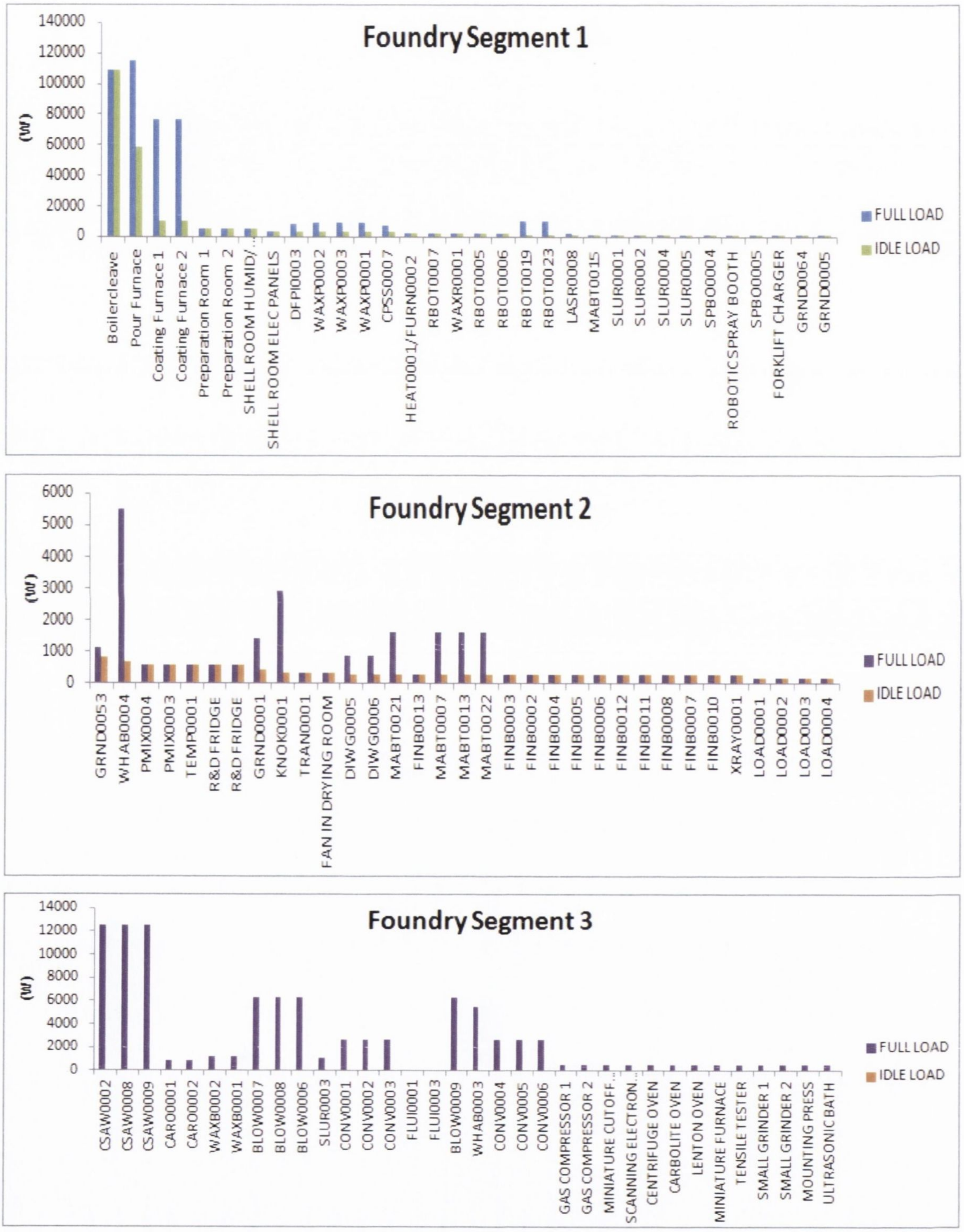


Figure 4.7 – Foundry flow and significant energy user electrical consumption

It can be seen from both figures 4.7 and 4.8 that a range of power consumption behaviour exists by both manufacturing states.



Foundry Segment 1

Foundry Segment 2

Foundry Segment 3

Figure 4.8 – Segmented foundry full load energy consumption data by manufacturing state

The analysis highlights a number of significant energy users within the production area with the boilerclave being the most dominant. It was noted that its energy consumption is constant irrespective of manufacturing activity. Utilisation data was used to understand the significance of both states for the most significant energy users within the process chain. Figure 4.9 summarises consumption by manufacturing state and usage rate. The measurement data highlighted the level of significance of these individual users. These tool types were noted to account for 50% of total power consumption (615.3kW) and 70% of idle power consumption (267.7kW) within the foundry process chain. In particular the significance of the boilerclaves energy consumption while in a non value add manufacturing state highlighted an area for further characterisation.

Tool	Running (W)	Idle (W)	Utilisation (%)
Boilerclave	108780	108780	20
Pour Furnace	114660	58800	53
Coating Furnace 1	77028	10584	42
Coating Furnace 2	77028	10584	42

Figure 4.9 – Foundry significant energy user energy consumption and utilisation

In conclusion, phase 2 identified a manufacturing process chain for further characterisation. Electricity was selected as the category from phase 1 for further characterisation. The study that resulted characterised energy behaviour for the process chain in terms of production consumption and idle consumption. This resulted in identifying the boilerclave as being the most significant energy consumer within the process chain. Due to the low level of utilisation, idle energy consumption was identified for further analysis in phase 3.

4.2.3 Phase 3: Production equipment opportunity identification

The purpose of phase 3 is to identify and characterise energy consumption within a significant energy user within the targeted production system. This consumption was referenced against the manufacturing behavior and manufacturing usage modes associated with the energy user. This required the development of equipment energy maps to reference against the use of principle components or modules within the tool.

The boilerclave tool was targeted for a more detailed study and specifically the non production manufacturing state – idle mode. An overview of the physical layout of the tool is shown in figure 4.10. The function of the tool within the foundry value stream is to deliver reliable, repeatable and risk-free dewaxing resulting from self steam regulation. It is an adiabatic process as there is no heat transfer into or out of the boilerclave system. It is a constant volume process. Heat transfer in the boiler can be considered in the context of equation 6 below:

$$dQ = nC_v dT \quad (6)$$

Where:

dQ = Quantity of heat flowing into the boiler (J)

n = moles of gas at temp T (mol)

C_v = Molar heat capacity at constant volume ($\text{J·mol}^{-1}\text{·K}^{-1}$)

dT = Temperature change ($^{\circ}$K)

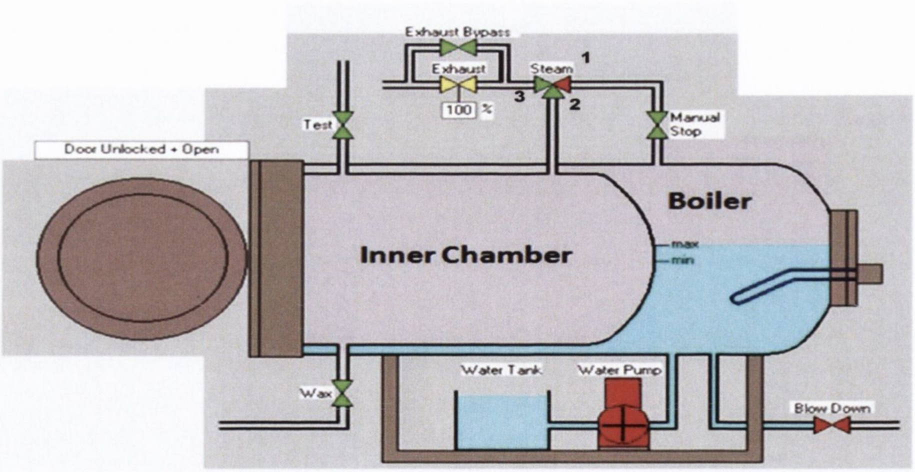


Figure 4.10 – Boilerclave layout

The boilerclave incorporates wax/residue blow down, controlled exhaust cycle and PLC control. Eight thermocouples are fitted within the main body of the vessel, allowing constant monitoring of thermal profiles. The PLC controller is instrumented to a pressure transducer which modulates temperature performance. A time in motion study of the boilerclaves principle components was completed and referenced against target parameters for the operational behaviour of the equipment, as shown in figure 4.11. This included both idle and production modes.

Where:

Valve open/pump off = 0

Valve closed/pump on = 1

Function	Door Closed	Lock	Cycle	Cycle Purge	Test	Unlock	Water Level Adjust
Door	0	1	1	1	1	1	0
Heaters	1	1	1	1	1	1	0
Manual Stop	0	0	0	0	0	0	0
Steam Valve 1	1	1	0	1	1	1	0
Steam Valve 2	0	0	0	0	0	0	0
Steam Valve 3	0	0	1	0	0	0	0
Exhaust Valve (Controlled Exhaust)	1	0	1	0	1	1	0
Exhaust Bypass (Normal Exhaust)	1	0	1	1	1	1	0
Test	0	0	1	1	0	0	0
Wax	0	1	1	1	0	0	0
Pump	0	0	1	0	0	0	1
Blowdown	1	1	1	1	1	1	1
Inner Chamber Temp Target (K)	438.00	438.00	438.00	438.00	438.00	438.00	438.00
Inner Chamber Pressure Target (kPa)	0.00	0.00	937.93	0.00	0.00	0.00	0.00
BoilerTemp Target (K)	453.00	453.00	453.00	453.00	453.00	453.00	453.00
Boiler Pressure Target (kPa)	937.93	937.93	937.93	937.93	937.93	937.93	937.93

Figure 4.11 – Boilerclave operational behaviour

An energy behaviour study was completed to understand energy performance which is a consequence of the operational parameters under which the tool functions. In this exercise production was defined as to when the tool was being utilised for production purposes. This includes the machine events: cycle, cycle purge, test and unlock. Idle was defined as when the tool was not being utilised for production for example in an unlock event. As shown in figure 4.9, the tool is in an idle or unlocked state of 80% and suggested a significant opportunity for energy optimisation as a result.

Within the boilerclave, the inner chamber is operated under the operational temperature target condition of 438°K (165°C) resulting in 937 kPa (135 psi) of steam for processing requirements. The boiler chamber is operated under the fixed temperature target condition of 453°K (179.85°C) resulting in 937 kPa (135 psi). It is isolated from the inner chamber until raw material is introduced for processing. Tool interlocks allow the inner chamber to pressurise when a steam valve was opened to the boiler chamber as outlined in figure 4.10. This process was the only operational requirement of the tool and was repeated continuously as per production requirements. The electrical behaviour which resulted is shown in figure 4.12 highlighting current consumption by manufacturing state. This reflects a constant energy usage within the boiler chamber irrespective of the operational behaviour shown in figure 4.11.

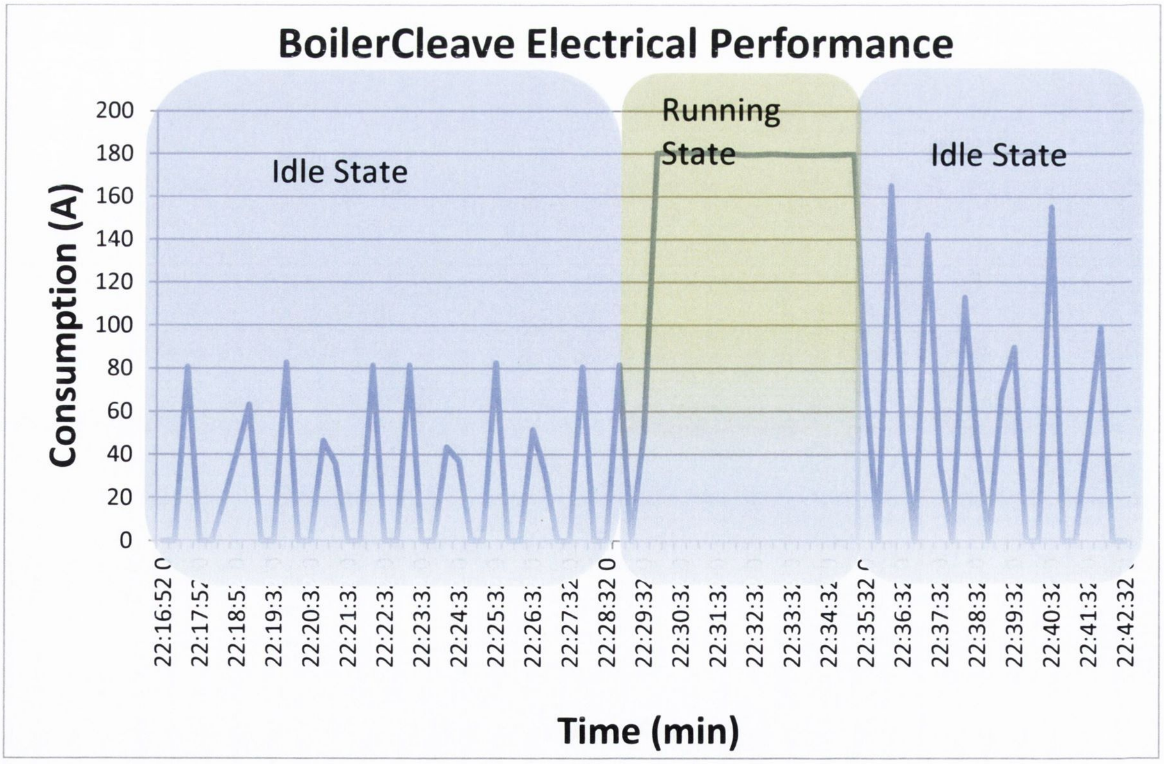


Figure 4.12 – Boilerclave energy behaviour

It can be seen from figure 4.12 that the behaviour outlined reflects increased ampere consumption due to the equalisation of pressure between the inner and boiler chambers to allow processing. There is a period of stabilisation post running state attributed to boiler chamber stabilisation post processing. A review of the tool schematic lay out, as shown in A1.4 and a physical walk of tool modules confirmed one significant energy consumer within the system: 5 x 24kW heaters, with each heater being fed from a 40A MCB. Each MCB draws 35A for 20 secs and then is off for 90 seconds. This is repeated continuously as per the configuration set up. As a result of this process, this module was identified as the most significant module in terms of consumption as per phase 4Fe of the fourth phase.

In conclusion, phase 3 characterised a production tool for further study: the boilerclave. Through correlating tool operational performance to energy behaviour, it was shown that 5 X 24 kW heating elements were the principle consumer of electricity within the system itself. Idle state consumption was identified as the principle opportunity for energy optimisation, specifically the boiler chamber energy consumption.

4.2.4 Phase 4: Risk and cost benefit analysis

The purpose of phase 4 is to identify opportunities to optimize idle state energy consumption of the boilerclave system. These opportunities were evaluated in 3 sub-phases to assess risk to both equipment performance and cost of implementation. Risk to equipment performance is addressed in terms equipment functionality and OEE performance.

A team based exercise was performed using a kaizen process to map out an operational future state for the boilerclave system, is shown in figures 4.13 and 4.14.

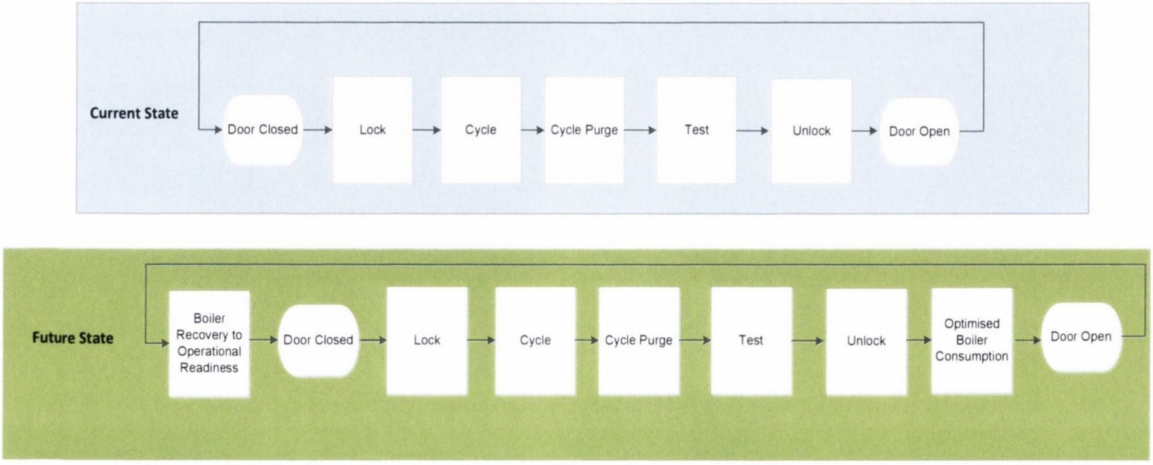
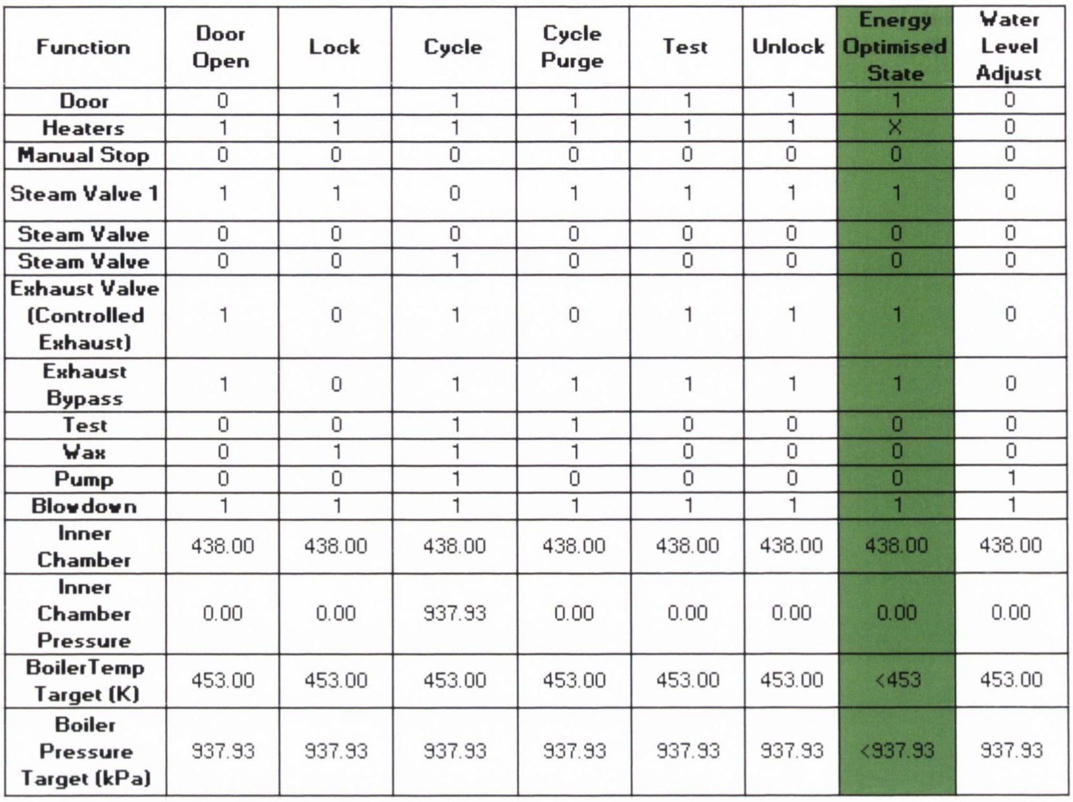


Figure 4.13 – Current and future state map of operational behaviour



Function	Door Open	Lock	Cycle	Cycle Purge	Test	Unlock	Energy Optimised State	Water Level Adjust
Door	0	1	1	1	1	1	1	0
Heaters	1	1	1	1	1	1	X	0
Manual Stop	0	0	0	0	0	0	0	0
Steam Valve 1	1	1	0	1	1	1	1	0
Steam Valve	0	0	0	0	0	0	0	0
Steam Valve	0	0	1	0	0	0	0	0
Exhaust Valve (Controlled Exhaust)	1	0	1	0	1	1	1	0
Exhaust Bypass	1	0	1	1	1	1	1	0
Test	0	0	1	1	0	0	0	0
Wax	0	1	1	1	0	0	0	0
Pump	0	0	1	0	0	0	0	1
Blowdown	1	1	1	1	1	1	1	1
Inner Chamber	438.00	438.00	438.00	438.00	438.00	438.00	438.00	438.00
Inner Chamber Pressure	0.00	0.00	937.93	0.00	0.00	0.00	0.00	0.00
BoilerTemp Target (K)	453.00	453.00	453.00	453.00	453.00	453.00	<453	453.00
Boiler Pressure Target (kPa)	937.93	937.93	937.93	937.93	937.93	937.93	<937.93	937.93

Figure 4.14 – Current and future state map of operational and energy behaviour

The kaizen exercise was managed by the manuscript author and included maintenance and engineering resources from the organisation that operated the boilerclave system. The vendor of the system – Leeds Bradford Boilerclave Corporation (LBBC) was also consulted for clarifications required for future state configurations. A maintenance review was completed of procedures associated with the boilerclave system. This was completed to investigate any failure modes primarily with respect to the boilerclave heating elements but also any other tool components that impact equipment performance. No issues or anomalies were noted in terms of failure mechanisms or increased consumption of parts with respect to the heating elements post maintenance. This data analysis was completed in parallel with vendor consultation and the energy metering performed. Vendor participation was enthusiastic due to no customer based energy characterisation being completed previously. LBBC felt the proactive approach to characterise energy consumption would support their strategy development to improve their products environmental performance.

4.2.5 Phase 4 Functionality: Equipment evaluation of optimised energy behaviour

Although the boilerclave system demonstrated a significant robustness in terms of ramping/deramping capability, an understanding of the environment in which the boilerclave operated was required. To facilitate this, the key performance indicators were identified using both the functionality flow chart outlined in figure 3.12 and the input/output requirements in appendix 1. This highlighted availability, quality and cost being the primary metrics boilerclave operations were managed to. Within these metrics, availability was highlighted as the primary metric of importance reflecting the boilerclave as a standalone system within the foundry area. As a result, energy behaviour investigations of any proposed future state idle settings and respective recovery times were identified as the key areas to investigate, as highlighted in figure 4.15.

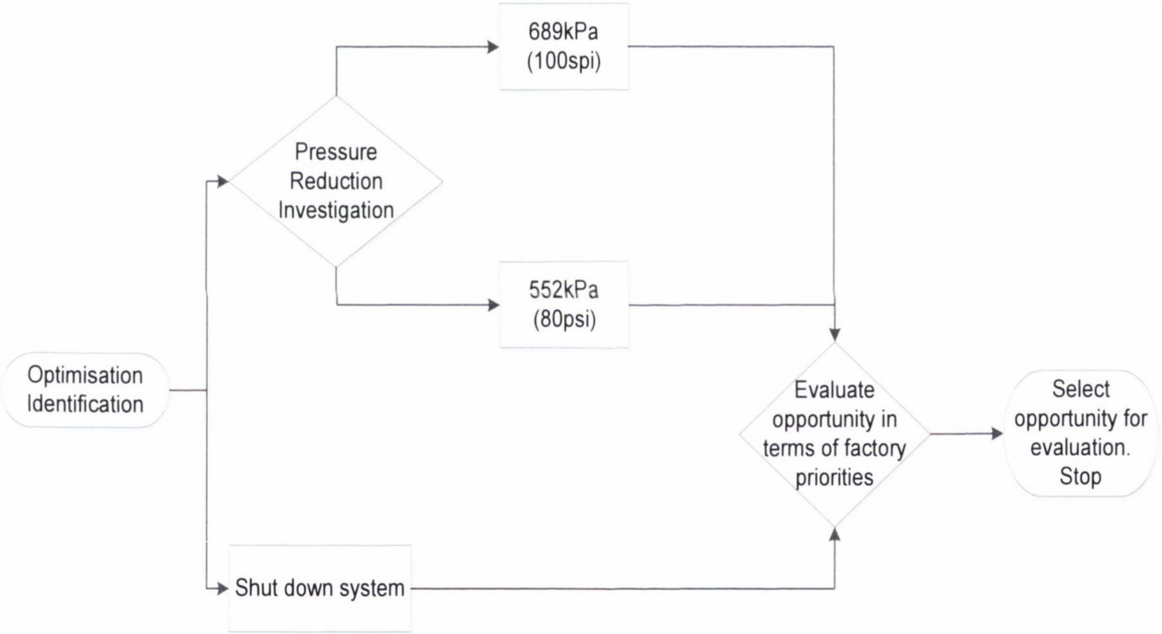


Figure 4.15 – Optimisation opportunities considered

Both 80 psi and 100 psi settings were monitored and compared to the operational reference of 136 psi as shown in Figure 4.16 where it can be seen that the different settings are reflected in different power consumption profiles. The reduced pressure settings reflected a difference in energy behaviour which corresponded to less heater contact frequency. These settings also reflected operational behaviour the system undertook over time and as such were considered within operational boundaries.

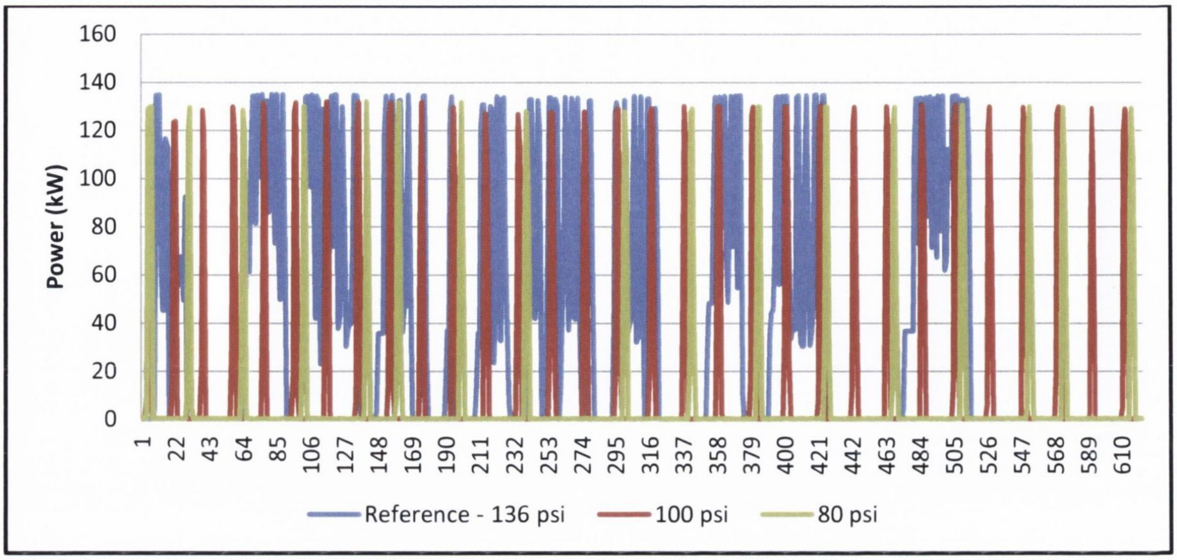


Figure 4.16 – Boilerclave idle setting performance

Pressure decay was also studied to identify the time required to reach each future idle state indicating a linear relationship, as shown in Figure 4.17. It can be seen from this figure that it indicates the behaviour of the boilerclave and the loss of pressure over time which necessitated constant energy consumption to maintain the operational set point of 136 psi.

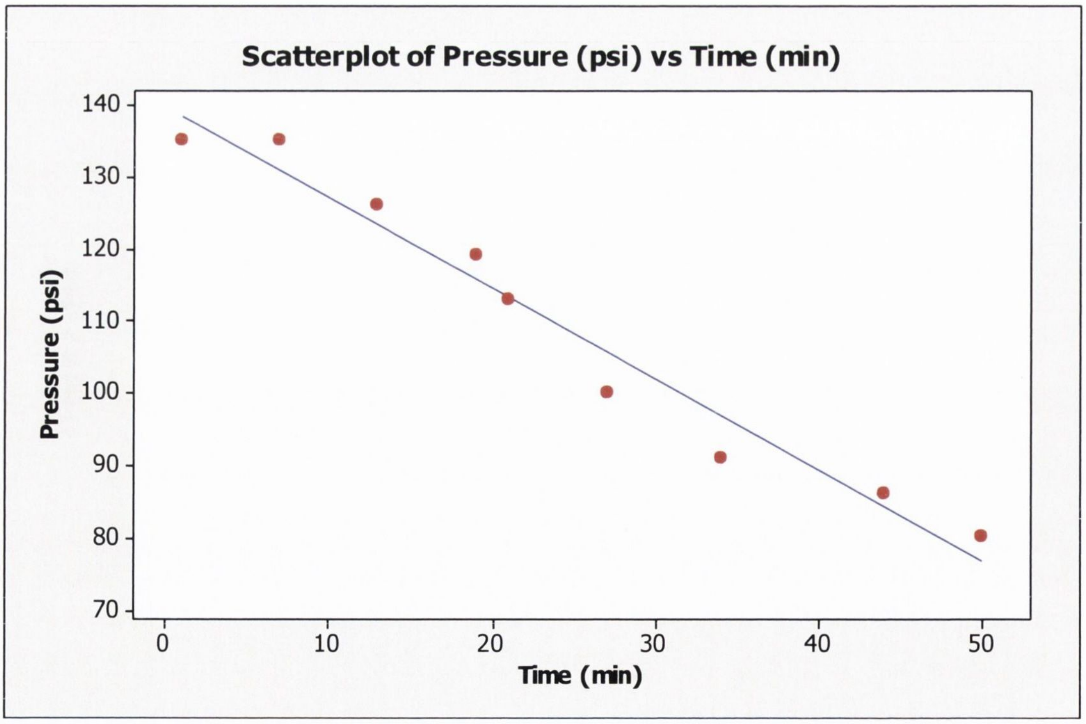


Figure 4.17 – Boilerclave pressure decay performance

In terms of optimising energy consumption and taking account of the operational constraint of availability, table 7 highlights a summary of the experiments completed. The 100 psi pressure setting was selected for further evaluation based on recovery time to the reference pressure setting of 136 psi.

Exp	Pressure setting (psi)	Mean Power (kW)	Recovery Time
Reference	136	27	0
Exp #1	100	14	6 mins
Exp #2	80	7	12 mins 47 secs

Table 7 – Experimental summary of idle settings investigated

Testing of recovery times from both settings was completed, in particular the energy consumption required to recover to the operational setting of 136 psi, as shown in figure 4.18. Although there is an increased consumption to support recovery, this was considered negligible considering the 20% utilisation rate of the boilerclave tool.

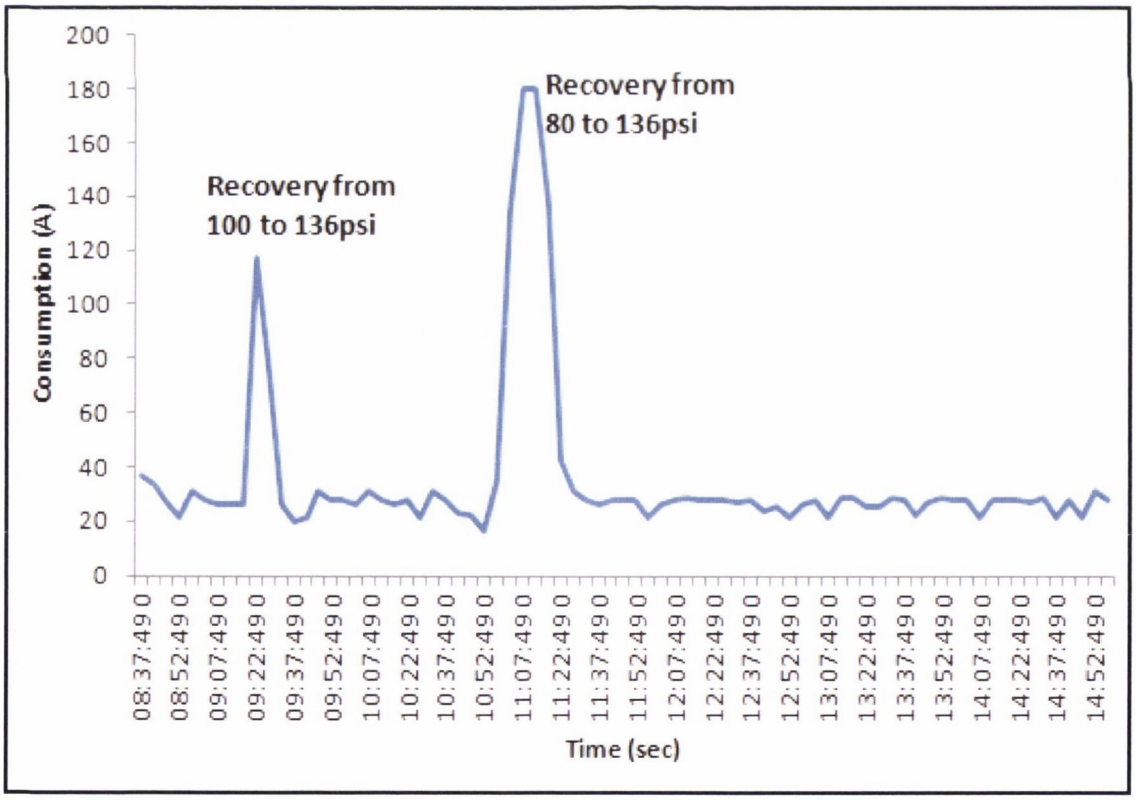


Figure 4.18 – Energy behaviour observed recovering to operational readiness

From this energy performance data, cost performance was considered using equations 7 and 8:

$$E\,(T_1)_m = E(c_h)\ \times\ Util \times t \qquad (7)$$

$$E_f\,(T_1)_m = E_f(c_h)\ \times\ Util \times t \qquad (8)$$

Where:

$E\,(T_1)_m$ = current metered energy cost for tool

$E_f(T_1)_m$ = future metered energy cost for tool

$E(c_h)$ = current power consumption of heating element component

$E_f(c_h)$ = future power consumption of heating element component

Util = utilisation of boilerclave

t = time (8760 hours)

This allowed a calculation of current energy cost for the boilerclave during its non productive manufacturing state idle:

$$E\,(T_1)_m = €18981$$

As idle energy consumption is equal to running consumption, total yearly metered energy consumption $E\,(T_1)\frac{y}{m}$:

$$E\,(T_1)\frac{y}{m} = €\ 23652$$

An estimate of future idle energy consumption for the selected power setting of 14kW was calculated using eq. 8:

$$E_f\,(T_1)_m = €9811$$

From this phase, a future state condition was identified that had the potential to significantly reduce the energy consumption of the boilerclave system by 51%. However, analysis to this point has focused on equipment functionality, with an initial understanding of the principle operational consideration: availability and the impact to this metric, to which the boilerclave system is constrained. Further analysis and evaluation was required to understand the long term affect of this setting from an operational performance perspective as well as what investment requirements would be needed for potential upgrades to the system itself.

4.2.6 Phase 4 Risk: Formal evaluation of equipment capability to manage project(s)

The operational KPI metrics availability (A_1), quality (A_2) and cost (A_3) were prioritised using the pair wise comparison technique outlined in appendix 1. Members of the workforce aligned to boilerclave operations supported this exercise such as maintenance, operations technicians and area management. This resulted in normalised values which reflected priorities within the boilerclave area, as shown in table 8.

KPI	Prioritisation
Availability	0.7
Quality	0.2
Cost	0.1

Table 8 – Normalised values reflecting priorities of area

It can be seen from this table that a 0.7 score reflects the workforces feedback that 70% of the areas priority and daily focus is on maintaining availability and as a result represents a significant portion of their daily workload. This suggests that any extended testing which must be completed within phase 5 of the methodology must prioritise an availability metric as part of any evaluation.

In order to understand the capability of each KPI to support energy based change to the boilerclave system. Workforce experience was again used to understand how capable these factory KPI's are and in particular the KPI monitors used within the factory. Capability was investigated in terms of:

- Likelihood = the possibility of a change to the selected KPI due to implementing a project
- Detectabilty = the ability to see a change on the selected KPI due to implementing a project
- Severity = the level or degree to which the change has affected the selected KPI.

Table 9 shows a summary of factory personnel feedback in terms of importance, what they value based on their experience, about the KPI monitors which measure availability, quality and cost.

Variable Importance	Likelihood	Detectability	Severity
Availability	0.25		0.75
Quality	0.07	0.73	0.20
Cost	0.25		0.75

Table 9 – Normalised values reflecting KPI attribute importance to the workforce

Pair wise comparisons for likelihood and severity were only completed for availability and cost. This reflects the high level of direct monitoring of these KPI's at the tool or boilerclave level. In terms of equipment quality performance, a detectability category was added to the pair wise comparisons. This reflects the integrated effects that can occur downstream within the manufacturing process chain that the boilerclave can indirectly impact.

Workforce experience was then used to assess the probability of a successful implementation of an idle setting of either 100 psi or 80 psi. Using their knowledge of the production line and the previously selected KPI's, each project is assessed in terms of likelihood, detectability and severity, as shown in table 10.

Variable	Project	Likelihood	Detectability	Severity
Availability	Idle Setting at 100	8		8
	Idle Setting at 80	3		3
Quality	Idle Setting at 100	8	8	8
	Idle Setting at 80	8	8	8
Cost	Idle Setting at 100	9		9
	Idle Setting at 80	9		9

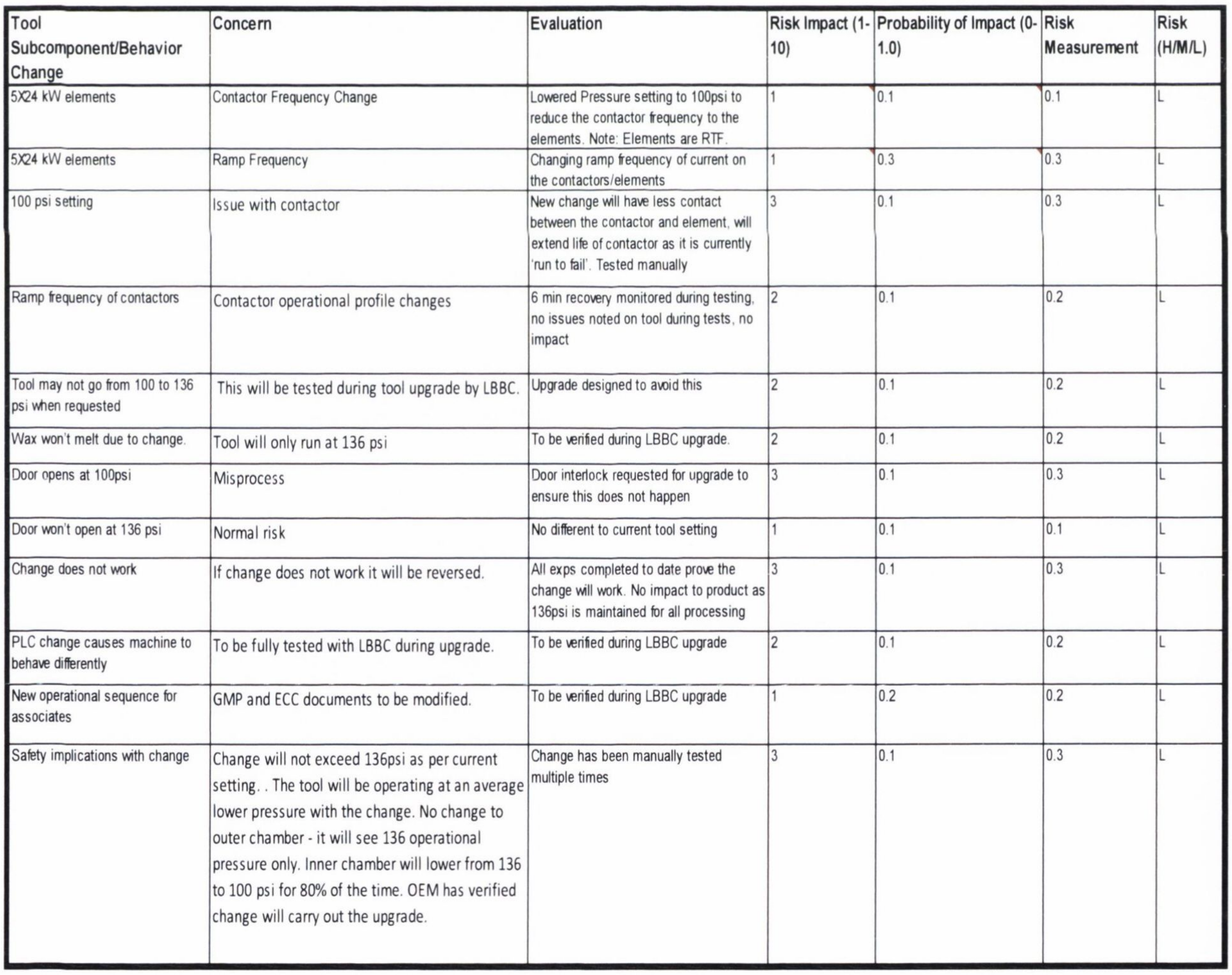
Table 10 – Workforce input on ability on monitor boilerclave energy projects

Using the data collected, each project was then scored. The value obtained outlined the capability of the factory to monitor each project appropriately rather than a success rate, as shown in table 11.

Project	Capability
Idle Setting at 100	8.1
Idle Setting at 80	4.6

Table 11 – Project capability scores

It can be seen from this table that the relative difference within the scores highlights based on the collective experience of the workforce used, gaps in a factory's capability to manage a change. In terms of the boilerclave projects identified, the relative difference in scoring is attributed to the impact on the availability KPI. The workforce considered the slow recovery of in-excess of 12 minutes to production readiness from an 80 psi setting as having a highly likely and severe impact to availability performance. From this analysis it was decided that the idle setting of 100 psi was the appropriate project to formally assess in terms of a cost based assessment. A cause-effect assessment was completed to understand potential operational issues that may impact the boilerclave, as shown in figure 4.19. Workforce and vendor engagement was utilised to support the analysis with specific testing identified as part of any potential upgrades. All concerns highlighted were categorised as low risk, as shown in figure 4.19. The factory maintenance database and vendor data was used to support this analysis.



Tool Subcomponent/Behavior Change	Concern	Evaluation	Risk Impact (1-10)	Probability of Impact (0-1.0)	Risk Measurement	Risk (H/M/L)
5X24 kW elements	Contactor Frequency Change	Lowered Pressure setting to 100psi to reduce the contactor frequency to the elements. Note: Elements are RTF.	1	0.1	0.1	L
5X24 kW elements	Ramp Frequency	Changing ramp frequency of current on the contactors/elements	1	0.3	0.3	L
100 psi setting	Issue with contactor	New change will have less contact between the contactor and element, will extend life of contactor as it is currently 'run to fail'. Tested manually	3	0.1	0.3	L
Ramp frequency of contactors	Contactor operational profile changes	6 min recovery monitored during testing, no issues noted on tool during tests, no impact	2	0.1	0.2	L
Tool may not go from 100 to 136 psi when requested	This will be tested during tool upgrade by LBBC.	Upgrade designed to avoid this	2	0.1	0.2	L
Wax won't melt due to change.	Tool will only run at 136 psi	To be verified during LBBC upgrade.	2	0.1	0.2	L
Door opens at 100psi	Misprocess	Door interlock requested for upgrade to ensure this does not happen	3	0.1	0.3	L
Door won't open at 136 psi	Normal risk	No different to current tool setting	1	0.1	0.1	L
Change does not work	If change does not work it will be reversed.	All exps completed to date prove the change will work. No impact to product as 136psi is maintained for all processing	3	0.1	0.3	L
PLC change causes machine to behave differently	To be fully tested with LBBC during upgrade.	To be verified during LBBC upgrade	2	0.1	0.2	L
New operational sequence for associates	GMP and ECC documents to be modified.	To be verified during LBBC upgrade	1	0.2	0.2	L
Safety implications with change	Change will not exceed 136psi as per current setting. . The tool will be operating at an average lower pressure with the change. No change to outer chamber - it will see 136 operational pressure only. Inner chamber will lower from 136 to 100 psi for 80% of the time. OEM has verified change will carry out the upgrade.	Change has been manually tested multiple times	3	0.1	0.3	L

Figure 4.19 – Cause-effect analysis of potential failure mechanisms

4.2.7 Phase 4: NPV of equipment with optimised energy behavior

Based on the investigations and risk assessments completed, a number of options were reviewed to enhance the boilerclave capability to utilise a lower idle setting. The original equipment manufacturer proposed two potential solutions: an upgrade to the human machine interface which would enable the new setting to be activated and the installation of a physical switch to enable the new setting. The install prices and anticipated maintenance costs for each solution are highlighted in figure 4.20.

Option	Upgrade	Install Price (€)	Annual maintenance costs (€)	Annual replacement cost (€)	NPV Year 2 (€)	NPV Year 5 (€)
1	HMI Upgrade	10,000	200	800	-1,408	70,728
2	Switch Installation	5,000	500	500	13,591	100,728

Figure 4.20 – NPV for boilerclave upgrades

Due to cost being one of the KPI's identified it was necessary to understand the financial impact as a result of implementation of either option. Each project was assessed in terms of net present value. A discount rate of 10% was used for the NPV analysis for both projects as shown in equations 9 and 10 highlighting option 2 over a 5 year period as having a higher time value of money.

$$\text{Option 1: } NPV_{(10\%)} = \sum_{t=1}^{5} \frac{R_t}{(1+i)^t} = €70{,}728 \quad (9)$$

$$\text{Option 2: } NPV_{(10\%)} = \sum_{t=1}^{5} \frac{R_t}{(1+i)^t} = €100{,}728 \quad (10)$$

The calculation template is shown in figure A1.2. Although both options were favourable in terms of financial return, the physical switch was selected due to the financial constraints of the factory.

4.2.8 Phase 5: Pilot implementation

A pilot test was completed utilising the 100 psi idle setting over an extended period of time, as shown in figure 4.22. The pilot was completed to ensure repeatability of performance with predictable recovery. It can be seen from this figure that the stability of the autoclave system over time is maintained during this stress testing. No operational or tool related issues were highlighted through the testing.

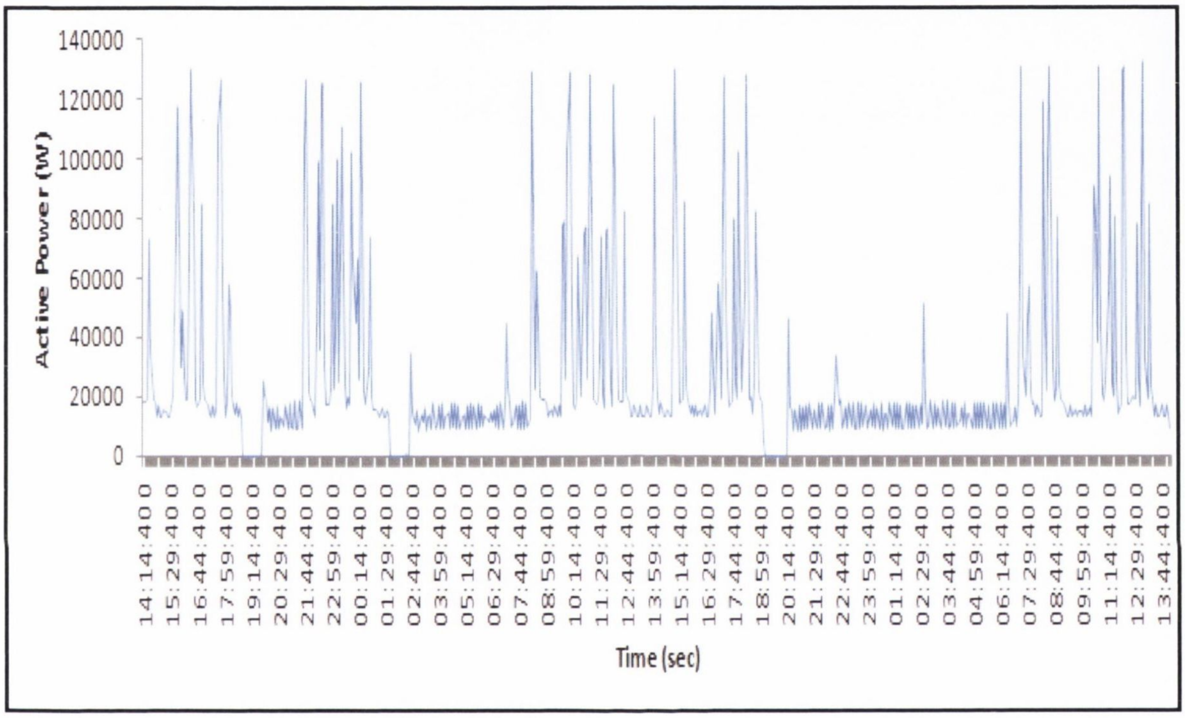


Figure 4.22 – Stability testing of switch solution

An analysis of performance highlighted repeatable behaviour compared to previous functionality testing. The reference energy consumption mean was observed to be slightly higher than observed during the functionality testing. This was due to a number of production runs being completed during the pilot phase testing which skewed the average higher. A non-parametric test was used to evaluate both populations to understand the statistical significance of the evaluation completed as no assumption was made on the specific distribution of the population. The hypothesis criteria used are outlined within figure 4.23 where η = population mean. This resulted in a P-value of 0.2595 highlighting the test was significant indicating H_a cannot be rejected. The optimised setting was observed to have a more bimodal behaviour due to less energy consumption required to maintain the lower 100 psi setting compared to the reference setting, as shown in figure 4.24.

Step 1: Hypothesis definition

H_0: There is no difference in parameter performance. $\eta = \eta_0$

H_a: There is a difference in parameter performance. $\eta \neq \eta_0$

Step 2: Significance outline:

Level of significance: 0.05 (or 95%)

Step 3: P Value calculation:

Prob $(z > z_\alpha)$
Where $z = \eta - \eta_0 / s\sqrt{n}$

Step 4: Decision criteria documentation:

If $P < 0.05$ then reject H_0

Step 5: Conclusion:

Determine equivalency or non equivalency.

Figure 4.23 – Hypothesis test criteria

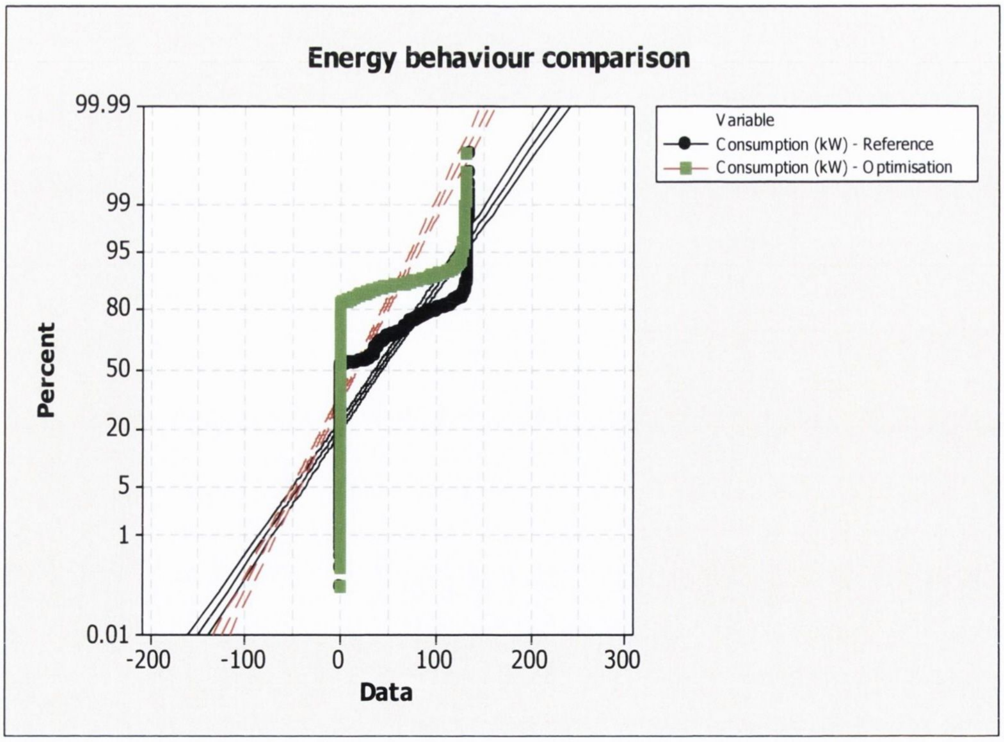


Figure 4.24 – Boilerclave pilot energy behaviour vs. reference

4.2.9 Phase 6: Factory integration

A review of potential solution paths was completed to evaluate the most appropriate avenue to ensure a controlled solution was identified. Table 12 highlights the solution paths analysed.

Option	Solution Path	Description
1	Automation	PLC/switch enabled 100 psi setting
2	Equipment configuration change	1200cc to 900cc replacement
3	Semi-automation	Manufacturing defined event created to allow optimised
4	Manual Checklist	Documented procedure to activate manually through O/S

Table 12 – Control solutions

The solution paths were identified through a workshop event comprising of the maintenance technicians and engineering resources that supported the work to date vendor engineering and led by the manuscript author. Vendor engineering ratified option 1 and 2 in terms of available upgrades. Factory engineering consulted with factory IT resources to understand if a manufacturing event could be created for option 3 within the factory enterprise systems to ensure the boilerclave could be logged into a low energy event. The manual checklist for option 4 was created by the maintenance technicians to manually log the boilerclave into a lower energy consuming state.

Option 1 identified was a fully automated solution to avoid any human factor dependence with PLC integration of the optimised idle setting into the boilerclaves operational control logic. This option, as shown previously in figure 4.20 was evaluated from a financial perspective. This was the favoured option due to the fully automated nature of the solution and no dependence on human factor interaction. The study of the boilerclave highlighted the over capacity of the system in place and suggested that option 2 was technically possible: replacing the current 1200cc system with a more energy efficient 900cc system. This however was cost prohibitive within the current climate due to an investment requirement of €250,000.

Option 3 considered the creation a manufacturing event called an 'optimised idle state', as shown in figure 4.25 where it can be seen that factory floor personnel could log the boilerclave tool into this event while in an non production scenario to ensure energy reduction savings could be realised on an ongoing basis. The option was not favoured due to the flexibility demanded within the production environment and the discipline required by the manufacturing personnel to enact the idle state on the boilerclave system. However the concept highlighted the need for an automated manufacturing system which integrates both production equipment and material control. This however was beyond the current capability of the facility involved in this energy research.

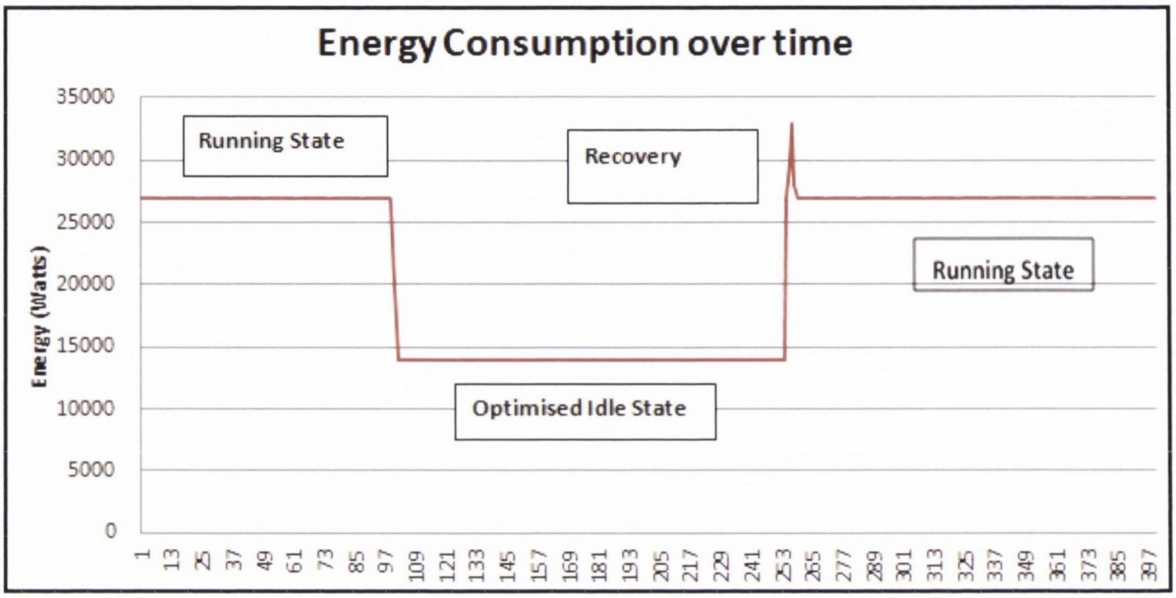


Figure 4.25 – New boilerclave idle manufacturing state concept

Option 4 involved the creation of a GMP checklist which would document a procedure to manually bring the boilerclave into an optimised state and recover as required for production. As previously in option 3, this option was not favoured due to the reliance on human factor interaction to realise the opportunity and recover the system. The potential also existed to incorrectly recover the system and incur tool availability and quality issues as a result.

4.3 Discussion of methodology application

The organisation which supported the validation of the methodology outlined had previously achieved ISO 50001 certification. As a result, the organisation had demonstrated both a functional and accountable energy management system (EnMS). A large amount of energy based performance information was available and this allowed an early effective understanding of the energy and resource categories used within the factory in phase 1. This also allowed a breakdown of energy use at a system level which highlighted the significance of manufacturing process operations in terms of consumption. Due to the highly regulated and compliant nature of these operations, developing an understanding of energy behaviour had not been undertaken previously due to a management perception that operations would not be capable of supporting energy based improvements. Historically within the factory all energy based improvements had focused on both building management and facilities support for example areas such as environmental control and chilled water temperature reductions. Energy mapping completed in phase 2 allowed an initial understanding of the energy behaviour exhibited by defined manufacturing states: these states were production and idle states. The impact of this was to formally identify and quantify the significant energy users within the foundry value stream and assess energy consumption in terms of non value added activity. This was further reinforced by correlating factory consumption to manufacturing activity within the foundry highlighting the potential impact of foundry operations to factory energy consumption. This highlighted the need for a more in-depth understanding of both boilerclave operations and energy consumption. The factory level data analysed within the initial two phases was energy data collected at a frequency of 15 minutes. For subsequent phases a higher time resolution of 1 second was necessary to thoroughly understand energy behaviour at a tool level to ensure a complete baseline of performance was obtained. This required a significant level of manual metering as 1 second time resolution capability was beyond the factory's EnMS existing capability. In addition, the research completed in the initial two phases was communicated to factory management to ensure site stakeholder support for subsequent phases as dedicated workforce resources would be needed.

Through phase 3, the metering of tool energy behaviour and engagement with equipment maintenance and engineering, improvements in equipment performance were identified. This was based on leveraging the experience of both disciplines in maintaining and troubleshooting the boilerclave system. The study of the boilerclave also highlighted the over capacity of the system and highlighted the opportunity and impact that effective and early manufacturing process chain design can have on factory level design in terms of energy efficiency if considered at an early stage. This phase also delivered the baseline performance measurements required on which further research into optimisation would be referenced. Optimisation opportunities were also identified for the subsequent risk analysis phase. The technical capability demonstrated by the equipment maintenance and engineering disciples gave confidence to management to allow energy improvement investigations in a highly compliant factory production environment.

In order to ensure a successful project selection or to ensure potential mitigation actions are identified, the potential impact on both tool performance and production line performance were comprehended as a result of project implementation. In terms of equipment performance, an evaluation of functionality of both opportunities was undertaken. This required an understanding of equipment performance metrics and how an energy optimisation project could impact these metrics. It also drove a need to understand in detail the energy service requirements of the boilerclave system for example the desired outcome within a production process that necessitates the usage of energy. In terms of the boilerclave and the characterisation work completed in phase 3, this meant understanding why the system had a setting of 136 psi while the system was idle. It was as a result of this understanding that optimisation settings became evident through brainstorming ideas with the appropriate members of the workforce. Due to the highly integrated nature of the manufacturing process chain and the compliance obligations, a further understanding of manufacturing process chain capability was required. What this meant was ensuring functionally validated projects were evaluated against the appropriate KPI within the manufacturing process chain. To perform this effectively the KPI's identified had to be understood in terms of the value they present to their organisation for example monitor sensitivity. As manufacturing process chains are highly dynamic, ensuring an understanding how KPI's are monitored can support effective long term monitoring of energy changes. The benefit of this approach was to ensure a prescriptive and defined approach to understanding the consequences of energy changes within a manufacturing line environment. The AHP analysis completed supported this approach. See A1.2 for all templates and calculations involved. This generated a high level of confidence that the indicators monitoring the foundry value stream were capable of evaluating the optimised idle setting. This setting and the potential energy savings could then be evaluated in terms of investment potential.

The level of understanding and analysis completed ensured a high level of confidence in evaluating the new setting over a longer period which was the requirement of phase 5. Subsequent monitoring of this optimisation displayed repeatability and ensured a level of confidence in identifying the appropriate solution path in the final phase of factory integration. To support this, the original equipment manufacturer was engaged to identify likely solution paths. This required a unique hardware based switch with PLC control to be developed. This demonstrated an improved eco-design opportunity which had been previously unknown and showed the benefit of considering energy efficiency performance at the design phase for future models of the boilerclave system. An alternative solution path resulted in the identification of the need for a separate idle state for the boilerclave system in which the system could be logged into during low utilisation periods. However, the level of production line control and IT infrastructure required within the foundry value stream to realise this was not sufficient to proceed with this option. The methodology described and the case outlined has demonstrated how a legacy factory can improve its energy performance by understanding at a deeper level the energy behaviour of its manufacturing production systems.

5 Use case application with multiple constraint criteria

5.1 Introduction

The focus of the research completed to this point was on validating the methodology through its application within an industrial setting. This resulted in the identification of a significant energy user within a targeted manufacturing process chain and the identification of an energy optimisation opportunity for a selected manufacturing state. The use case selected although beneficial is limited to energy evaluations against single functional constraints, in the use case outlined: tool availability. It is necessary to expand this approach to validate and consider more complex equipment configurations and environments. As a result it is necessary to consider how the existing methodology can be expanded to comprehend more complex environments for example production tools with multiple module configurations as well as environments where multiple functional constraints exist. Figure 5.1 highlights the expanded approach taken compared to the earlier case and the multiple criteria data collection steps needed within phase 4 functionality to support a multiconstraint environment. The expanded approach focuses on identifying appropriate data sources to ensure a comprehensive overview of current and potential future states is understood. This includes the identification of risk categories such as tool module performance and production line operational impacts. As well as comprehending mitigation requirements to ensure operational compliance. An ICT based production environment was selected to support this exploration as the technology centre membership consisted of several ICT companies who were willing to support a more complex validation of the methodology. The equipment configurations within these environments were also the most complex within the portfolio of company membership.

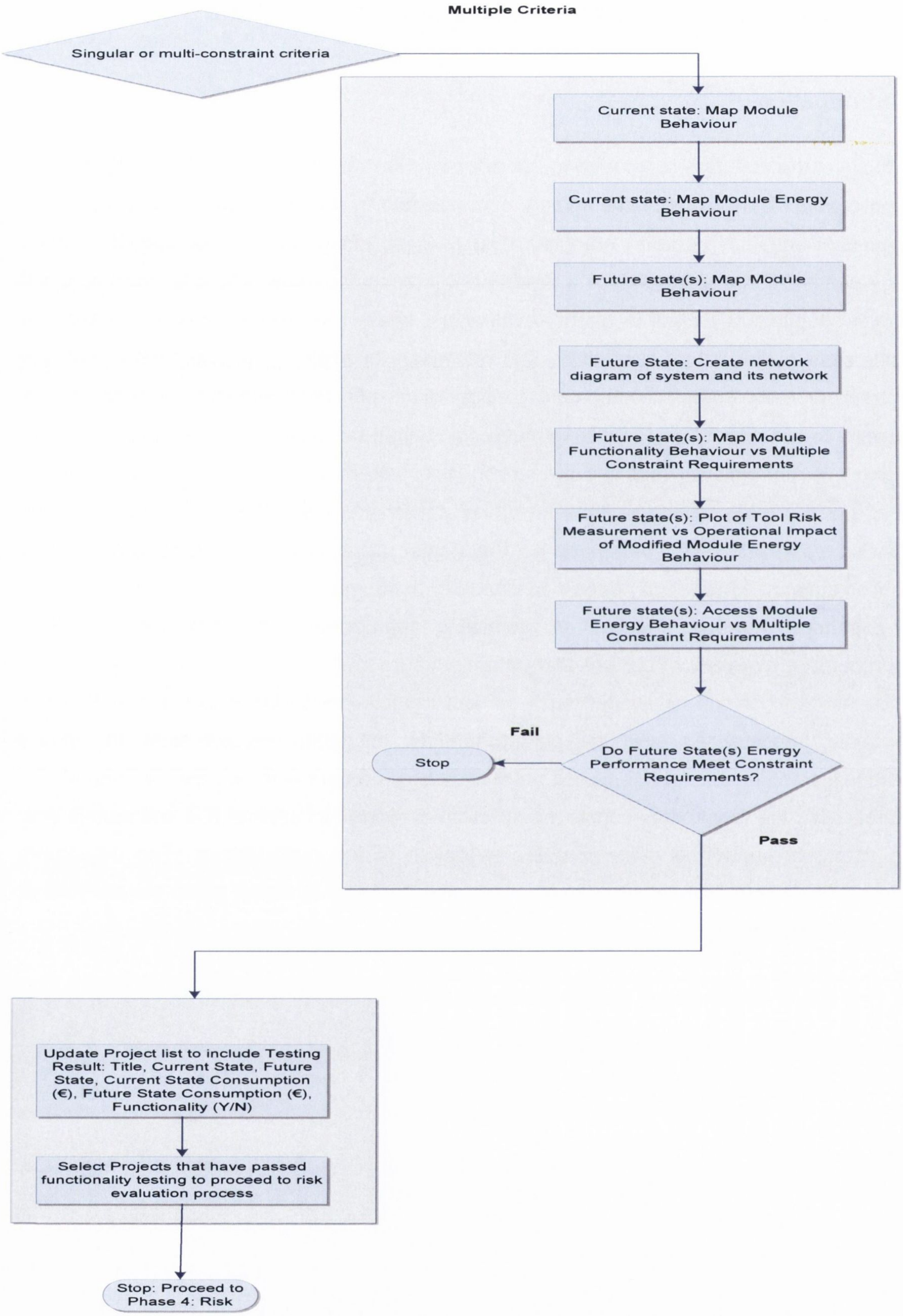


Figure 5.1 – Analytical approach to support additional functionality testing of complex equipment

5.2 Use case energy consumption characterisation

Using the methodology previously outlined in chapter 3, a more complex discrete manufacturing process chain was identified for energy characterisation. This was undertaken to further validate the methodology in a more complex environment with multiple operational constraints on a production tool with multiple modules. In the ICT environment production is processed sequentially through individual process operations. These operations can be segmented into the 5 disciplines outlined: photolithography, etch, oxide deposition, film deposition and thermal anneal/implantation as shown in figure 5.2. Energy segment characterisation was completed using a fluke 1735 power logger with a sample rate of 10.24 kHz and a 1 second time resolution to study tool energy behavior.

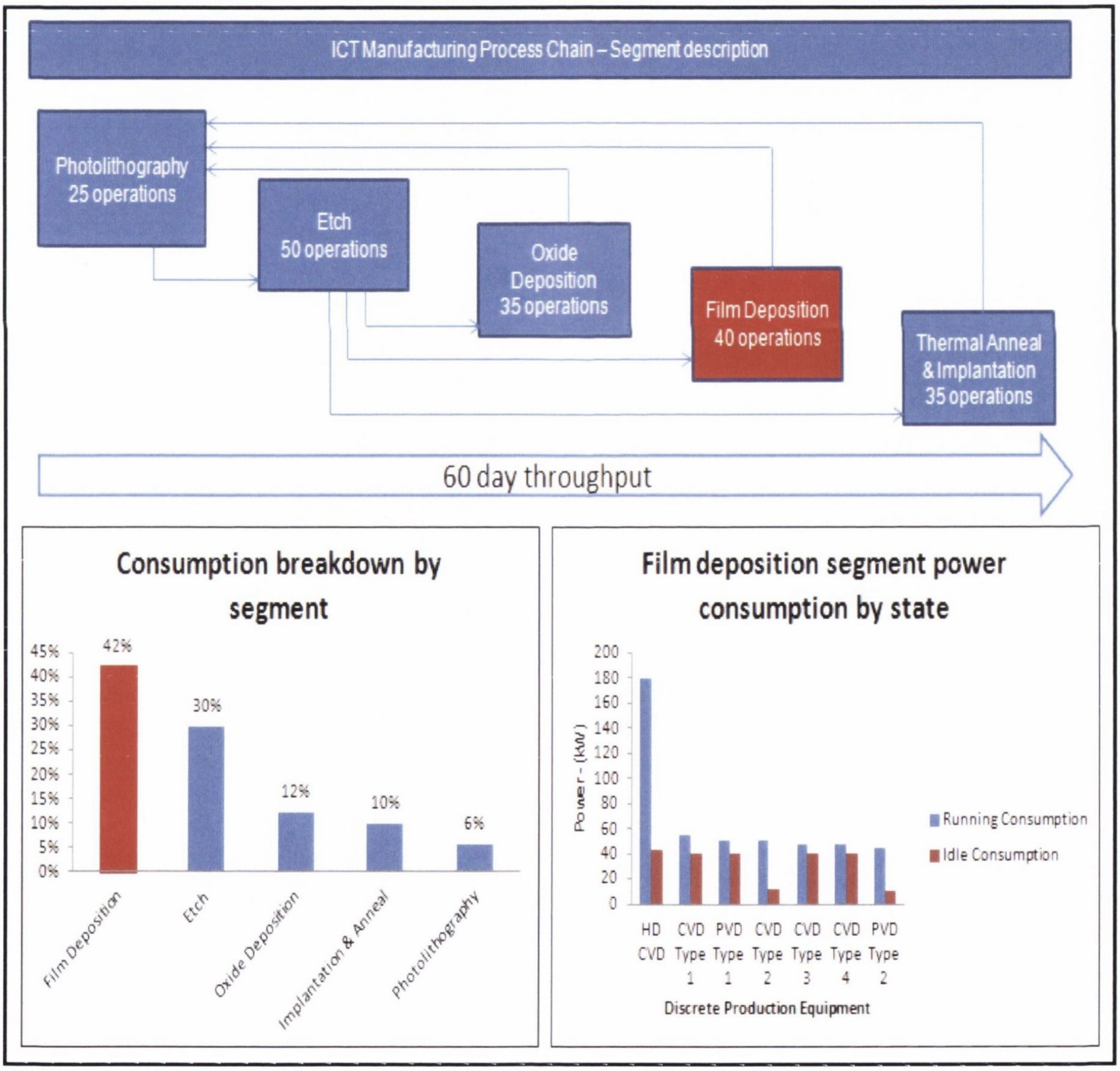


Figure 5.2 – ICT production line energy consumption data by manufacturing state

The production environment studied has an annual consumption of 14 GWh per annum. Each tool type within the film deposition segment was studied for a 24 hour period to ensure a typical reflection of tool manufacturing activity. This involved identifying and characterising 2 manufacturing states: running and idle. As shown in figure 5.2 this highlighted the film deposition segment as being the most significant in terms of energy consumption with one tool type being the most significant in terms of kW consumption for both manufacturing states.

It can be seen from this characterisation shown, the level of consumption relating to the manufacturing idle state or non productive time (T_{NP}). From figure 5.2 it can be seen that idle energy consumption (E_{NP}) across the targeted production line was significant when compared to running energy consumption (E_P), with E_{NP} being equivalent to 47% of E_P. To further understand the significance of T_{NP}, utilisation rates were assessed through the factory manufacturing enterprise system over a 1 month period to understand the significance of idle rates as a percentage of total energy consumption, as shown in table 13.

Tool Type	**ENP (kWh)**	**TNP (%)**
HD CVD	44	35
CVD Type 1	40	35
PVD Type 1	40	38
CVD Type 2	12	37
CVD Type 3	40	35
CVD Type 4	40	30
PVD Type 2	10	30

Table 13 – Idle rates by equipment type

It can be seen from table 13 that T_{NP} averages 34% across the tool types sampled within the films segment highlighting that E_{NP} is a significant consumption category within the films segment. It can also be seen from the data presented in table 13, that there is one significant energy user in terms of both running and idle consumption: this was a High Density Chemical Vapour Deposition system (HD CVD). This system formed the basis of further work on new energy efficient manufacturing states. As a consequence of using the methodology it was decided to focus on the further characterisation of the idle manufacturing state in terms of energy consumption as a basis to developing new energy efficient manufacturing states.

5.3 System overview

An overview of the discrete tool identified for further study as shown in figure 5.3. The system delivers deposition of an insulation layer – SiO_2 ranging from 5000 Å to 10000 Å in thickness, for the manufacturing of advanced silicon based devices.

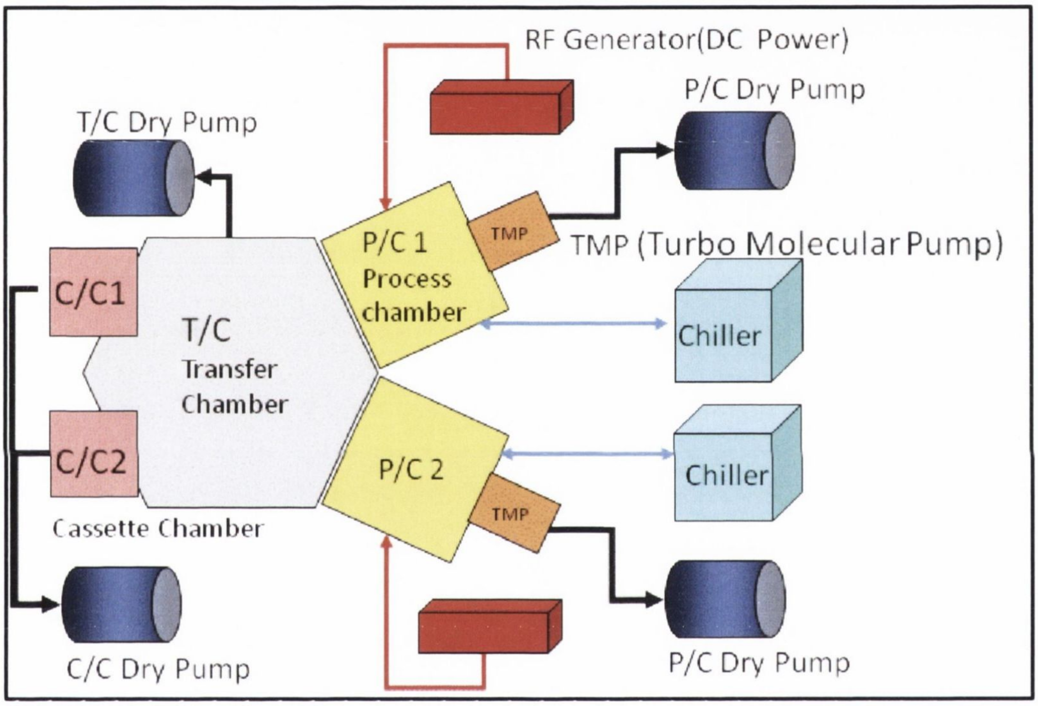


Figure 5.3 - Discrete system studied: High density plasma CVD tool

The process can be considered in the context of equation 11:

$$SiH_2 + O_2 + Ar \rightarrow SiO_2 \quad (11)$$

Gaseous SiH_2 and O_2 react within an Ar plasma based environment to form a layer of SiO_2 which acts as an insulating layer between patterned conducting metal films. The process occurs at an operational pressure of 6 $\times10^{-3}$ Torr (0.799 Pa). The process and turbo molecular pumping configurations outlined support maintaining this vacuum performance. Gaseous Ar is added to form a plasma, which is created using RF power ranging from 2.5 to

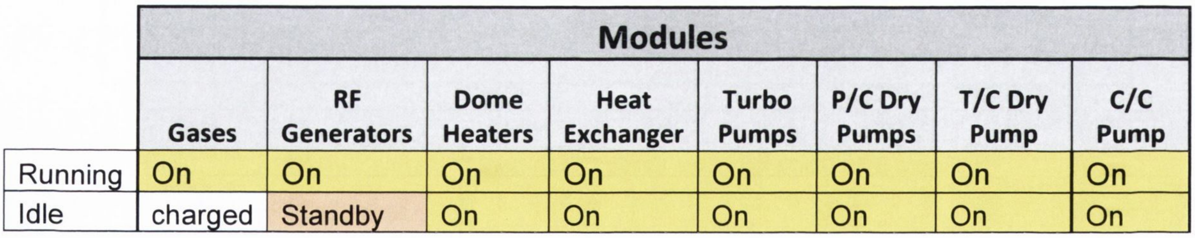
5kW, this is the sole purpose of the RF generators. This creates a variable high density plasma allowing Ar to dynamically sputter the silicon dioxide layer as it deposits ensuring film uniformity. A process temperature range of 400°C (673°K) to 450°C (723°K) is used depending on thickness requirements which is delivered through a ceramic temperature controlled dome within each process chamber P/C1 and P/C2, as shown in figure A1.3. Each process chamber uses an individual chiller or heat exchanger to maintain heat transfer control of the cooling water flowing through each ceramic dome. The target performance of the chillers is 75°C (348°K). Lower vacuum conditions of 10^{-3} Torr (0.13Pa) are maintained in the cassette and transfer chamber modules using process pumps.

5.4 Current state module behaviour

The tool (T_1) was assessed during its running and idle operational states to assess module functionality, as shown in figure 5.4.
Where:

On = running and consuming energy to process requirements
Charged = gas lines charged but isolated from process chamber and not in use
Standby = idle and consuming energy to lower standby state to maintain functionality

It can be seen from this assessment that while the tool is running and processing material, all modules are operational. While the tool is in its idle state all modules remain operational with the exception of both process gas supply and RF generators.



	Modules							
	Gases	**RF Generators**	**Dome Heaters**	**Heat Exchanger**	**Turbo Pumps**	**P/C Dry Pumps**	**T/C Dry Pump**	**C/C Pump**
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On

Figure 5.4 – Current state of tool modules for operational manufacturing states

This modular behaviour was referenced against energy consumption. The study captured both running (E_P) and idle energy consumption (E_{NP}) behaviour over a 3 hour period. Figure 5.5 highlights tool behaviour in terms of energy consumed in both running and idle mode - $E(T_1)_m$. It can be seen from this figure that running mode requires a period of increased energy consumption which is seen as a series of power cycles up to 100kW in consumption. This relates to the striking of plasma to create the reactive species from the gaseous material introduced into the process chamber. This generates uniform plasma of between

10^{11}-10^{12} ions/cm^3. During running mode, a series of RF pulses are used to control the ion density within the plasma which is measured and controlled through plasma temperature. During idle mode the RF module is in a standby condition which does not require any plasma process control.

An energy consumption ($E_c\,(T_1)_m$) by module study was completed for the idle manufacturing state (E_{NP}) to identify the significant energy consumers by module such that

$$E_c\,(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n) \qquad (12)$$

The tool was supplied by 2 electrical distribution boards, the first supplied the pumping systems and the second supplied the remainder of the tool modules. Both boards were measured individually while each module was recovered from a powered down state. Each module (C_1 to C_n) was recovered and metered sequentially using existing preventative maintenance manufacturing procedures as shown in figure 5.6.

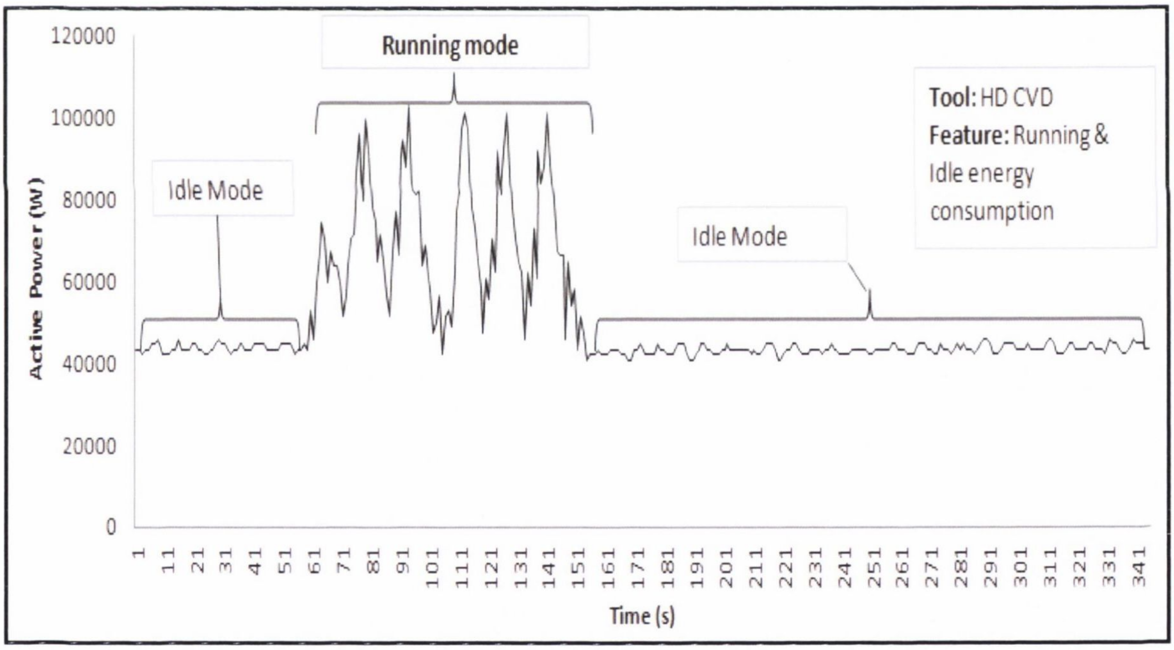


Figure 5.5 – HD CVD current state energy behaviour

This process quantified the major energy consumption modules within the HD CVD system (T_1). In addition energy efficiency estimates of each module were undertaken to assess end use electrical power utilisation based on existing research completed [225, 226] categorising the conversion of electrical power into functional behaviour. This formed the basis for future opportunity identification for energy reduction based on potential impact.

The large energy consumption relating to dome heaters and heat exchanger is attributed to maintaining process ready conditions: the energy consumption relating to RF generators is attributed to standby consumption.

Component	Energy consumption	Energy Efficiency (η)
Dome Heaters	34%	80%
Heat Exchanger	23%	87%
RF Generators	17%	95%
P/C Pumps x 2	15%	90%
Turbo Pumps x 2	7%	90%
C/C & T/C Pumps	4%	90%

Figure 5.6 – Module energy consumption

5.5 Future state identification

A brainstorming activity was completed with key personnel who interact with the system, these were maintenance, operations and engineering personnel who managed the system on a daily basis and were familiar with the factory information systems relating to the HD CVD system such as maintenance and operational logs. Using a 'current state – future state' model associated with kaizen exercises, the activity was performed to identify potential future states that would demonstrate improved metered energy consumption: $E_f(T_1)_m$. Figure 5.7 highlights an initial overview of future states. The kaizen activity was administrated by the author of this manuscript. 3 potential states were identified as potentially having reduced energy consumption. A number of boundary conditions were outlined as part of the study:

- The energy optimised states were related to when the system was in an idle state due to the energy consumption and the significance of idle time noted in section 5.2
- No impact to operational constraints was a condition of the study such as availability, recovery time, toolset capacity and quality
- The states studied should include a comprehension of risks associated with each state

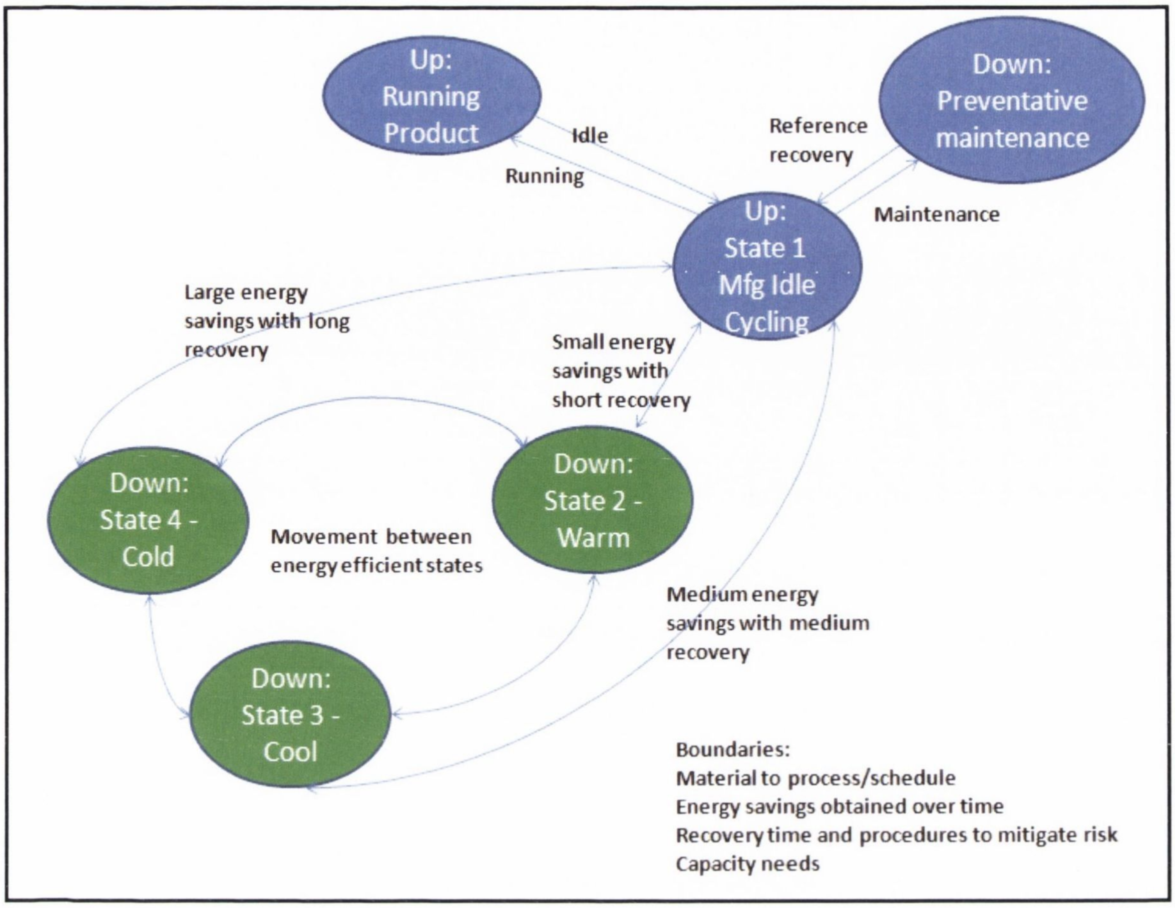


Figure 5.7 – Future energy consumption states identified

This future state map highlighted the information sources needed for state verification, the categories of which are shown in figure 5.8. The personnel who supported this activity included operations, maintenance and both vendor and manufacturing engineering resources ensuring appropriate human factor experience was comprehended. It was a requirement that all of the personnel which supported future state identification had a high level of familiarity and experience with the HD CVD system and specifically the types of data utilised to ensure compliance. As a result a number of other concerns were also highlighted specifically the risk mitigation plans and the need in terms of recovery procedures to bring the system back to production. This required the identification of appropriate equipment and production line performance metrics for future state compliance validation.

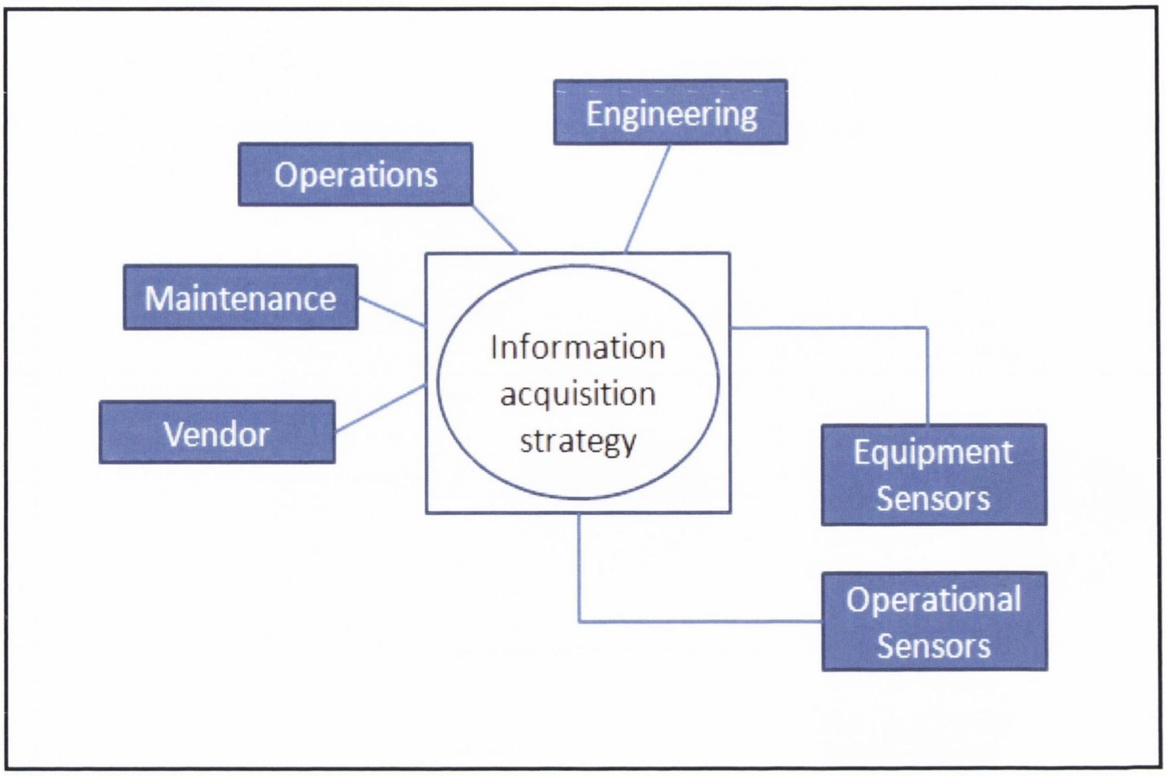


Figure 5.8 – Information sources needed for future state identification

From this approach a risk classification to optimised modules in terms of operational performance for example, recovery impact can be achieved. These data sources can support a failure mode effects analysis (FMEA) of potential future states. This includes understanding operational related issues historically linked to tool MTTF. Human factor experience of maintenance logs and OEM manuals can be leveraged to identify issues linked to unscheduled equipment fails.

Potential future state categories were identified for investigation. The objective was to identify what was technically possible initially before considering the practical application of these states. High level operational constraints were considered in these states including recovery times, which would comprehend and include risk mitigation steps.

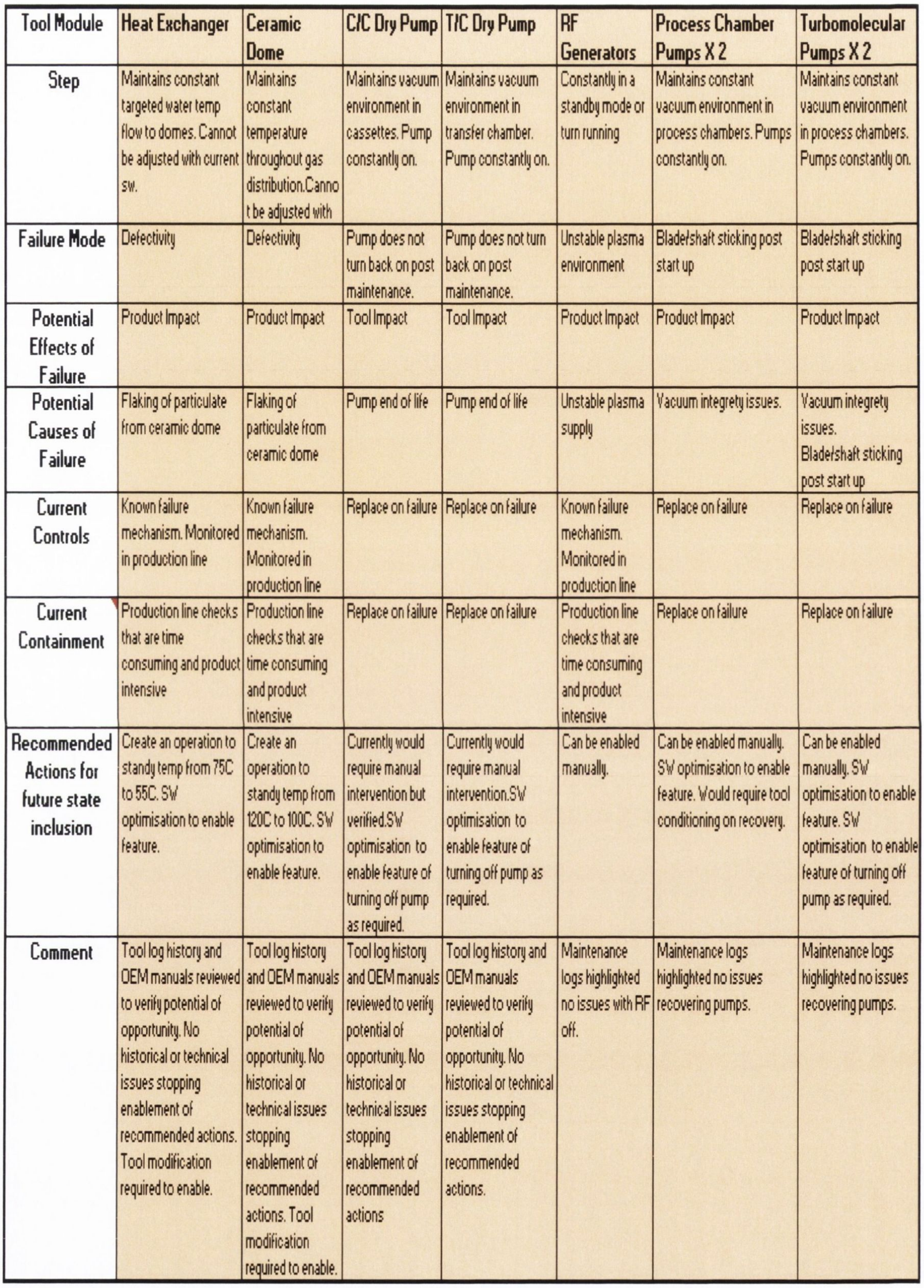
The types of states considered were:

- State 2 $E_{f2}\ (T_1)\ _m$: the potential for a reduced energy consumption state involving a recovery procedure to allow tool readiness within a 12 hour timeframe. This potential state would require operations to factor in this short recovery period before use.
- State 3 $E_{f3}\ (T_1)\ _m$: the potential for a reduced energy consumption state involving a recovery procedure to allow tool readiness within a 72 hour time frame. This potential

state would require operations to factor in this long recovery period before system use.

- State 4 $E_{f4} (T_1)_m$: the potential for a reduced energy consumption state involving a recovery procedure to allow tool readiness with a 2 week timeframe. This potential state would require operations to factor in this extensive recovery period before system use.

Within the mapping event, each state was designed to consider varying levels of energy reduction while the tool was in an idle state. A workshop was completed using maintenance, operational and engineering resources. This was completed to review and comprehend all potential failure mechanisms relating to the HD CVD system. The approach used initially concentrated on identifying and categorising known failure modes which could impact each state. Potential mitigation steps were then identified. These mechanisms were identified though reviewing maintenance, operational logs and historical quality issues that arose from HD CVD performance deviations. Using a FMEA template, the initial part of the exercise focused on failure identification to ensure all potential failures were captured rather than frequency and associated consequences. This quantification is documented in section 5.6. It can be seen from this summary, as shown in figure 5.9 that the concerns highlighted relate to process non-conformities and run to fail events rather than significant tool functionality or reliability issues. This was related to the extensive preventative maintenance procedures and schedules undertaken to ensure a high level of reliability in terms of tool availability. Maintenance schedules included weekly, monthly, semi-annual and annual preventative maintenance designed to maintain performance. The mitigation steps or recommended actions identified were improvement steps identified within the brainstorm which would support the realisation of the potential future energy consumption states outlined. Initially, the workshop focused on identifying all failure mechanisms. The factory information systems were then used to further clarify these failures in terms of likelihood of occurrence and impact to both tool performance and operational performance. The workshop was administrated by the author of this manuscript.



Tool Module	Heat Exchanger	Ceramic Dome	C/C Dry Pump	T/C Dry Pump	RF Generators	Process Chamber Pumps X 2	Turbomolecular Pumps X 2
Step	Maintains constant targeted water temp flow to domes. Cannot be adjusted with current SW.	Maintains constant temperature throughout gas distribution.Cannot be adjusted with	Maintains vacuum environment in cassettes. Pump constantly on.	Maintains vacuum environment in transfer chamber. Pump constantly on.	Constantly in a standby mode or turn running	Maintains constant vacuum environment in process chambers. Pumps constantly on.	Maintains constant vacuum environment in process chambers. Pumps constantly on.
Failure Mode	Defectivity	Defectivity	Pump does not turn back on post maintenance.	Pump does not turn back on post maintenance.	Unstable plasma environment	Blade/shaft sticking post start up	Blade/shaft sticking post start up
Potential Effects of Failure	Product Impact	Product Impact	Tool Impact	Tool Impact	Product Impact	Product Impact	Product Impact
Potential Causes of Failure	Flaking of particulate from ceramic dome	Flaking of particulate from ceramic dome	Pump end of life	Pump end of life	Unstable plasma supply	Vacuum integrety issues.	Vacuum integrety issues. Blade/shaft sticking post start up
Current Controls	Known failure mechanism. Monitored in production line	Known failure mechanism. Monitored in production line	Replace on failure	Replace on failure	Known failure mechanism. Monitored in production line	Replace on failure	Replace on failure
Current Containment	Production line checks that are time consuming and product intensive	Production line checks that are time consuming and product intensive	Replace on failure	Replace on failure	Production line checks that are time consuming and product intensive	Replace on failure	Replace on failure
Recommended Actions for future state inclusion	Create an operation to standy temp from 75C to 55C. SW optimisation to enable feature.	Create an operation to standy temp from 120C to 100C. SW optimisation to enable feature.	Currently would require manual intervention but verified.SW optimisation to enable feature of turning off pump as required.	Currently would require manual intervention.SW optimisation to enable feature of turning off pump as required.	Can be enabled manually.	Can be enabled manually. SW optimisation to enable feature. Would require tool conditioning on recovery.	Can be enabled manually. SW optimisation to enable feature. SW optimisation to enable feature of turning off pump as required.
Comment	Tool log history and OEM manuals reviewed to verify potential of opportunity. No historical or technical issues stopping enablement of recommended actions. Tool modification required to enable.	Tool log history and OEM manuals reviewed to verify potential of opportunity. No historical or technical issues stopping enablement of recommended actions. Tool modification required to enable.	Tool log history and OEM manuals reviewed to verify potential of opportunity. No historical or technical issues stopping enablement of recommended actions	Tool log history and OEM manuals reviewed to verify potential of opportunity. No historical or technical issues stopping enablement of recommended actions.	Maintenance logs highlighted no issues with RF off.	Maintenance logs highlighted no issues recovering pumps.	Maintenance logs highlighted no issues recovering pumps.

Figure 5.9 – Failure modes and mitigation steps

5.6 System evaluation of module and integrated risk

A network modelling approach was used initially to evaluate the discrete system in order to assess module reliability performance. This involved using a combination of both series and parallel networks to analyse the configuration outlined in figure 5.3. This approach was used as the HD CVD system has a complex operating system and configuration control logic that ensures that all modules are monitored and controlled either in series or parallel logic. Figure 5.10 highlights the reliability diagram relating to the HD systems operation. In addition, the extensive preventative maintenance schedules in place allowed a study to be completed of the system in terms of module failures only, rather than any other issues such as calibration or process related issues. Table 14 shows the calculations undertaken to assess the current reliability performance which were based on 12 months of system performance data.

System Component	Component description	Value
R_1	Cassette chamber dry pump	0.999
R_2	Cassette chamber 1	0.9999
R_3	Cassette chamber 2	0.9999
R_4	Transfer chamber dry pump	0.999
R_5	Transfer chamber	0.9999
R_6	Process chamber 1 dry pump	0.999
R_7	Process chamber 1 Turbo-molecular pump	0.999
R_8	Process chamber 1 RF generator	0.9999
R_9	Process chamber 1 dome heater	0.99
R_{10}	Process chamber 1 gas delivery	0.9999
R_{11}	Process chamber 1 heat exchanger	0.999
R_{12}	Process chamber 2 dry pump	0.999
R_{13}	Process chamber 2 Turbo-molecular pump	0.999
R_{14}	Process chamber 2 RF generator	0.9999
R_{15}	Process chamber 2 dome heater	0.99
R_{16}	Process chamber 2 gas delivery	0.9999
R_{17}	Process chamber 1 heat exchanger	0.999
R_{18}	$= R_2 + R_3 - R \times R_3$	1
R_{19}	$= R_4 \times R_5$	0.9989
R_{20}	$= R_6 \times R_7 \times R_8 \times R_9 \times R_{10} \times R_{11}$	0.9868
R_{21}	$= R_{12} \times R_{13} \times R_{14} \times R_{15} \times R_{16} \times R_{17}$	0.9868
R_{22}	$= R_1 \times R_{18} \times R_{19}$	0.9979
R_{23}	$= R_{20} + R_{21} - R_{20} \times R_{21}$	0.9999
R_{24}	$= R_{22} \times R_{23}$	0.9978

Table 14 – Current state reliability performance calculations

It can be seen from table 14 that in terms of module reliability, the system demonstrates a high level of performance. This reliability performance reflects the operational policy of run to failure on system modules rather than implementing a proactive maintenance schedule. The reliability of the HD CVD system over time can now be defined as R(t): the probability that a component or system will perform a required function for a given period when used under stated operating conditions [227], where

$$R(t) = R_{24} = 0.9978$$

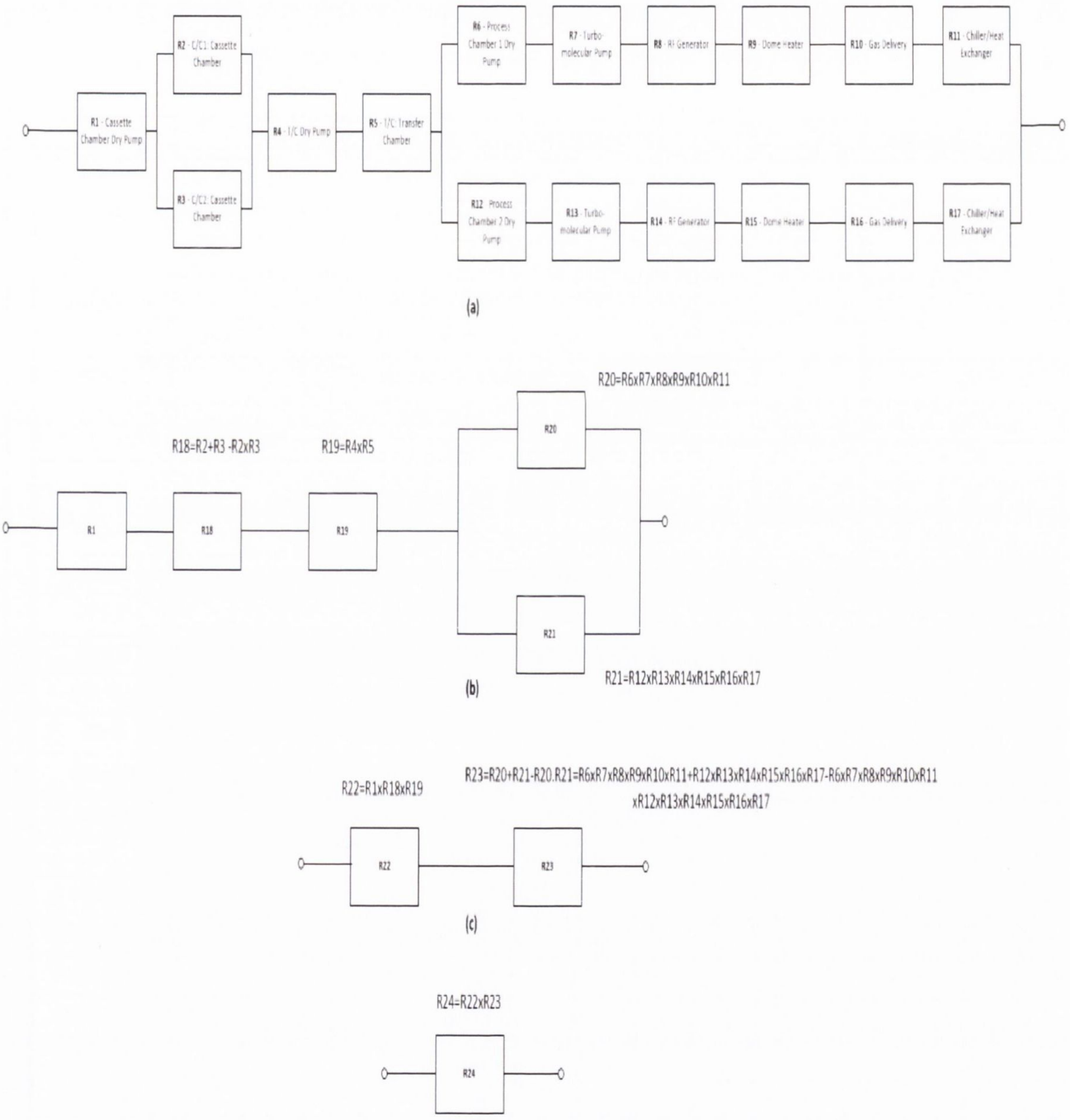


Figure 5.10 – Network evaluation of system

This current state reliability performance evaluation created an understanding of reference reliability performance from which any energy efficient future states $E_{f2-4}\ (T_1)_m$ could be evaluated. However this initial assessment only considered the probability of module failure in terms of system availability. The exercise outlined in figure 5.9 outlined the potential module optimisations and impact of issues to future states $E_{f2-4}\ (T_1)_m$.

In order to further quantify this impact understanding, these future state modifications were assessed in terms of risk, where risk is defined as the effect of uncertainty to these future states $E_{f2-4}\ (T_1)_m$. In this context, risk is expressed in terms of a combination of the consequences or impact of an event and the associated likelihood or probability of an occurrence [228]. These future states were evaluated in terms of tool functionality and risk to the processes which the tool influenced, where risk considered impact, probability of impact and customer weighting. Using tool maintenance histories and workforce experience of recovery issues observed during maintenance recovery a risk measurement was created for each tool module experiment, RM_{module}. Using the data collected in figure 5.9, factory data was used to calculate the likelihood of a tool failure occurrence and the impact. This was completed evaluating for current state performance with maintenance experience embodied within the workforce used to evaluate future state performance of tool module functionality as shown in figure 5.11. Equation 13 highlights this functionality review considering both impact and reliability where:

I_{module} = Impact of module project to tool functionality

$R(t)$ = Reliability of tool over time due to module project

$$RM_{module} = I_{module}.R(t) \qquad (13)$$

Current State: Idle					
Module	**Current State Performance**	**Risk Impact (1-10)**	**R(t) - Likelihood of Impact (0-1.0)**	**RMmodule - Risk Measurement**	**Risk (High/Medium/ Low)**
Heat exchanger	On at constant temp	3	0.001	0.003	L
Process chamber	On at constant temp	7	0.01	0.07	L
DC Generater	On	1	0	0	L
TMP	On	3	0.001	0.003	L
Process chamber pumps	On	3	0.001	0.003	L
Product transfer chamber pump	On	2	0.001	0.002	L
Handler pump	On	2	0.001	0.002	L

Future State: Lower consumption Idle					
Module Experiment	**Evaluation**	**Imodule - Risk Impact (1-10)**	**R(t) - Likelihood of Impact (0-1.0)**	**RMmodule - Risk Measurement**	**Risk (High/Medium/ Low)**
Heat exchanger	Off	8	0.7	5.6	M
Heat exchanger	Optimised	8	0.1	0.8	L
Process chamber	Off	8	0.7	5.6	M
Process chamber	Optimised	8	0.2	1.6	L
DC Generater	Off	10	0.3	3	L
DC Generater	Standby	5	0	0	L
TMP	Off	10	0.4	4	L
Process chamber pumps	Off	3	0.4	1.2	L
Product transfer chamber pump	Off	10	0.3	3	L
Handler pump	Off	5	0.3	1.5	L

Figure 5.11 – Risk Measurement: Current and future state functionality

The risk measurements calculated were categorised into low, medium and high using scoring ranges from 1 to 3 (low), 4 to 6 (medium) and 7 to 10 (high) respectively. This allowed a categorical understanding of the risk involved to tool functionality in selecting module optimisation opportunities. It can be seen from figure 5.11 that workforce input highlighted potential differences in performance in terms of future tool reliability. It can also be seen that the scale of impact of some of the module modifications to tool performance are potentially prohibitive if pursued without further characterisation.

In addition, an evaluation was completed to understand the potential consequences of selecting these system based opportunities in terms of production line process performance. This required additional workforce input in terms of comprehending operational needs and issues and how an energy optimised tool would integrate into a production line. Figure 5.12 highlights this consideration. Using tool operational histories and workforce experience an integrated risk measurement or operational impact was created for each module experiment, IR_{module} to reflect the impact to production line performance. An impact score, from 1 to 10 was assigned to each module project to assess the impact to production line operations. This was then weighted in terms of importance to the stakeholders supporting this assessment. This allowed an understanding of the consequences involved to production line performance in selecting module optimisation opportunities.

Equation 14 highlights this review considering both impact to operational and process parameters: $I_{operations}$ and weighting: *w* where:

$I_{operations}$ = Impact to operations from module optimisation

w = Importance weighting of category

$$IR_{module} = \sum_{i=1}^{n} Ioperations\,.\,w \qquad (14)$$

It can be seen from figure 5.12 that a number of the future states have potentially prohibitive impacts that would require further characterisation.

Current State Performance		Customer Input					
		Defects	Qualification time	Tool Down Impact	Cycle Time	Cost	
Rating of Importance to Stakeholder		7	7	6	5	3	**Total Value**
Module	Current State Behaviour						
Heat exchanger	On at constant temp	3	1	1	1	1	42
Process Chamber Dome	On at constant temp	5	3	3	1	1	82
RF Gen	On	2	1	2	1	1	41
Turbo Pumps	On	3	2	3	4	1	76
Process Chamber Pumps	On	1	1	4	2	1	51
T/C Pump	On	1	1	1	1	1	28
C/C Pump	On	1	1	5	1	1	52

Future State Performance		Customer Input					
		Defects	Qualification time	Tool Down Impact	Cycle Time	Cost	
Rating of Importance to Stakeholder		7	7	6	5	3	**Total Value**
Module	Evaluation						
Heat exchanger	Off	6	4	7	3	1	130
Heat exchanger	Optimised	3	1	1	1	1	42
Process Chamber Dome	Off	7	7	7	4	5	175
Process Chamber Dome	Optimised	5	3	3	1	1	82
RF Gen	Off	1	4	4	1	1	67
RF Gen	Standby	2	1	2	1	1	41
Turbo Pumps	Off	3	4	3	4	1	90
Process Chamber Pumps	On	1	1	4	2	1	51
T/C Pump	Off	1	1	4	1	4	55
C/C Pump	Off	1	1	4	1	4	55

Figure 5.12 – Integrated Risk: Current and future state customer impact

In order to further comprehend how the opportunities outlined could be evaluated a scatter plot of RM_{module} vs. IR_{module} was completed as shown in figure 5.13. The purpose of this was to comprehend how a tool reliability issue could impact process operations. Historically risk measurement calculations focus on tool reliability performance only which does not comprehend this impact in terms of production line performance. By comprehending integrated risk, this allowed a visual understanding of future state risk in terms of both tool functionality and operations impact to be presented to the workforce. It can be seen from figure 5.13 that future states can be considered within 4 quadrants categorising module performance into high and low functionality and integrated risk. This allowed the workforce involved evaluating their involvement in terms of project possibilities, for example a review of figure 5.13 highlights the risk to implementation of two energy efficient future states for the heat exchanger module. This can support the selection of the appropriate project considering module functionality risk and operations risk taking into consideration both reliability and impact.

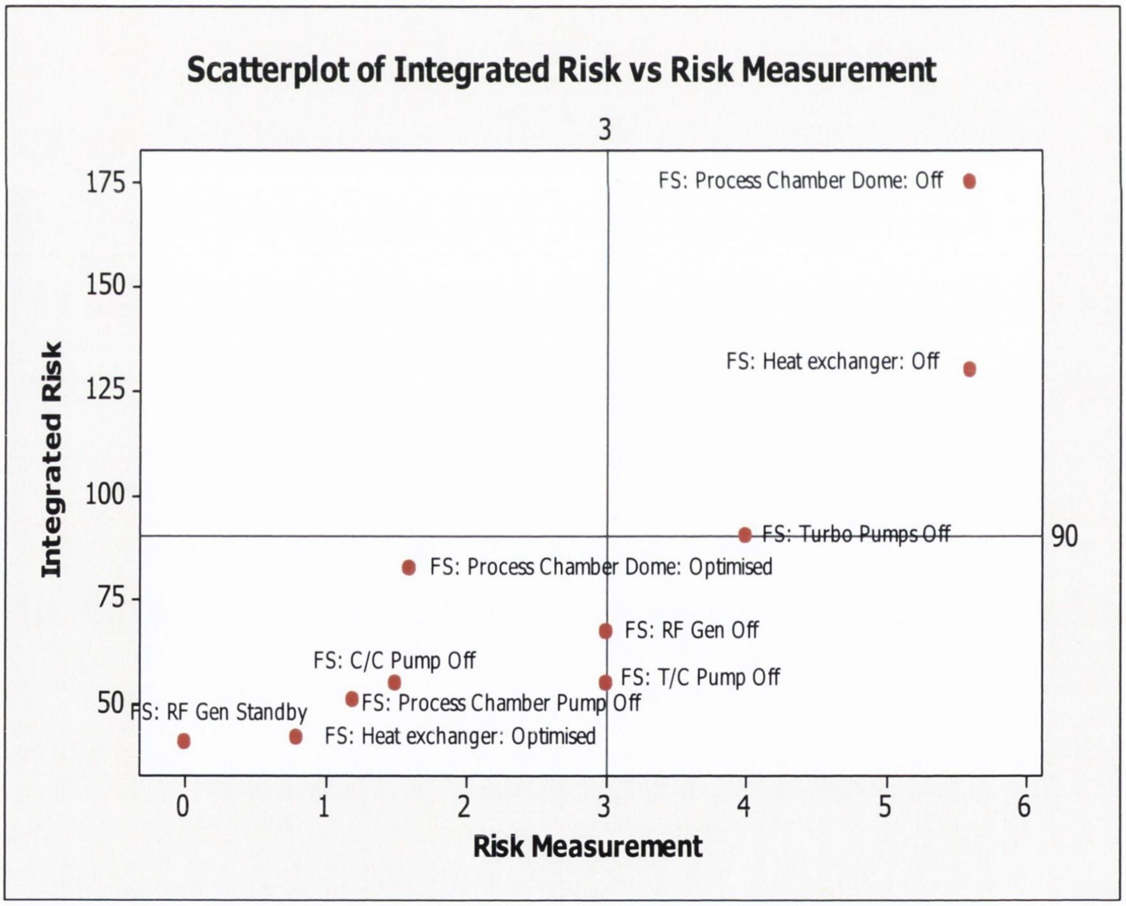


Figure 5.13 – Scatter plot of future state module risk in terms of functionality and operations

5.7 Energy behaviour by module

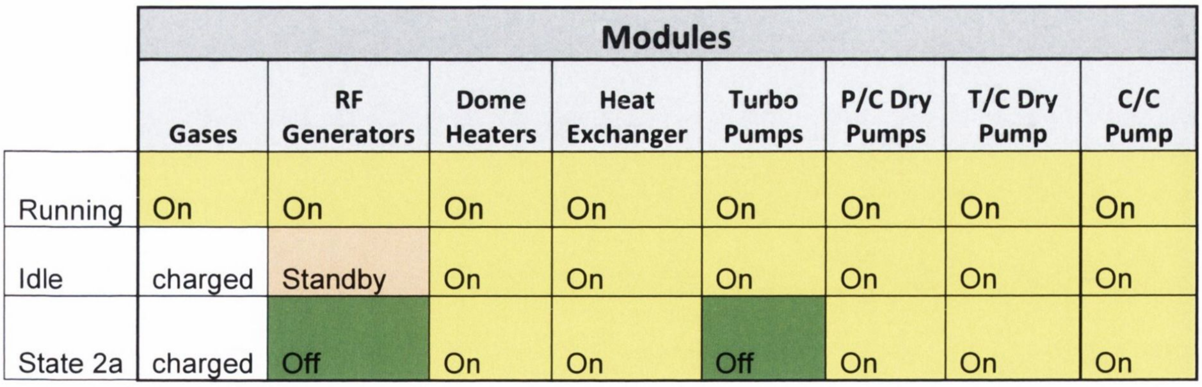
Using the output derived from both the future state brainstorms and the risk evaluations in sections 5.5 and 5.6 a series of experiments were designed to understand the energy behaviour and savings potential that could be obtained by combinations of future state module optimisations. The savings potential $E_{savings}$ can be considered in terms of current and future state performance as shown in equation 15 where:

E_c = current energy consumption
E_f = future energy consumption

$$E_{savings} = E_c - E_f \qquad (15)$$

5.7.1 Future state: 2a and 2b

An initial lower energy consuming future state configuration was defined as state 2a which powered down both the RF and turbo molecular pump modules manually, as figure 5.14 highlights. This approach was considered to highlight the ability of the current system to demonstrate a lower consumption idle state. This configuration was evaluated over a 5 week period during low periods of utilisation where the tool was placed manually in this state for a twelve hour period once a week.



	Modules							
	Gases	RF Generators	Dome Heaters	Heat Exchanger	Turbo Pumps	P/C Dry Pumps	T/C Dry Pump	C/C Pump
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On
State 2a	charged	Off	On	On	Off	On	On	On

Figure 5.14 – State 2a: current and future state

Energy behaviour was monitored to characterise any modification of consumption behaviour, as shown in figure 5.15. It can be seen from this figure that power consumption was reduced on average from 44kW to 34kW through disabling both the RF and turbo molecular pump modules sequentially. It can also be seen that on recovery to a manufacturing ready idle state, the energy consumption reflects this transition when both modules were reactivated. This behaviour was repeated over the five data points collected.

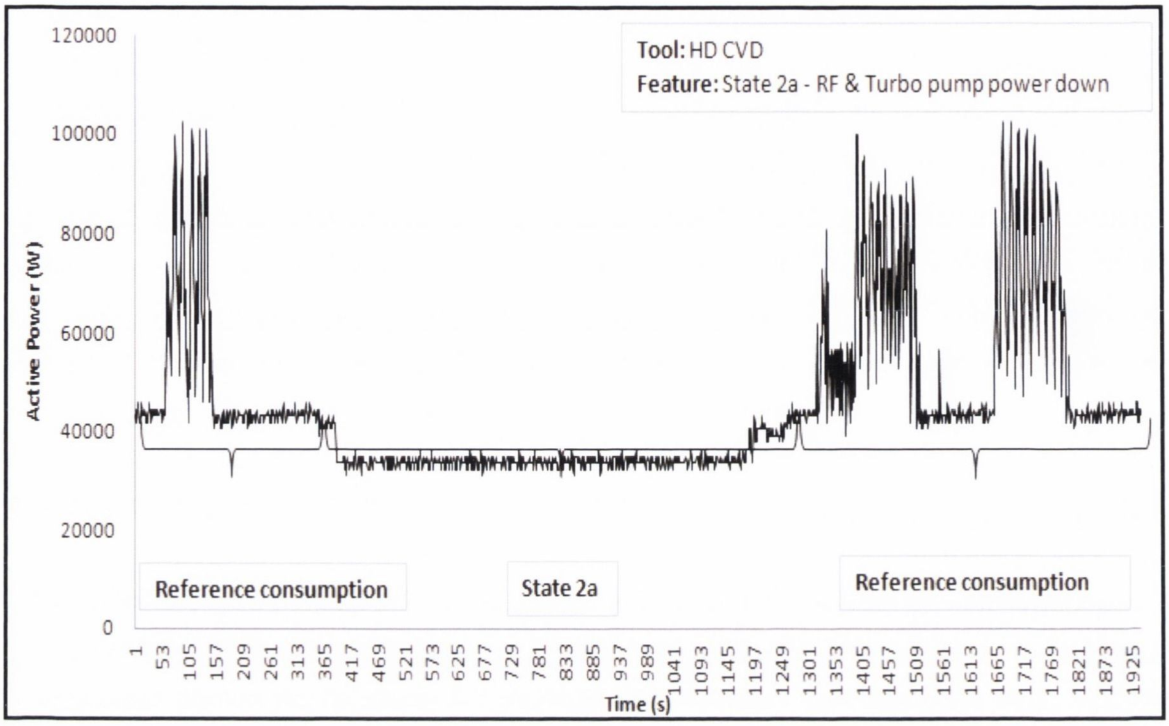
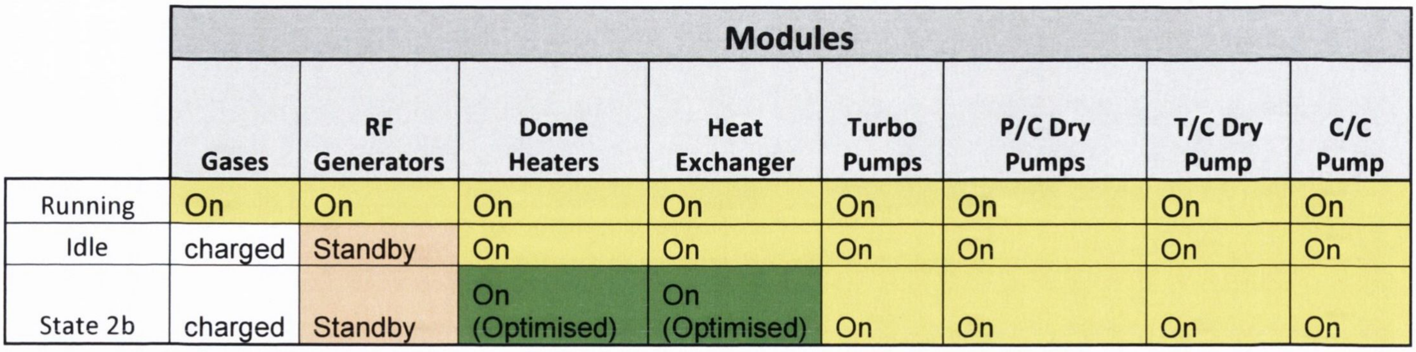


Figure 5.15 – State 2a: energy behaviour

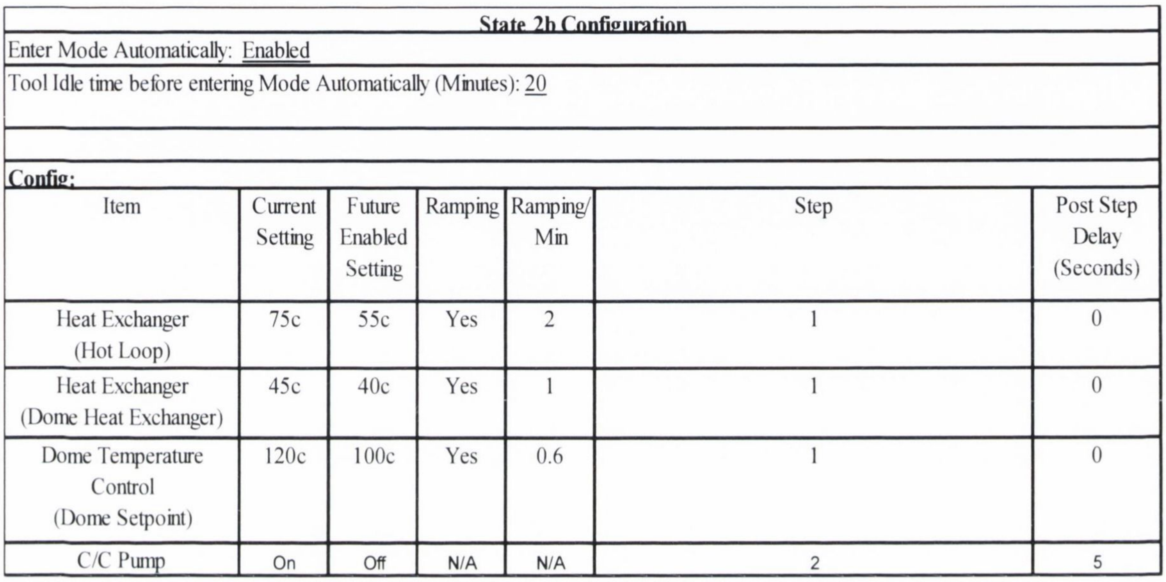
A second lower energy consuming future state configuration was defined as state 2b. This investigated the potential of using a modification of the tools operating system (o/s) to allow optimisation of previously evaluated risk modules. Figure 5.16 highlights the future state configuration in terms of module settings.



	Modules							
	Gases	RF Generators	Dome Heaters	Heat Exchanger	Turbo Pumps	P/C Dry Pumps	T/C Dry Pump	C/C Pump
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On
State 2b	charged	Standby	On (Optimised)	On (Optimised)	On	On	On	On

Figure 5.16 – State 2b: current and future state

It can be seen from this figure that optimisation settings are required to reduce energy consumption of these modules. Initially, the current tool o/s did not have this capability. This required an additional software (s/w) configuration to be developed in collaboration with the OEM to augment the systems existing capabilities as shown in figure 5.17. The future enabled settings were identified through the FMEA exercise which accessed both historical maintenance issues and workforce knowledge of the tool itself.



State 2b Configuration

Enter Mode Automatically: Enabled

Tool Idle time before entering Mode Automatically (Minutes): 20

Config:

Item	Current Setting	Future Enabled Setting	Ramping	Ramping/ Min	Step	Post Step Delay (Seconds)
Heat Exchanger (Hot Loop)	75c	55c	Yes	2	1	0
Heat Exchanger (Dome Heat Exchanger)	45c	40c	Yes	1	1	0
Dome Temperature Control (Dome Setpoint)	120c	100c	Yes	0.6	1	0
C/C Pump	On	Off	N/A	N/A	2	5

Figure 5.17 – State 2b: software modification summary

It can be seen from this figure that the optimisation opportunities identified relate to lower temperature settings on both the heat exchanger and dome temperature: 55^{0}C and 100^{0}C respectively. These were identified as the most significant energy consuming modules while the tool was in an idle mode state. This approach was considered to highlight the ability of the current system to demonstrate a lower energy consuming idle state through modification. This optimised configuration was evaluated over a five week, as previously done during a period of low utilisation where the tool was placed manually in this state for a twelve hour period once a week, as shown in figure 5.18.

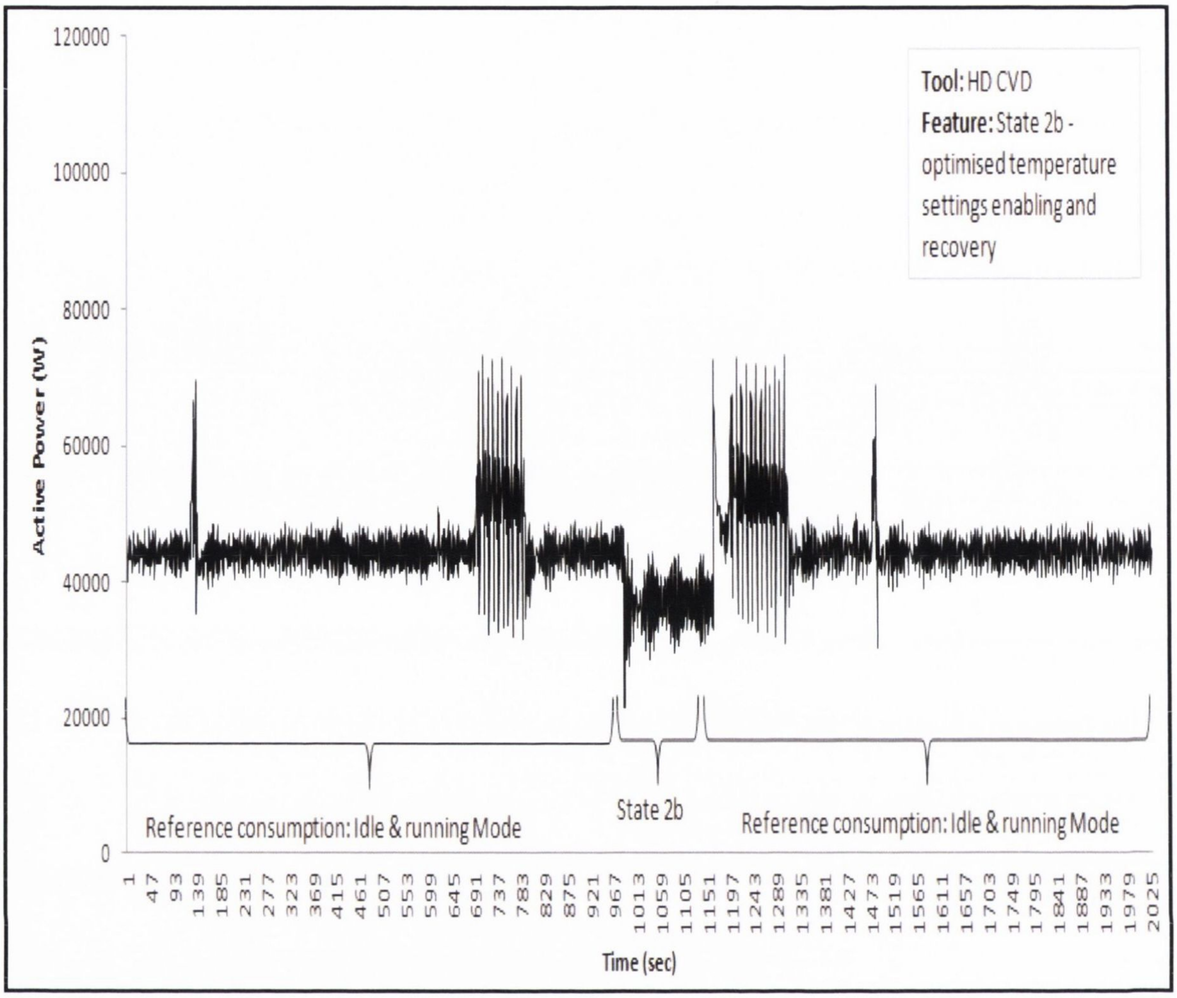
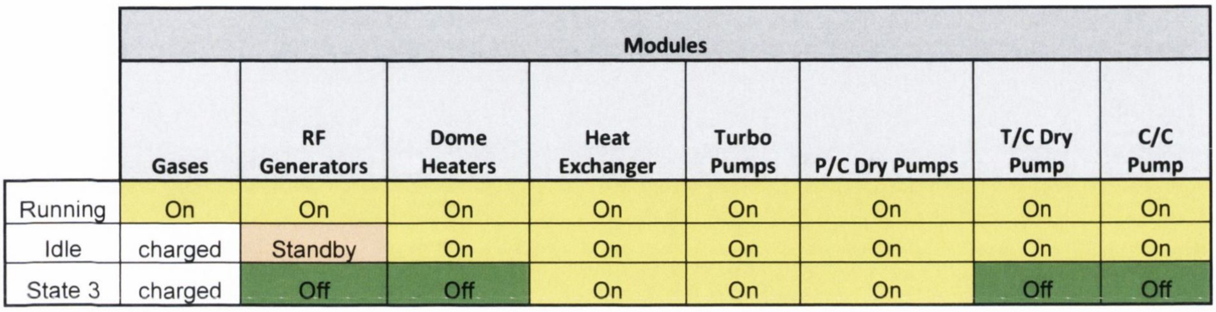


Figure 5.18 – State 2b: Energy behaviour

It can be seen from this figure that power consumption was reduced from on average 44kW to 36kW through the optimised temperature settings on both the heat exchanger and the dome temperature

5.7.2 Future state: 3

A third lower energy consuming future state configuration was defined as state 3. This investigated the potential of developing larger energy savings compared to previously mechanisms used in states 2a and 2b. Figure 5.19 highlights the future state configuration in terms of module settings.



	Modules							
	Gases	**RF Generators**	**Dome Heaters**	**Heat Exchanger**	**Turbo Pumps**	**P/C Dry Pumps**	**T/C Dry Pump**	**C/C Pump**
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On
State 3	charged	Off	Off	On	On	On	Off	Off

Figure 5.19 – State 3: current and future state

It can be seen from this figure that modular power downs are required to reduce energy consumption of these modules. The future enabled settings were identified through the FMEA exercise which accessed both historical maintenance issues and workforce knowledge of the tool itself. This future state required preparatory preventative maintenance on the system to ensure the safe power down of the documented modules. This optimised configuration was evaluated over a 5 week period, through a period of low utilisation where the tool was placed manually in this state for a 48 hour period once a week, as shown in figure 5.20. The future state was enacted through a phased shut down of the modules. The sequence identified was RF generator, heater and pumps. This was to allow adequate time to ensure shut down procedures were adhered to as well as ensuring tool stability before proceeding as well as allowing energy reductions to be verified on a phased basis. Tool recovery was in the opposite sequence. It can be seen from figure 5.20 that energy behaviour reflects this modular approach with significant energy reductions reflecting the modular shut downs. This resulted in an average power reduction of 52%, from on average 44 kW to 22.9kW.

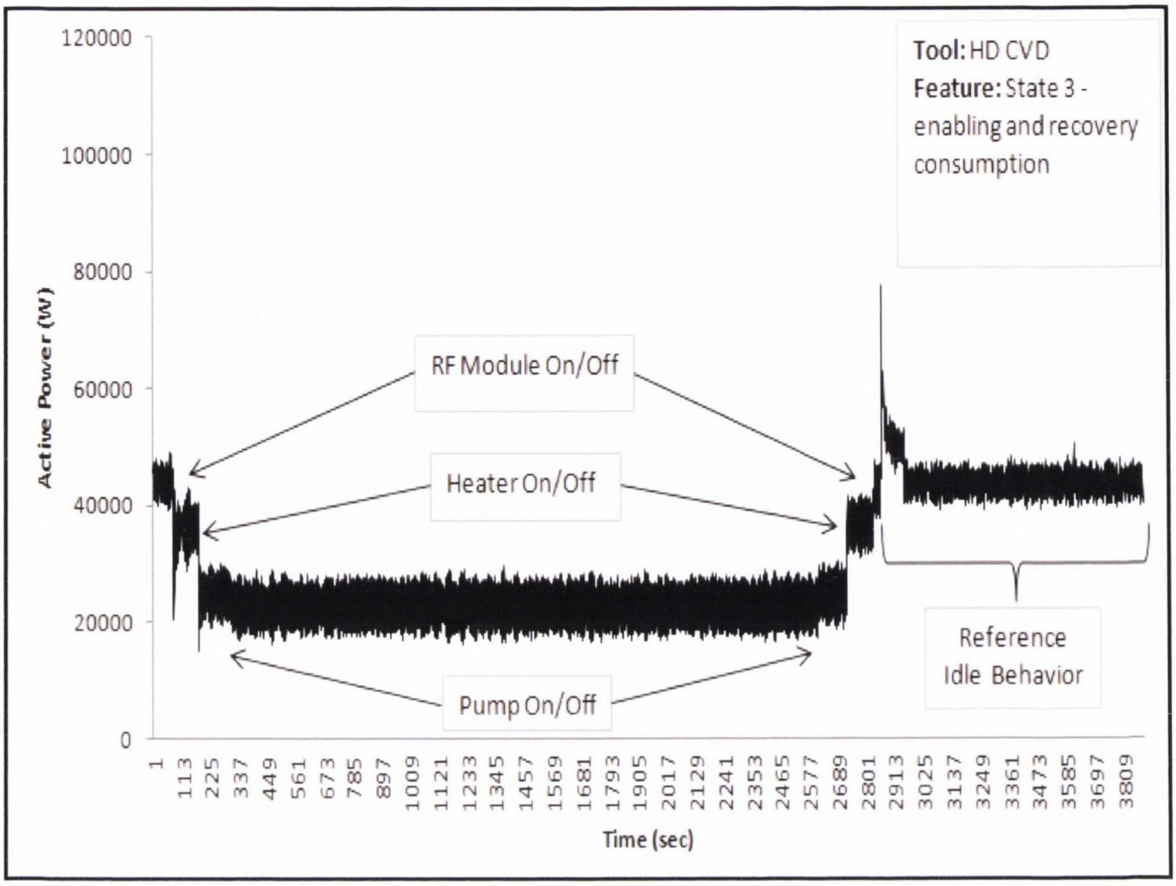
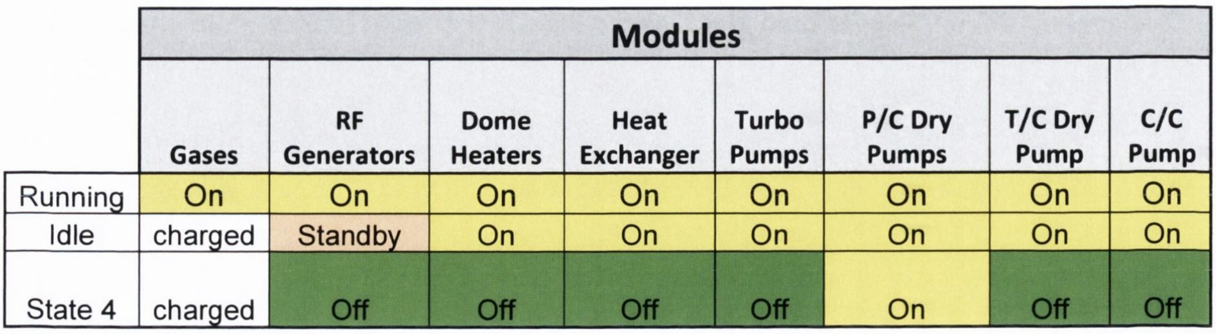


Figure 5.20: State 3: Energy behaviour

5.7.3 Future state: 4

A fourth lower energy consuming future state configuration was defined as state 4. This investigated building on the potential of further developing larger energy savings compared to the previous state three. Figure 5.21 highlights the future state configuration in terms of module settings.



	Modules							
	Gases	RF Generators	Dome Heaters	Heat Exchanger	Turbo Pumps	P/C Dry Pumps	T/C Dry Pump	C/C Pump
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On
State 4	charged	Off	Off	Off	Off	On	Off	Off

Figure 5.21 - State 4: current and future state

The future state identified built on the previous state 3 evaluations. This future state considered the additional power down of the heat exchanger and turbo molecular pumps. This became the fourth phase of the shutdown/start up sequence defined for state 3. Figure 5.22 highlights the energy behaviour exhibited. It can be seen from this figure that state four demonstrated a lower power consumption of 77% of the reference idle consumption or a reduction of 44kW to 9.9kW.

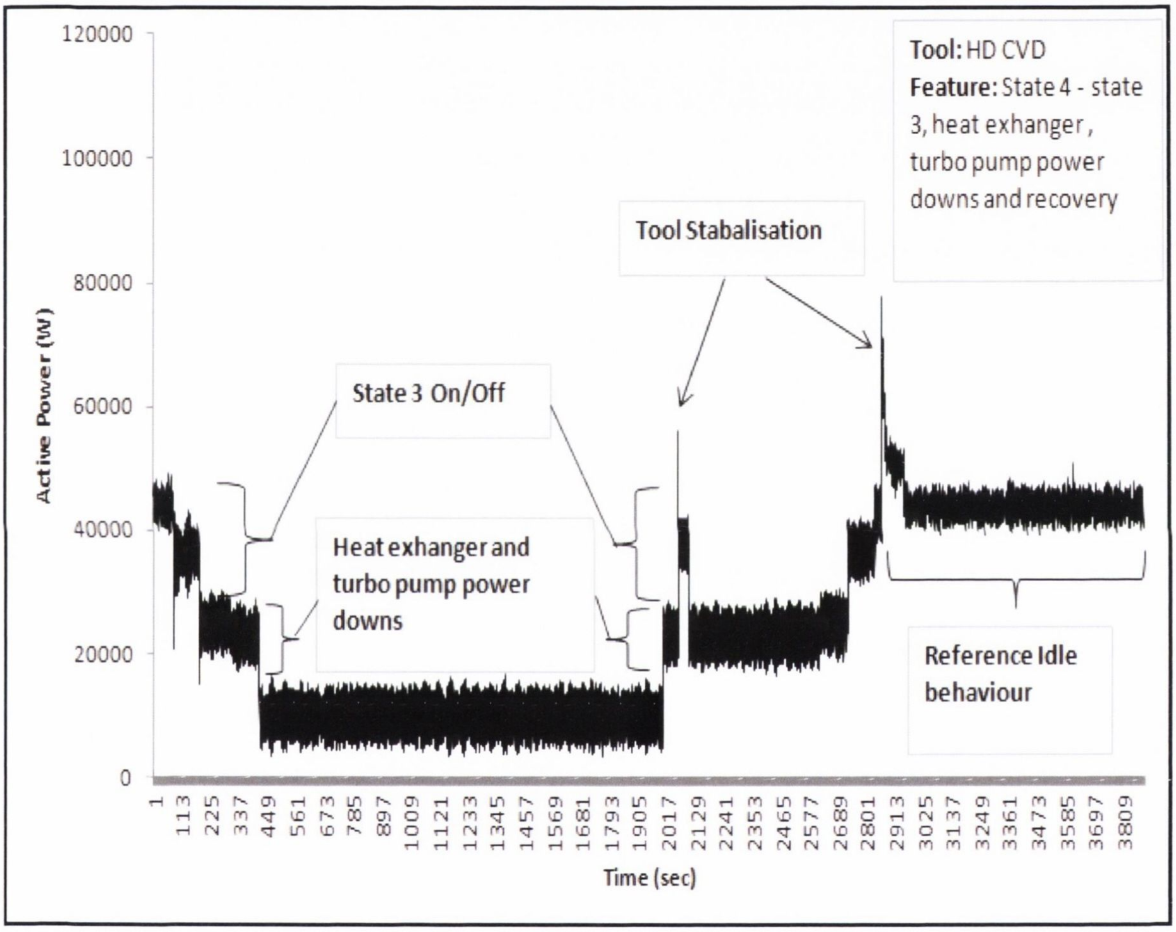


Figure 5.22 – State 4: Energy behaviour

5.8 Impact characterisation

Previous sections 5.6 and 5.7 considered future state energy performance $E_{f2\text{-}4}\,(T_1)_m$ in terms of idle state or non productive time - T_{NP}, energy saving - $E_{savings}$, module functionality: RM_{module} and operations: I_{module}. 2 Critical to Quality (CtQ) indicators were identified using phase 3, step 4Fd of the process described in chapter 3. These were process performance (A_1) and recovery times (A_2). This was also supported by reviewing the operations categories $I_{operations}$ previously shown in figure 5.12 where both A_1 and A_2 reflected operational concerns regarding defectivity, qualification time and tool down impact to capacity. This allowed a CtQ data collection plan for the 4 future states assessed in section 5.7 to be defined. The objective of this part of the process was to develop an understanding of the scale of potential consequences, both positive and negative to the system for the future states studied $E_{f2\text{-}4}\,(T_1)_m$. The review of tool maintenance and operational procedures also highlighted the need for qualitative checks post maintenance which included module shut down, as well as tool readiness checks if the tool was idle for greater than 1 hour. This indicated process performance could significantly influence recovery times. Reference recovery time performance data was initially collected to assess future state recovery performance as shown in figure 5.23.

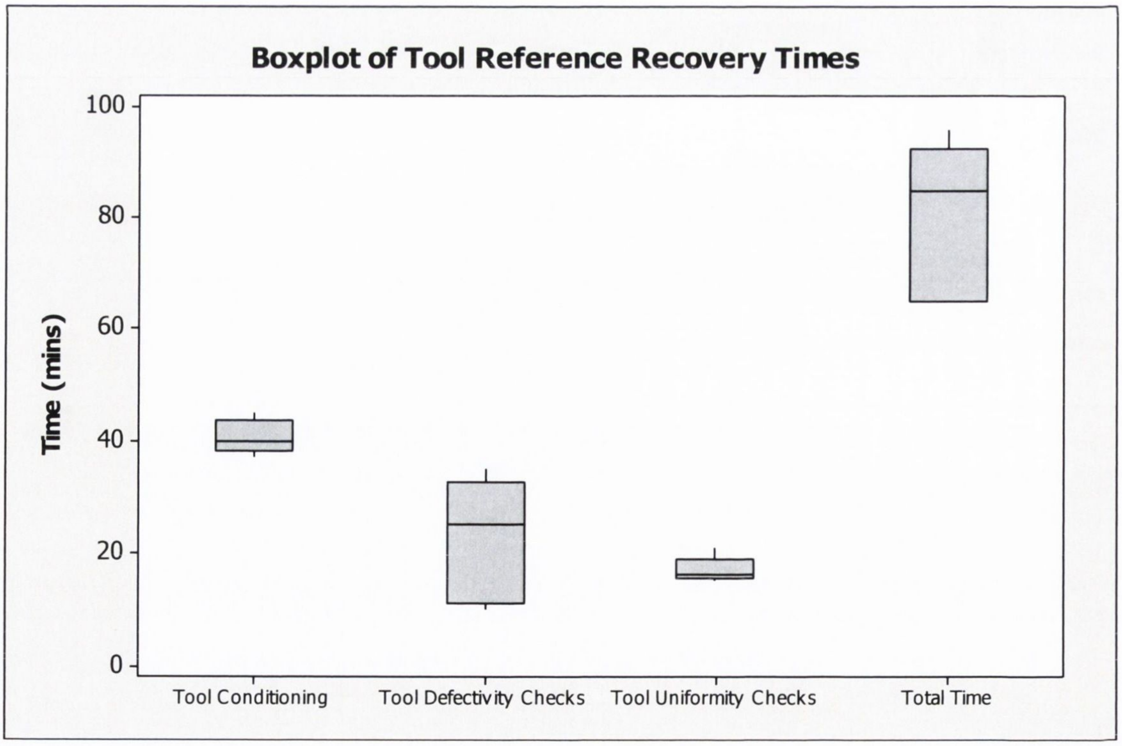
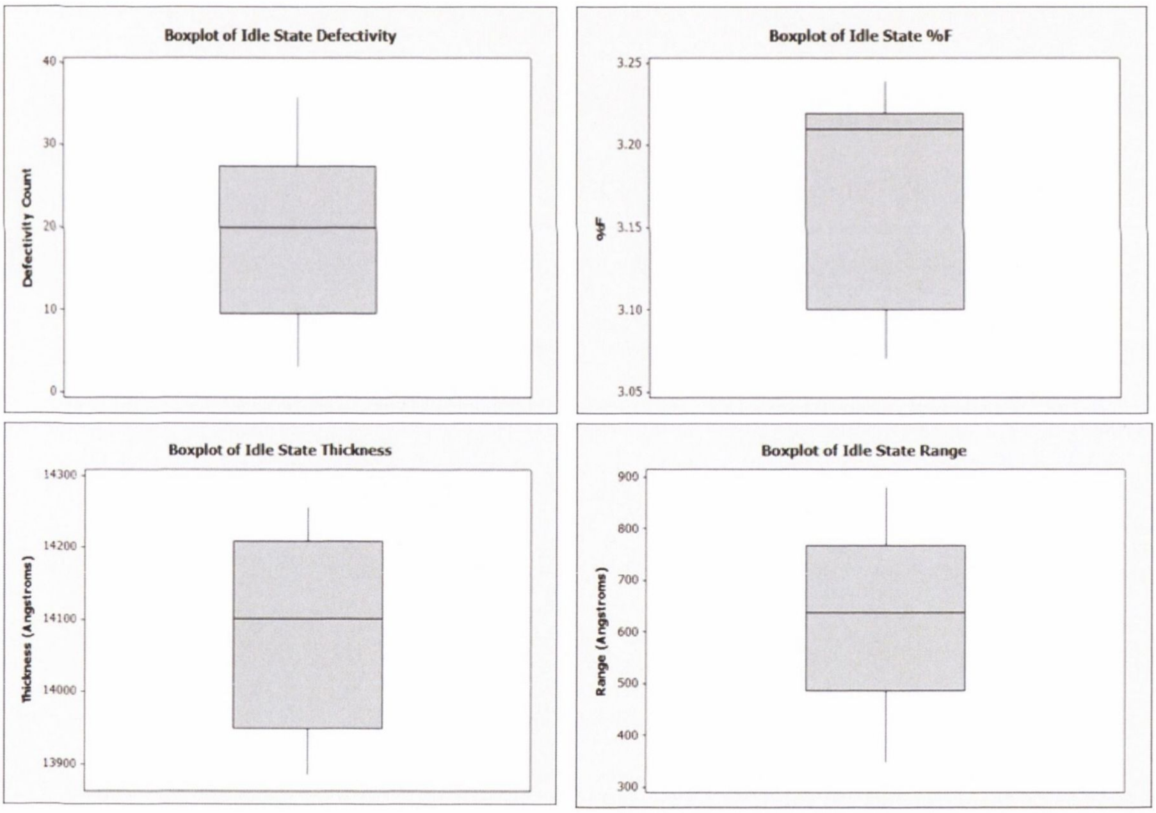


Figure 5.23 – Reference recovery times

It can be seen from this figure that recovery times are heavily influenced by production line quality management concerns requiring on average an 80 minute recovery procedure to be performed if tool modules are powered down or tool idle time is greater than 60 minutes. This confirmed the initial FMEA study in terms of process concerns and the need to mitigate failure modes in any energy state recovery.

Reference process performance data collected was categorised into defectivity and uniformity checks. A single parameter was collected for defectivity which required all non-conformities to be optically measured. Within the uniformity category three parameters were collected: Stoichiometry or fluorine percentage, film thickness and range which was measured in Angstroms and consisted of nine tests per measurement category. Figure 5.24 highlights the reference process data collected with figure 4.23 outlining the hypothesis criteria followed.


Boxplot of Idle State Defectivity

Boxplot of Idle State %F

Boxplot of Idle State Thickness

Boxplot of Idle State Range

Figure 5.24 – Reference process data

In terms of process assessment a paired t-test evaluation was undertaken to assess a level of equivalency of tool performance before and after testing as an initial evaluation of the potential of the approach documented. The outline of the approach used is highlighted in section 4.2.8.

5.8.1 Process considerations: State 2a

Figure 5.26 highlights the process performance by measurement category post tool recovery for state $E_{f2a}\,(T_1)_m$.

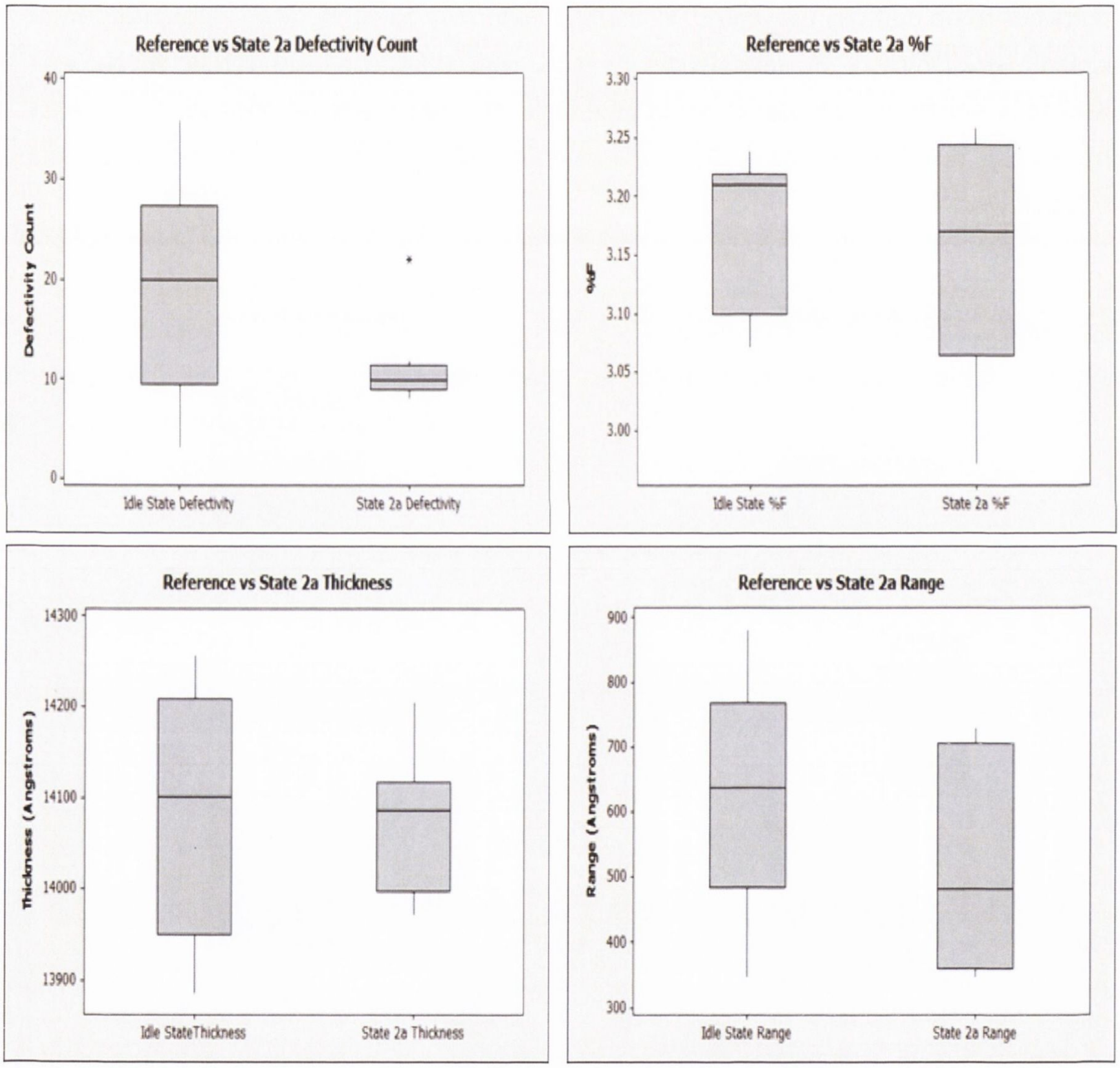


Figure 5.26 - State 2a: process performance

It can be seen from this figure that process performance equivalency is maintained which is supported through paired t-test evaluations resulting in equivalency being demonstrated to reference performance based on the sample studied. This is highlighted in figure 5.27.

Defectivity	0.078
Stoichiometry	0.716
Thickness	0.754
Range	0.178

Figure 5.27 – P values for state 2a

This initial performance reflected a decision to evaluate modules that do not impact process conditions while the system is in a non-productive state. From an operational perspective both modules are shown in figure A6.2. The function of the RF generator module is to provide plasma generation and control at 5kW with variable frequency via both top, side coil generators (2.0 ± 0.2 MHz) and bias generator (13.56 MHz). However while in standby mode this standby function as shown previously in figure 5.14 does have a power setting of 7 kW but is deemed a non-value add setting as it does not support processing or process readiness. The turbo molecular pump configuration although in operation as shown in figure 5.14 is isolated from the process chamber through a gate valve assembly while the system is in an idle state. This isolation ensures no impact to chamber process conditions while idle or if powered down.

5.8.3 Process considerations: State 2b

Figure 5.28 highlights the process performance by measurement category post tool recovery for state $E_{f2b}\,(T_1)_m$.

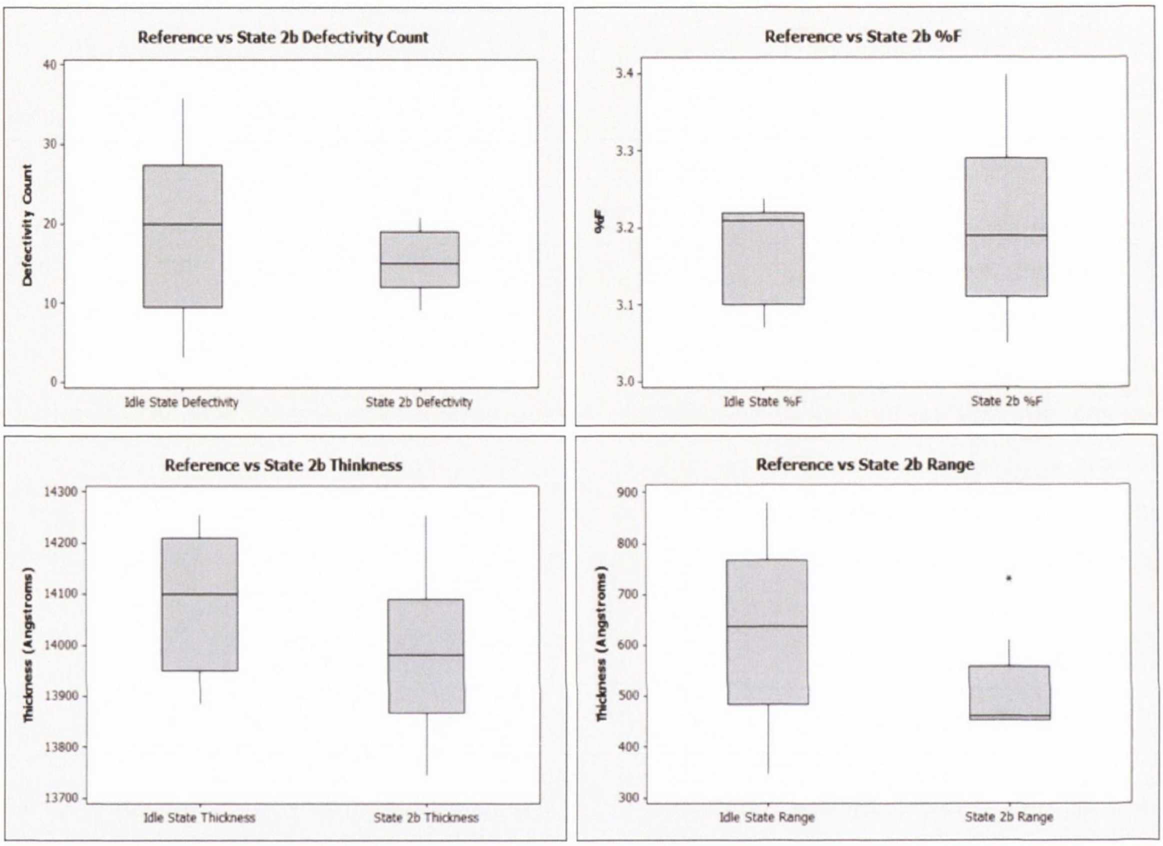


Figure 5.28 - State 2b: process performance

It can be seen from this figure that process performance equivalency is maintained which is supported through paired t-test evaluations resulting in equivalency being demonstrated to reference performance based on the sample studied. This is highlighted in figure 5.29.

Defectivity	0.388
Stoichiometry	0.344
Thickness	0.270
Range	0.089

Figure 5.29 – P values for state 2b

The future state realised to support this evaluation can be seen in figure 5.17 which defined an optimised temperature set point reduction of 20°C on the dome configuration. Figure A6.1 displays the dome configuration within the overall process chamber configuration. This opportunity was identified through the FMEA exercise which accessed both historical maintenance issues and workforce knowledge of the tool itself.

The optimisation settings identified on the chiller module were a consequence of the lower dome temperature setting which resulted in the identification of a 20°C and 5°C reduction in both the heat exchanger hot loop and dome heat exchanger respectively. Figure A6.3 displays the chiller configuration and sensors adjusted to support the future state evaluation.

5.8.4 Process considerations: State 3

Figure 5.30 highlights the process performance by measurement category post tool recovery for state $E_{f3}\,(T_1)_m$.

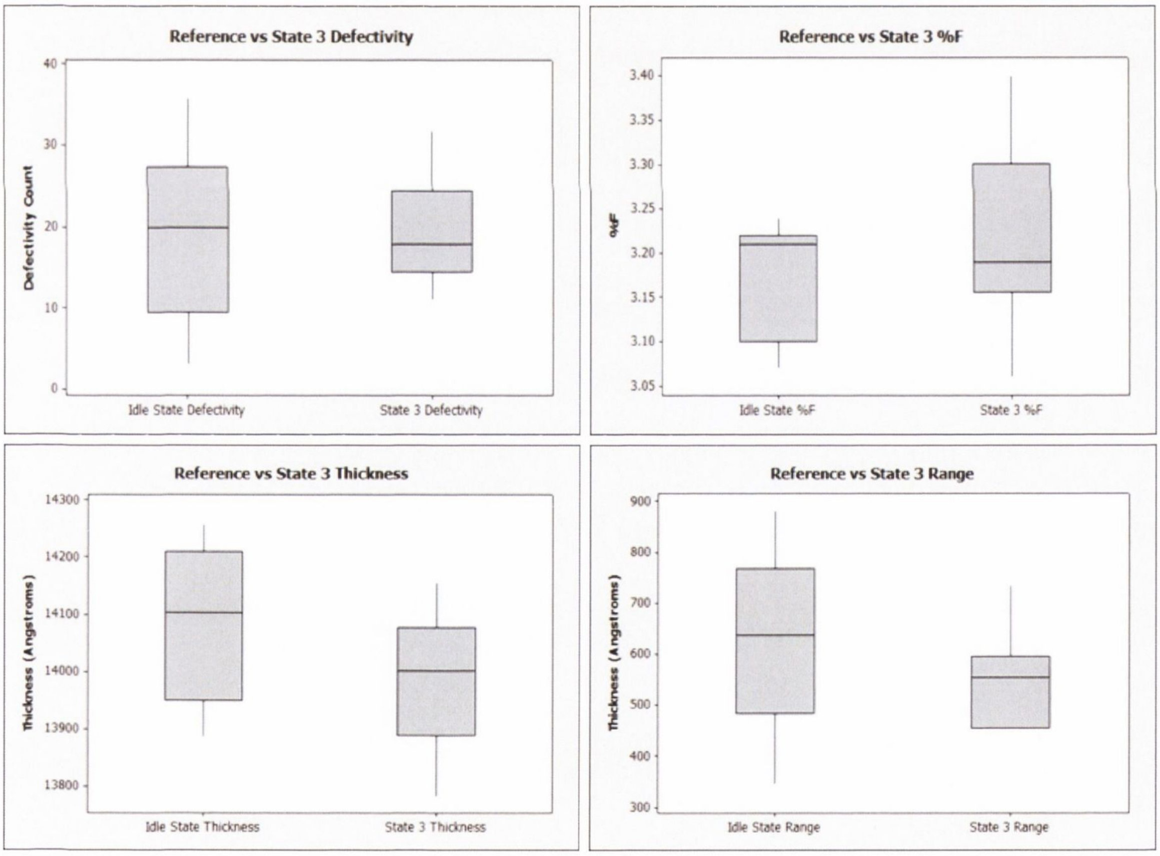


Figure 5.30 – State 3: Process performance

It can be seen from this figure that process performance equivalency is maintained which is supported through paired t-test evaluations resulting in equivalency being demonstrated to reference performance based on the sample studied. This is highlighted in figure 5.31.

Defectivity	0.696
Stoichiometry	0.117
Thickness	0.216
Range	0.156

Figure 5.31 - State 3: P values for state 3

The future state identified to support this evaluation built on previous states: $E_{f2a,b}\,(T_1)_m$ which involved powering off the RF generators and the ceramic dome heater with the addition of powering down the dry pumps within the cassette and transfer chamber modules. Figure A 6.4 highlights the pump configuration within these modules: these systems use positive displacement to repeatedly expand a cavity allowing gases to flow from a chamber which allows these gases to be exhausted separately. The FMEA exercise which accessed historical maintenance issues and specifically run to fail issues highlighted the functional possibility of this opportunity. As the functional requirement of both the turbo molecular and dry pumps is to maintain vacuum integrity during processing, their power consumption during idle time was categorised as non-value added but also minimal risk to process performance once vacuum has been established as tool processing is interlocked to vacuum integrity.

5.8.5 Process considerations: State 4

Figure 5.32 highlights the process performance by measurement category post tool recovery for state $E_{f4}\,(T_1)_m$.

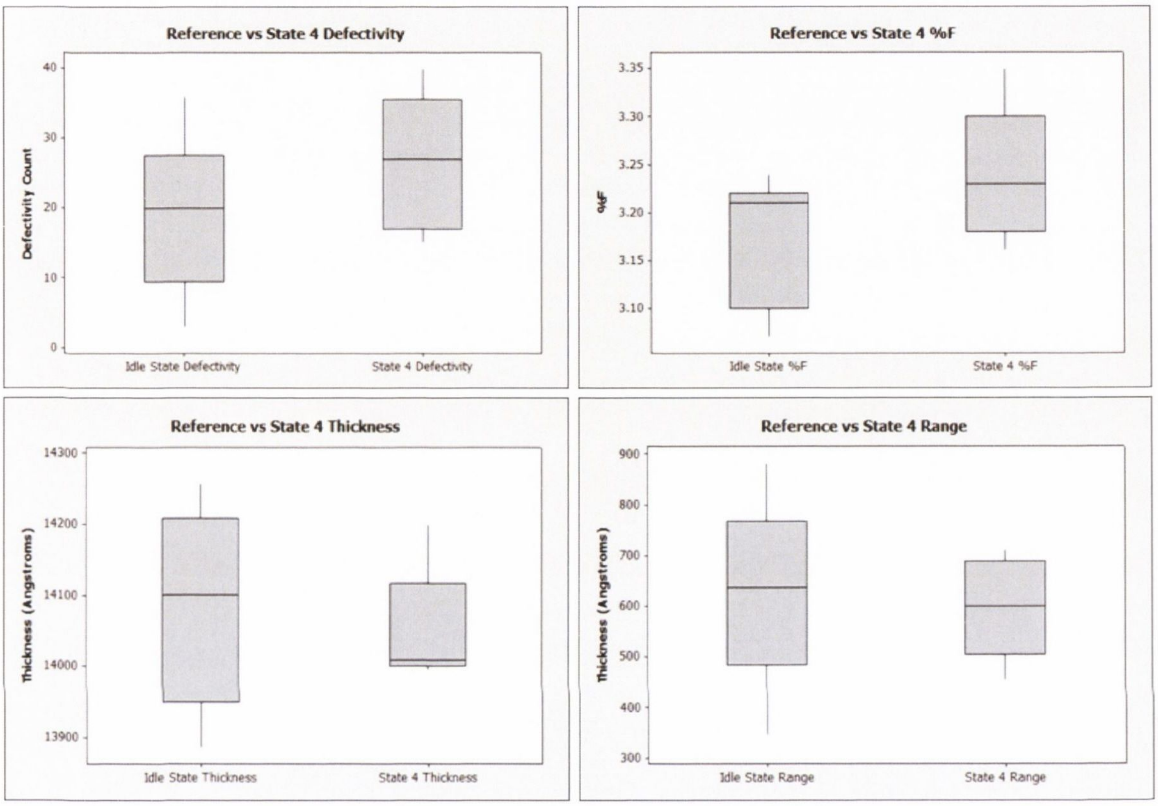


Figure 5.32 - State 4: Process performance

It can be seen from this figure that process performance is potentially influenced with both defectivity and stoichiometry demonstrating potential negative differences to reference performance and as a result non-equivalency to reference. This is highlighted in figure 5.33.

Defectivity	0.006
Stoichiometry	0.001
Thickness	0.592
Range	0.449

Figure 5.33 - State 4: P values for state 4

The future state to support this evaluation was built on previous states: $E_{f2a,2b\ 3}\,(T_1)_m$ with the addition of powering down both the turbo molecular pumps and the heat exchanger.

5.9 Future state impacts: Recovery considerations

Although the overall process performance outlined initially indicated the potential of the future states developed to meet process equivalency. The operational consequences of realising the future states outlined were not comprehended. As outlined within the process flow as shown in figure 5.1, recovery performance investigations were also required to comprehend operational impacts of the future states outlined.

5.9.1 Recovery considerations: state 2a

As the system was taken out of production to evaluate future states it was necessary to return the system to a production ready state to support processing. The FMEA process output outlined in figure 5.9 highlighted both a defect failure mode concern relating to the RF generator power down and a potential run to fail impact relating to the turbo molecular pumps shut down. These concerns required a series of conditioning recipes to be run on the system to ensure both process chambers were production ready and the turbo molecular pumps were functional. It can be seen that the median recovery time involved a further 151 minutes, as shown in figure 5.34. The chamber conditioning steps were undertaken before qualitative checks to verify process readiness and to ensure minimal risk to both system and production post recovery. It can be seen from this figure the significance of conditioning in terms of recovery time accounting for 56% of the total time.

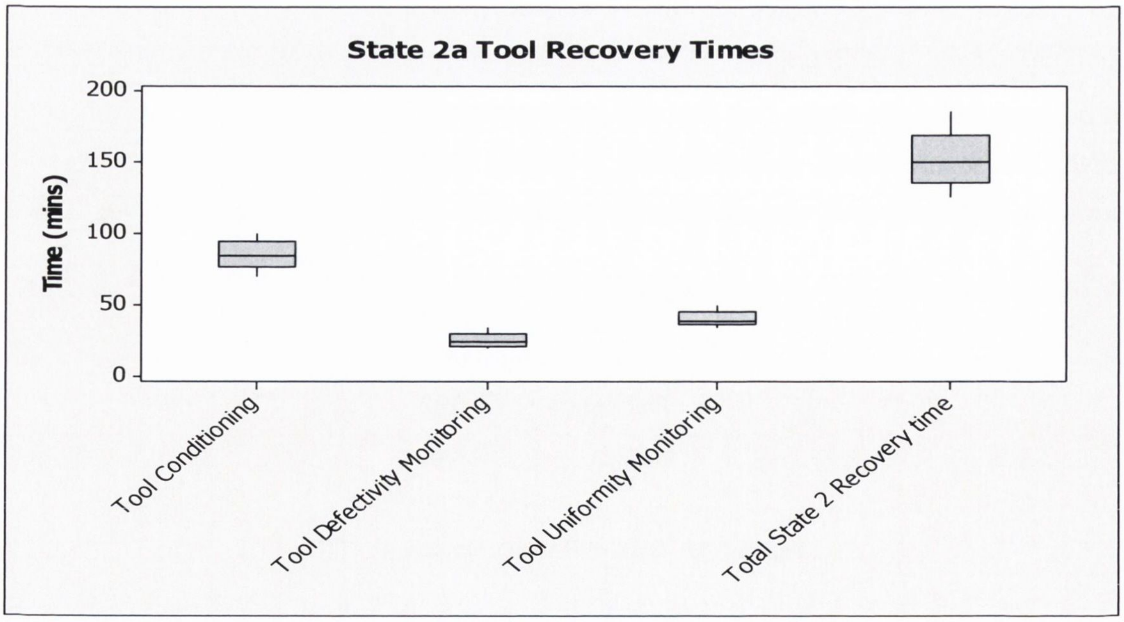


Figure 5.34 - State 2a: Recovery times

5.9.2 Recovery considerations: State 2b

As previously outlined, state 2b required a similar requalification procedure to ensure manufacturing readiness as the system was taken out of production to perform the functionality testing. This requirement was developed from the FMEA process concerns outlined in figure 5.9 highlighting potential defectivity concerns from ceramic dome condition. This delayed the average median recovery of the tool for a further 146 minutes, as shown in figure 5.35. As with the previous series of experiments, this involved a series of chamber conditioning steps to be undertaken before qualitative checks could be undertaken. This was necessary to ensure minimal risk to production post recovery. It can be seen from this figure, again the significance of conditioning in terms of recovery time impact, accounting for 68% of the total time.

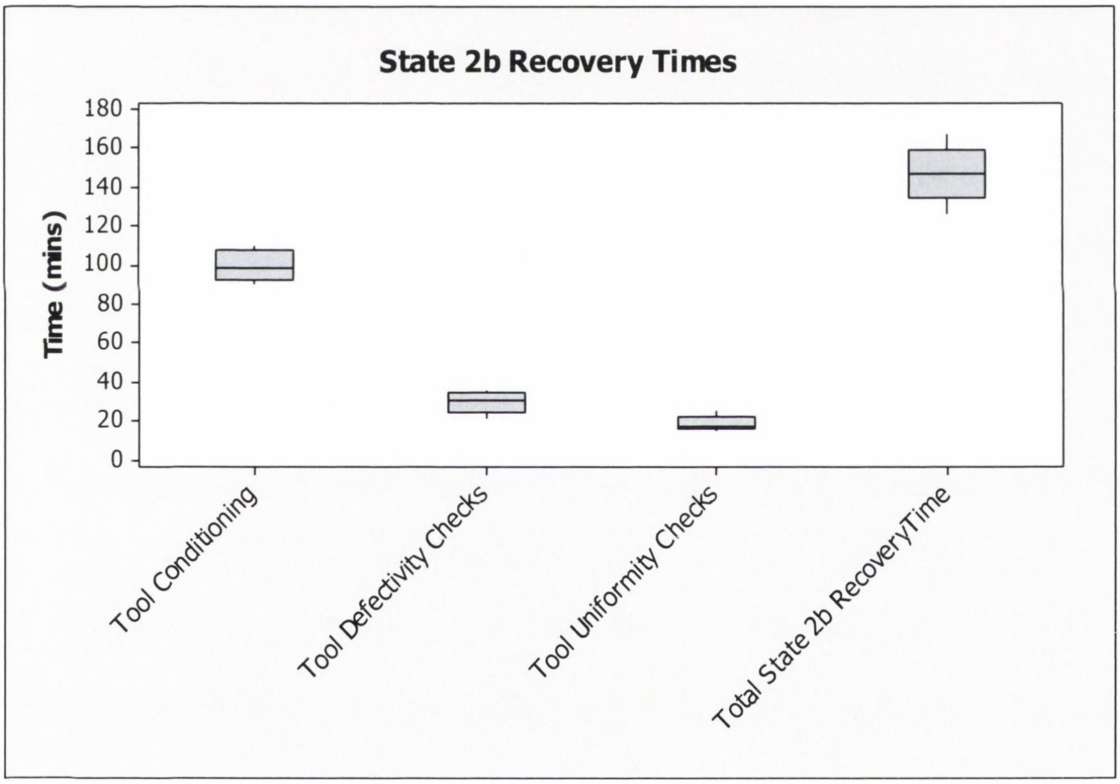


Figure 5.35 - State 2b: Recovery times

5.9.3 Recovery considerations: State 3

Due to the significance of module configuration changes for state 3 and state 4. A more detailed recovery procedure was necessary in terms of operational evaluation and process readiness. This required planned preventative maintenance to be performed. Both procedures required a 48 hour series of maintenance tasks. This leveraged manufacturing operating procedures normally used by the organisation and focused on dome preparation and recovery. This FMEA analysis shown in figure 5.9 highlighted the impact to process performance from dome issues and how this module can contribute to defectivity issues. The resulting recovery times are shown in figure 5.36. It can be seen from this figure, the significance of maintenance in terms of recovery time accounting for 70% of the total time. Due to the significant level of module adjustment within the experimentation, the requalification procedures previously used in states 2a and 2b were reused to ensure manufacturing readiness due to the qualitative concerns highlighted. This preparatory maintenance and recovery requirements delayed the tool readiness for an average of 56 hours, as shown in figure 5.36.

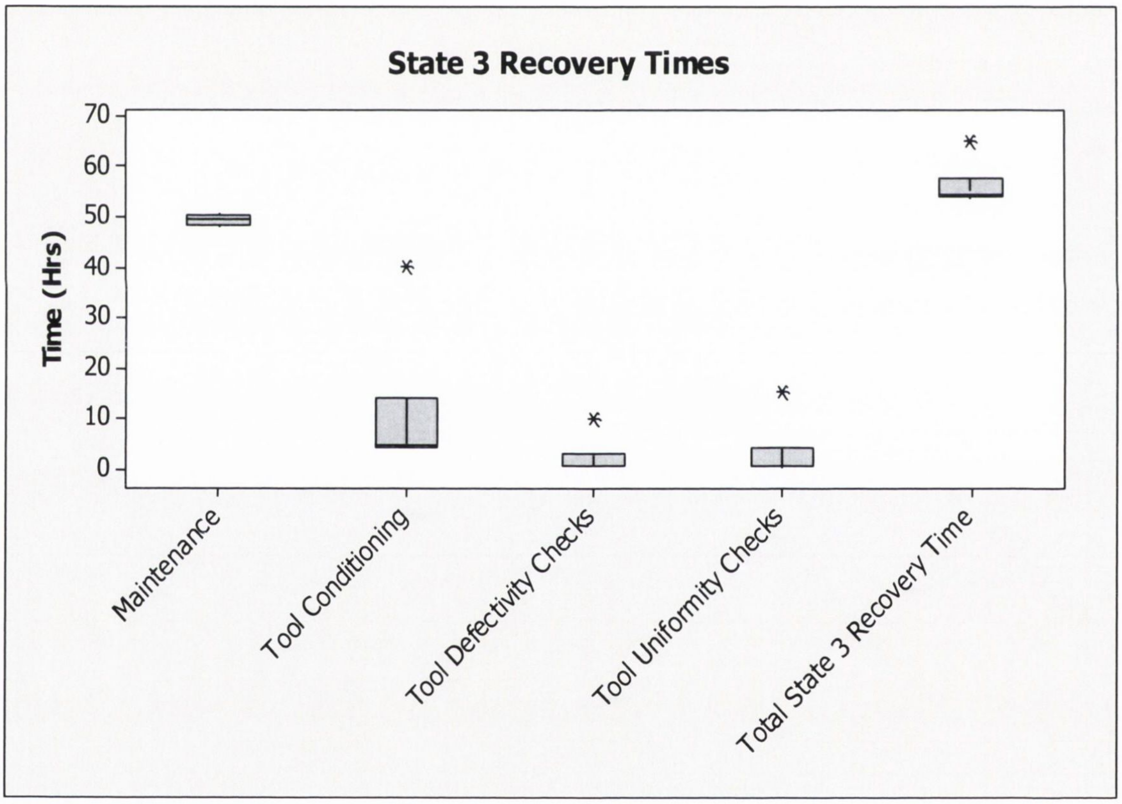


Figure 5.36 - State 3: Maintenance and recovery times

5.9.4 Recovery considerations: State 4

The study undertaken to evaluate state 4 was completed on manufacturing systems which were not production ready systems due to capacity requirements. This was due to a low demand period resulting in an excess of tool capacity. A number of systems were left in a permanently idle state as a result. The preparatory and recovery procedures used were annual maintenance tasks which allowed for process chamber conditioning, heat exchanger, turbo molecular and pump power downs. Figure 5.37 displays the recovery times measured. It can be seen from this figure, the significance of maintenance preparation and recovery times as well as tool conditioning in terms of significance to recovery time accounting for 80% of the total recovery time required. This impacted further investigations due to the significant resources required to complete the maintenance tasks resulting in 3 data points.

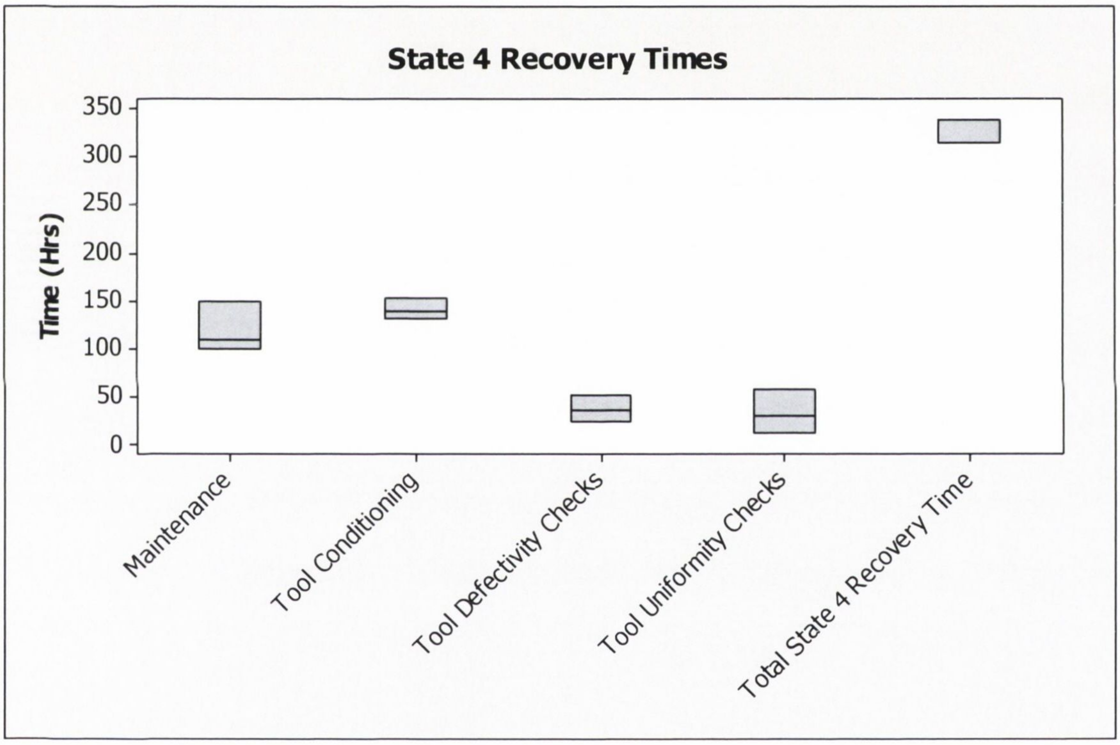
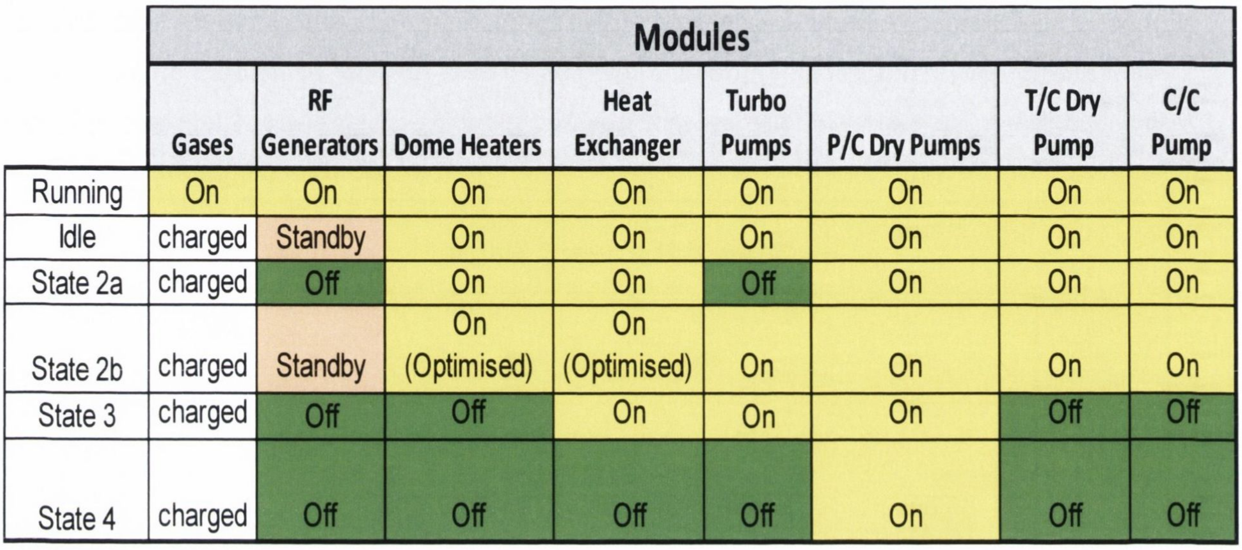


Figure 5.37 - State 4: Maintenance and recovery times

5.10 Future state module configuration

4 future state opportunities: $E_{f2a,2b,3,4}\ (T_1)_m$ were identified to support ongoing energy efficient evaluations. Phases 4 and 5 of the original lean methodology outlined in figure 3.2 can facilitate how these future states can be characterised in terms of production system acceptance. The approach developed resulted in a modular breakdown of the system studied highlighting how various future states can be realised as shown in figure 5.38. It can

be seen that this figure outlines how energy optimisation of system modules can be realised by considering both functionality and impact from FMEA considerations. This allows the final part of the flow to be realised as shown in figure 5.1 which is an updated project list of future state energy reduction opportunities documenting consumption opportunities with functionality considerations verified. This will support project progression formally into phase 4: Risk where factory priorities are considered.



	Modules							
	Gases	**RF Generators**	**Dome Heaters**	**Heat Exchanger**	**Turbo Pumps**	**P/C Dry Pumps**	**T/C Dry Pump**	**C/C Pump**
Running	On	On	On	On	On	On	On	On
Idle	charged	Standby	On	On	On	On	On	On
State 2a	charged	Off	On	On	Off	On	On	On
State 2b	charged	Standby	On (Optimised)	On (Optimised)	On	On	On	On
State 3	charged	Off	Off	On	On	On	Off	Off
State 4	charged	Off	Off	Off	Off	On	Off	Off

Figure 5.38 – Future state summary of modular configurations

5.11 Discussion

The work in this chapter considered how to utilise the documented methodology shown in figure 3.2 to a more complex test case with multiple constraint criteria. The complexity of both the discrete system involved and its operational constraints drove the need for an additional approach to be developed to consider the factors which can influence the creation of energy efficient states such as the risk of implementation and recovery time to production readiness. An analysis of tool utilisation highlighted idle time (T_{NP}) to be significant for the system identified where:

$$T_{NP} = 35\% \text{ or } 3066 \text{ hours per annum}$$

As a result of this all future states focused on system modifications while the system was idle. The process outlined in figure 5.1 utilised factory resources: human factor experience, FMEA and maintenance histories to identify energy efficient future states: $E_{f2a,\ 2b,\ 3,\ 4}\ (T_1)_m$. These system level future states required the consideration of baseline system performance in terms of tool reliability. This approach initially highlighted the potential limitations of solely focusing on modular failure probabilities as this approach did not consider impacts to operations for example non conformities or recovery times which can impact tool uptime. This drove a need to consider the potential impact of module failures on operations or production performance beyond just equipment reliability considerations. Using factory information systems previously outlined: modular risk (eq.13) and integrated risk (eq.14) metrics were devised. These metrics supported a comprehension of future state performance in terms of both increased probability of module failure as well as an understanding of integrated impacts that operations could be impacted by. This quantified future state module performance through assessing both workforce input and a factory information systems review. This allowed an understanding of module behavior before functionality testing was performed.

The functionality testing of the future states $E_{f2a,\ 2b,\ 3,\ 4}\ (T_1)_m$, allowed a quantification of each state relative to current idle performance enabling an understanding of $E_{savings}$ using eq. 15 such that:

$E_{f2a}\ (T_1)_m = 10\text{kW}$

$E_{f2b}\ (T_1)_m = 8\text{kW}$

$E_{f3}\ (T_1)_m = 21.1\text{kW}$

$E_{f4}\ (T_1)_m = 34.1\text{kW}$

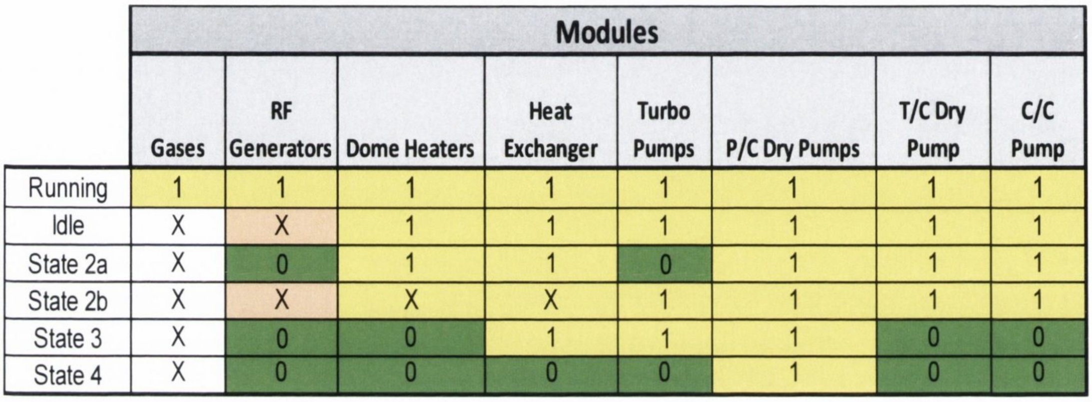
The functionality testing also allowed an understanding of module recovery as the testing criteria ensured a phased power down and recovery to support module quantification. This resulted in an enhanced understanding of operational behavior in terms of module performance as shown in figure 5.39.

Where:

Module operational = 1

Module off = 0

Module Optimised = X I 0<X<1



	Modules							
	Gases	**RF Generators**	**Dome Heaters**	**Heat Exchanger**	**Turbo Pumps**	**P/C Dry Pumps**	**T/C Dry Pump**	**C/C Pump**
Running	1	1	1	1	1	1	1	1
Idle	X	X	1	1	1	1	1	1
State 2a	X	0	1	1	0	1	1	1
State 2b	X	X	X	X	1	1	1	1
State 3	X	0	0	1	1	1	0	0
State 4	X	0	0	0	0	1	0	0

Figure 5.39 – Future state operational behavior of system

Although displayed within the systems truth table, no experimentation was undertaken with the gas box module as it was outside the scope of the research outlined. These values reflect normal idle behavior.

The significance of process compliance necessitated an understanding of process performance and the recovery requirements needed to deliver this performance. This resulted in the addition of extended process chamber conditioning being undertaken post recovery for all future states evaluated. Preventative maintenance tasks were also required for states $E_{f3,\ 4}\ (T_1)_m$, due to the additional modules evaluated and the potential impact considerations revealed though the FMEA process. The recovery time characterised for the future states developed exhibited a negative exponential relationship described by eqt.16:

$$Recovery\ Time = 2080.5e^{-0.18\ Active\ Power} \qquad (16)$$

Figure 5.40 highlights the recovery performance in terms of future state energy performance. It can be seen from this figure that in terms of recovery time, future states $E_{f3,\ 4}\ (T_1)_m$ exhibit significant recovery times and significantly influence the modeled relationship described by eq. 16.

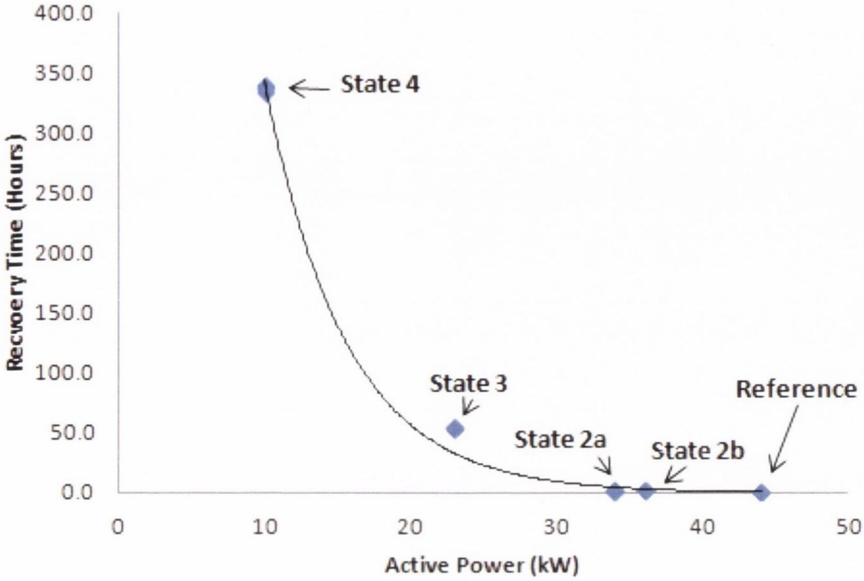
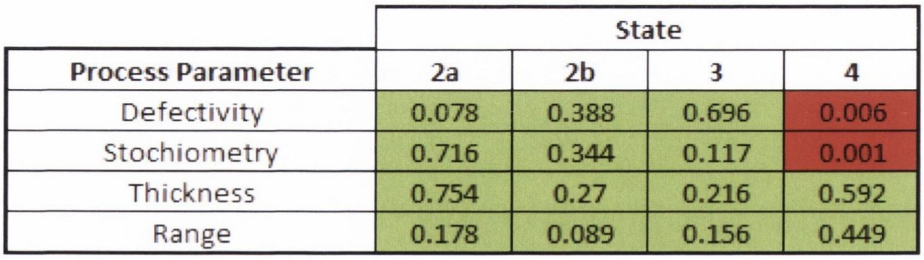


Figure 5.40 – Future state recovery times

In terms of process performance, the initial analysis highlights the potential of equivalency to reference performance for all potential future states $E_{f2a,\ 2b,\ 3,\ 4}\,(T_1)_m$ as shown in figure 5.41. However it can be seen from the summary that future state 4: $E_{f4}\,(T_1)_m$ results indicate potential noncompliant performance. This suggests further conditioning and preventative maintenance may be required to ensure process and operations compliance.



	State			
Process Parameter	2a	2b	3	4
Defectivity	0.078	0.388	0.696	0.006
Stochiometry	0.716	0.344	0.117	0.001
Thickness	0.754	0.27	0.216	0.592
Range	0.178	0.089	0.156	0.449

Figure 5.41 – Summary of future state paired t-test P-values

While undertaking the impact characterisation of the identified lower energy consumption future states, it was realised that further consideration was needed in terms of understanding the overall cost of recovery to an idle state from any of the future states implemented. This allowed a quantification of the total cost ($Cost_{total}$) of recovery, as shown in figure 5.42.

State	Maintenance (€)	Conditioning (€)	Quality Checks (€)	Total Cost (€)
Reference	-	1200	450	1650
State 2a	-	1200	450	1650
State 2b	-	1200	450	1650
State 3	7000	2500	1350	10850
State 4	20000	5000	2700	27700

Figure 5.42 – Summary future state recovery costs ($Cost_{recovery}$)

These costs were incurred post each recovery to an idle reference state. It can be seen from figure 5.42 in terms of recovery costs states 2a and 2b incur equivalent spend to reference while states 3 and 4 incur additional costs each time these states were used. Using equations (7) & (8) it is possible to calculate future state energy savings, as shown in figure 5.43.

	k W Savings	Cost/k Wh	Util Rate	Time (Hrs)	Annual $E_{savings}$ (€)
State 2a	10	0.1	0.65	8760	3066
State 2b	8	0.1	0.65	8760	2453
State 3	21.1	0.1	0.65	8760	6469
State 4	34.1	0.1	0.65	8760	10455

Figure 5.43 – Summary future state annual energy savings ($E_{savings}$)

Based on a utilisation rate of 65% which was recorded from the factory information systems and using an energy cost of €0.1/kWh a range of annual savings were possible based on the state utilised. It can be seen that from a financial perspective figures 5.42 and 5.43 represent significant variables in terms of comprehending the long term financial viability of the future states identified. By considering the NPV over 2 amortisation periods for example at yr 2 and yr 5, a range of values can be modelled as shown in figure 5.44.

State	NPV (2 yr)	NPV (5 yr)
2a	€8,185	€17,877
2b	€7,121	€15,554
3	€30,058	€65,653
4	€66,306	€144,827

Figure 5.44 – NPV at year 2 and year 5

However, this highlights a limitation of using the NPV calculation in this context. From a financial perspective, the cost allocation of the production tool over a time period had been completed: it was fully depreciated. For both states 2a and 2b the savings and costs associated with implementation were understood which allowed an accurate modelling of cash flows to be completed. For states 3 and 4, savings and the maintenance requirements for recovery were understood but not the frequency of use of these states.

Eq. 17 demonstrates how $E_{savings}$, $Cost_{recovery}$ and $Cost_{capital}$ considerations can inform cost savings gain or loss realised on a depreciated asset by implementing an energy efficient future state for a defined time period:

$$Cost_{total} = \left[\sum_{t=x}^{t=1} Annual\ energy\ savings - \sum_{n}^{1} Cost\Delta\right] - Cost_{capital} \qquad (17)$$

Where:

$Cost_{total}$ = cost gain or loss over the time period defined from realising an energy efficient future state

t = time period used to calculate $Cost_{total}$ from $t=1yr$ to $t=x\ yrs$

Annual energy savings ($E_{savings}$) = average savings by year

$Cost\ \Delta$ = difference between normal tool recovery cost vs. cost from recovery from an energy efficient future state

n = the number of times the state was triggered in the time period defined

$Cost_{capital}$ = system upgrade costs incurred to realise future states

From eq. 17 it can be seen that in terms of kWh pricing, a more compelling $Cost_{total}$ will be achieved with higher annual energy savings. An influencing factor of these savings is kWh pricing. A higher kWh cost would have a bigger impact on enabling bigger energy savings supported by states 3 and 4. This is reflected in figure 5.45 highlighting the $E_{savings}$ obtainable at a higher industrial kWh price of €0.3/kWh .

	k W Savings	Cost/k Wh	Util Rate	Time (Hrs)	Annual $E_{savings}$ (€)
State 2a	10	0.3	0.65	8760	9198
State 2b	8	0.3	0.65	8760	7358
State 3	21.1	0.3	0.65	8760	19408
State 4	34.1	0.3	0.65	8760	31365

Figure 5.45 – Summary of modeled annual energy savings ($E_{savings}$) at €0.3/kWh

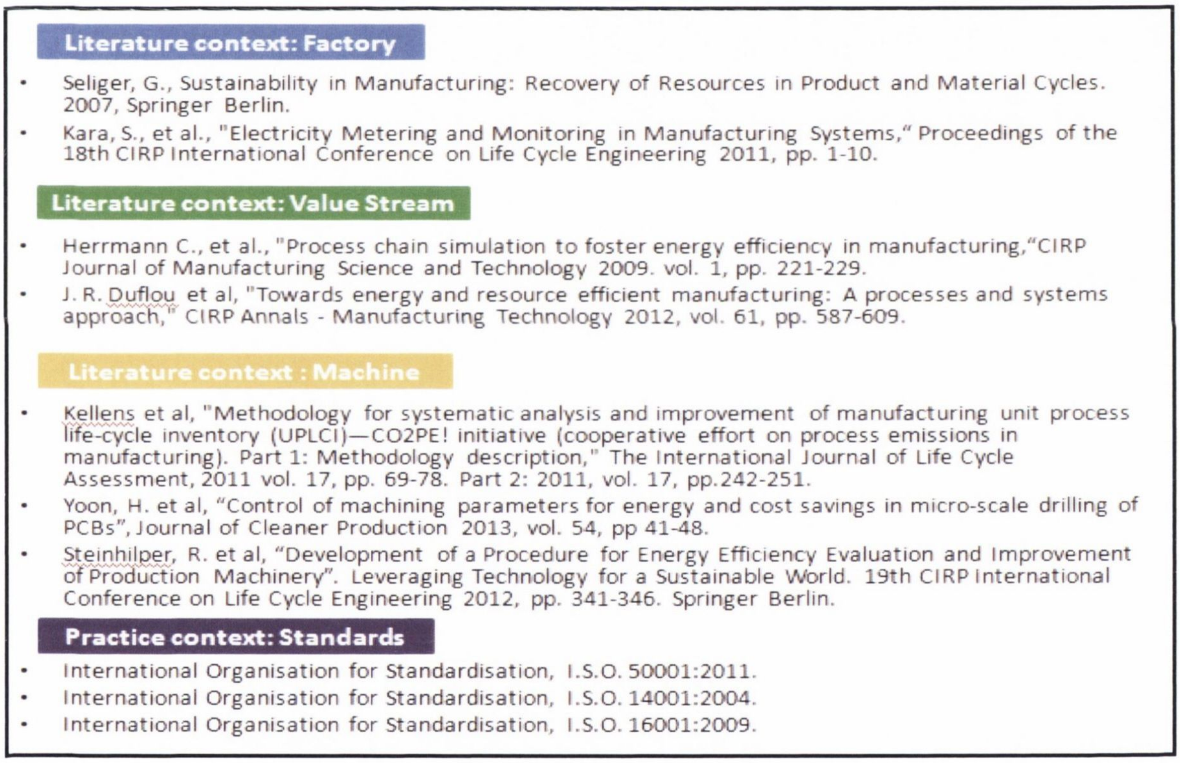
It was observed through the course of this study that lower pay back durations are being considered more frequently within industrial environments. Depending on the project identified a payback period of 2 years may be considered rather than 5 years. By reducing the impact of the variable 'CostΔ' in terms of cost of system recovery in equation 17 highlights a path to offset impacts of energy pricing and reducing timelines and highlights what could potentially be achieved. The optimisation opportunities identified in both use case chapters demonstrate the capability of manufacturing systems in legacy environments to be modified to achieve this objective. However considering this earlier within the design phase of production systems would further reduce this impact on future energy savings scenarios. A further opportunity to positively influence a more compelling cost gain is with lower investment costs or reducing $Cost_{capital}$. A potential path to lowering this variable is ongoing support for organisations considering this approach through increasing incentive programs or grant structures to offset against $Cost_{capital}$ thus lowering the impact of actual input costs in both NPV calculations and equation 17. This would also potentially offset longer payback time periods if needed.

The system recovery impacts and the importance of process equivalency verification present a challenge in terms of comprehending potential use case scenarios for all 4 identified states: $E_{f2a,2b,3,4}\ (T_1)_m$. Through the work outlined in this chapter, $E_{f2a,2b}\ (T_1)_m$ demonstrated this possibility both functionally and financially. In terms of $Cost\ \Delta$ both states demonstrated equivalency in terms of reference while also demonstrating lower recovery times relative to $E_{f3,4}\ (T_1)_m$. As a result of this evaluation both $E_{f2a,2b}\ (T_1)_m$ states could be recommended for future evaluation in phase 5 of the overall methodology with no initial limits in terms of the number of times both states could be activated. $E_{f3,4}\ (T_1)_m$ also demonstrated system capability to obtain further savings however based on initial data more evaluation of recovery procedures to ensure process compliance is necessary for state 4. Both future states did allow a quantification of $E_{savings}$ and highlighted opportunity in terms of long term tool shut downs to realise savings across a number of systems within the tool fleet. However from figures 5.42 and 5.43 it can be seen that $Cost_{recovery}$ of both $E_{f3,4}\,(T_1)_m$ is significant relative to $E_{savings}$. This suggests a limitation in terms of the practical application of both states. If scenarios existed where fleet capacity over time was being reduced and temporary recovery to manufacturing readiness would only be needed for a subset of tools for example a limitation to n in eq. 17 then both $E_{f3,4}\,(T_1)_m$ could potentially be beneficial in supporting long term energy reductions across a fleet of production tools.

6 Conclusions and recommendations for future work

6.1 Summary

Through a review of current literature and practice within industrial environments a correlation was identified between factory energy consumption and production systems. From this, an opportunity was identified for an original contribution based on legacy factory environments to understand the contribution of production systems to energy consumption. This built on work already completed to characterise the impact of manufacturing in terms of factory, value stream and machine consumption and the application of energy and environmental standards as shown in figure 6.1.



Literature context: Factory

- Seliger, G., Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles. 2007, Springer Berlin.
- Kara, S., et al., "Electricity Metering and Monitoring in Manufacturing Systems," Proceedings of the 18th CIRP International Conference on Life Cycle Engineering 2011, pp. 1-10.

Literature context: Value Stream

- Herrmann C., et al., "Process chain simulation to foster energy efficiency in manufacturing,"CIRP Journal of Manufacturing Science and Technology 2009. vol. 1, pp. 221-229.
- J. R. Duflou et al, "Towards energy and resource efficient manufacturing: A processes and systems approach," CIRP Annals - Manufacturing Technology 2012, vol. 61, pp. 587-609.

Literature context : Machine

- Kellens et al, "Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description," The International Journal of Life Cycle Assessment, 2011 vol. 17, pp. 69-78. Part 2: 2011, vol. 17, pp.242-251.
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Practice context: Standards

- International Organisation for Standardisation, I.S.O. 50001:2011.
- International Organisation for Standardisation, I.S.O. 14001:2004.
- International Organisation for Standardisation, I.S.O. 16001:2009.

Figure 6.1 – Literature and practice awareness

This thesis documents an approach to support the study and analysis of energy optimisation within manufacturing process chains. The structural approach outlined in this study facilitated a comprehensive analysis of industrial consumption categories and system level usage. This allowed a reclassification of factory systems compared to previous work completed in terms of thermal and non-thermal process systems [19]. The significance of production system electricity consumption was understood and quantified as well as production and idle use categories highlighting production significance across a sample of discrete manufacturing environments. The sample selection was based on ensuring an accurate representation of the membership within the technology centre consortium which supported this research.

On reviewing the application of the methodology in the industrial settings selected the organisations themselves significantly contributed and highlighted the type of organisation that would benefit from its application in its present form. A strong theme of continuous improvement and employee empowerment was noted. In this context, both organisations were cost sensitive and utilised lean methodologies as a basis to organisational change where employee participation was integral to organisational improvements. Both organisations leveraged state of the art thinking on international standards and were ISO compliant across a number of disciplines such as energy, quality, environmental, health and safety. As a result, the opportunity to evaluate the methodology outlined was well received by both organisations. This suggests a level of organisational sophistication is required to support the methodology's application. The methodology itself leverages organisational KPI's to verify compliance to organisational priorities. This suggests a data rich environment is also needed for its application.

The methodology focused on generating an energy characteristic for complex discrete part manufacturing equipment and identifying optimisation opportunities based on targeting non value added process states. A structured problem solving approach was used to identify and evaluate risk factors associated with the implementation of improvements where qualitative workforce input based on their experience with maintenance and recovery procedures and familiarity with production operations was used to support risk assessments of energy based change. An assessment of an organisations capability was developed to manage an energy improvement in order to minimise the risk to OEE metrics thereby ensuring opportunities are feasible and pragmatic. Two different application use cases were studied, as summarised in figure 6.2 demonstrating different complexity levels in terms of both tool and constraint complexity. Although demonstrating different complexity levels, both use cases are specific to discrete manufacturing industrial environments. Both use case environments studied also represent highly process compliant environments.

Study aspects	Use case #1: Medical device factory	Use case #2: ICT factory
Context	Light application of methodology	Complex application of methodology
Tool	Single module system	Multiple module system with multiple module interactions
Constraint	Single: Tool recovery	Multiple: Tool recovery and critical to quality indicators
Information level	Soft on historical performance data	Heavy level of historical performance data and hard evidence
Human factor influence	Huge bearing on opinion to support soft information	Huge bearing on opinion but supported by hard information

Figure 6.2 – Comparison of use cases

It can be seen from figure 6.2 that tool recovery was highlighted as a significant operational constraint within both environments. This constraint becomes more significant within the more complex environment studied due to the need to verify compliance to historical process performance data. This consideration had significant cost implications for the future states outlined which resulted in potentially limited use of the future states identified through the research. This risk mitigation approach entailed the identification and verification of selected critical to quality metrics which impacted recovery times but was necessary to validate compliance. As a result, the body of work presented contributes to further understanding how energy consumption can be improved within highly compliant industrial settings through managing multiple compliance criteria. In this context this work hopes to contribute in terms of improving operational efficiency through building on the methodology pillars presented in figure 6.3

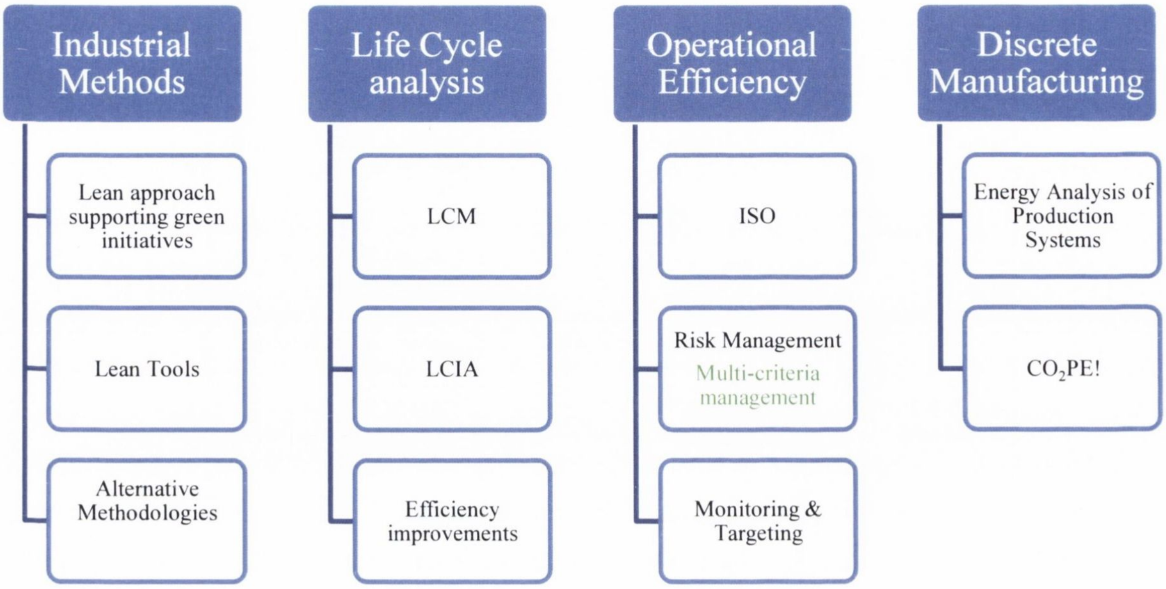

Figure 6.3 – Methodology pillars

6.1.1 Methodology

A structured methodology was developed to support characterising a factory's energy profile. It has been shown that a structured approach in characterising energy related aspects of manufacturing can yield significant opportunities [23]. The development of the methodology highlighted the need to leverage factory management to support enhanced characterisation of manufacturing process chains and subsequent improvements through the use of appropriate skill sets such as personnel with maintenance and operations knowledge. Utilising embedded factory metering, the contribution of manufacturing process chains to the factory energy profile was understood. Metering capability gaps were identified highlighting the need for higher sampling rate requirements to characterise production tool behavior. This was necessary to ensure appropriate reference profiles were generated for subsequent experimentation and highlighted a limitation to production system metering capabilities in both use cases studied. By generating a capability score the methodology ensured an understanding of how production priorities and operational metrics can influence energy based change. The methodology supports a critical assessment of both tool and production line monitoring strategies allowing a comprehension of potential gaps in assessing production tool energy change. Both use case applications highlighted the need to consider the impact to production equipment from implementing energy based change in terms of availability and cost performance.

6.1.2 Relationship between energy consumption and operational behaviour

The application of the methodology within manufacturing environments highlighted the significance of production system energy consumption and highlights the organisational benefits of sustainable development as argued by Despeisse et al [66]. Within both the medical device and ICT factories studied production systems were the most significant system consumer of energy, at 38% and 50% of total consumption respectively. Through the classification of tool energy consumption into value add or running mode and non value add or idle mode consumption, the significance of non value energy consumption was realised when considered in the context of tool utilisation rates. The low tool utilisation rates recorded, 20% in the biomedical environment and 65% in the ICT environment further highlighted the significance of non value add energy consumption. This identified a category of energy use which allowed both industrial use cases to further investigate with minimal impact to both organisations in terms of perceived risk to tool performance. This approach was successful in terms of organisational support in progressing to the experimentation stages in phases 3, 4 and 5 of the methodology. The approach of characterising tool energy consumption into value and non value added categories allowed a critical assessment of production equipment configurations in non value add or idle mode settings. This helped the identification of equipment configuration changes to support energy reduction experiments.

6.1.3 Risk identification using human factors

Previous authors have argued for the importance of risk consideration in process management [229] but seldom consider the mechanisms to quantify production impacts. This study outlines the importance of considering risk factors to minimise subsequent cost impacts ensuring successful energy based project selection. This is necessary to comprehend potential impacts on production environments which resulted in the need to comprehend recovery time to support this effort. The approach outlined helps to address perceptions and concerns that arise within industrial environments due to project implementation. The potential impacts documented include both tool performance and production line performance. Human factor understanding both of these considerations was shown to be crucial in terms of identifying optimisation opportunities but also compliance requirements. By using structured problem solving techniques this ensured the effective capturing of workforce knowledge in terms of work cell priorities, equipment functionality improvements, organisation capability to mange energy based change and identifying potential OEE impacts. To support this understanding kaizen workshops and cause-effect models utilised within the FMEA structure proved an effective tool to capture workforce experience through identifying potential failure mechanisms which may impact project implementation. The analytical hierarchy process proved effective at ensuring an accurate picture of work cell priorities were understood which allowed critical OEE metrics to be prioritised and monitored to ensure compliance. The structure outlined highlighted the cost impact of energy based projects within manufacturing process chains.

6.1.4 Cost benefit models using risk and energy saving data

The use cases presented demonstrated the need to consider potential consequences with respect to operational compliance. The production systems evaluated highlighted the limitations in solely focusing on tool energy reductions. This approach does not consider impacts to operations for example the cost of non conformities or recovery times. This suggests a need to consider the potential impact of tool or module fails on operations beyond just equipment reliability considerations. In this regard, the use cases studied have highlighted the 'cost of compliance' considerations which must be factored into any future state energy savings to mitigate operational production issues. The initial use case showed within a non complex scenario although no cost implications were recorded recovery time considerations influenced the energy savings which could be achieved. The complex scenario studied demonstrated how operations can influence energy savings. In all 4 future states examined in chapter 5 required compliance evaluations which incurred varying levels of costs all of which ultimately must be factored into actual energy savings realised. This consideration highlights how cost can have a profound effect on how production systems actually implement energy based improvements.

6.2 Recommendations for future work

The significance of production system energy consumption highlights an opportunity for further research into organisational support of future energy savings and supports previous work linking accountancy approaches to energy improvements [230]. Based on the work documented, the areas where future work could be undertaken include investigating optimum metering strategies for production systems, continued investigation for the development of structured approaches to support energy characterisation, consumption reduction approaches within production environments and the development of eco-design methodologies for production tools and systems in line with LCA models. These present opportunities for further research requiring continued academic and industrial collaboration.

6.2.1 Optimum metering strategies for production systems

Further evaluation of metering and sampling strategies is required to identify optimal configurations for data gathering. Recent work has highlighted the need for ongoing consideration into metering characteristics such as measurement, resolution and sampling rate [22, 231]. This is necessary to support the ongoing integration and development of energy metrics for production management. The development of more accurate energy and cost allocations to production systems will result in more accurate energy content per part understanding. The work outlined within this document has highlighted the significance of production line consumption in terms of energy and the limitations encountered when investigating consumption performance for example sample resolution. The establishment of appropriate metering strategies will enhance the ability of industrialists to continue to differentiate the need between physical and virtual metering solutions. This will result in improvements in production system modelling assumptions and drive a deeper understanding of energy behaviour.

6.2.2 Energy characterisation and consumption reduction within production environments

The methodology outlined has highlighted the significance production systems can have in terms of factory energy consumption. In order to identify future optimisation opportunities, workforce experience was leveraged to comprehend potential impacts to both tool performance and production line impacts. This allowed risk factors to be categorically assessed and a comprehension of mitigation actions to be understood in order to realise energy savings. This was needed due to the nature of the use cases involved: a simple and complex environment was explored within highly compliant discrete manufacturing settings. There is scope to develop the capability of the methodology within a wider context in terms of application to more industrial settings such as packaging, assembly and continuous processing and others such as building management.

From the work detailed, another area for future work is to develop a more sophisticated analysis of both human factors and knowledge capture to ensure a more thorough and comprehensive understanding of workforce experience is utilised. This was due to the level of expertise required on both use case studies to comprehend operational performance, energy consumption and optimisation opportunities. Expertise involvement ensured an appropriate level of quality and expert analysis needed to identify opportunity and mitigation steps.

6.2.3 Eco-design methodologies for production tools and systems in line with LCA models

The use cases documented have highlighted the impact of considering the relationship between manufacturing equipments operational behaviour and energy consumption. By understanding tool control behaviour, an in-depth 'current state' of tool energy performance can be described. This supports the development of 'future state' scenarios which take energy consumption into account. The impact of energy consideration at the design phase has been shown in both academic supported modelling [20] and applications [14] settings. The continued development of energy and environmentally efficient tool design approaches and methodologies will enhance the ability of original equipment manufacturers to characterise and influence the environmental impact of manufacturing operations on both factory and product performance. These approaches should also consider the electrical and resource performance of any eco-designs to ensure a comprehension of how consumption performance is influenced by this direction. There is also an opportunity to introduce a more sophisticated risk model to realise these eco concepts. In terms of both tool reliability and process systems, simulation techniques should be utilised to develop a longer term understanding of performance.

6.2.4 Overlap in LCA and ISO approaches to support environmentally conscious manufacturing

As a consequence, the methodology has outlined the need for a comprehensive approach to characterising energy consumption. Identifying and managing risk in terms of minimising the impact of energy based change to manufacturing operations. The ongoing improvement in ISO systems to support this objective, in particular the ISO 50001 standard is leading to its improvement through the ISO 50004 standard [223, 232] which will give guidance to ISO 50001 implementation. The methodology outlined has demonstrated within a mature organisation in terms of energy management the ability to support continuous improvement. This overlaps significantly with the intent of the ISO 50004 standard. The solutions identified in the case study highlights the benefit of environmentally aware design and the availability of energy efficient upgrades to support discrete manufacturing operations. Further work into the exploration of LCA and ISO standards in manufacturing environments would help inform future energy based improvement. This will require further industrial based characterisation to support this objective.

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A1 Appendix 1: Input/Output Document

Phase 1a

	Input	Model	Output
1a	Identify source of information: • Utility Bills • Finance Groups • Facility Management • Vendor or Service Management • Building Metering •Automated Reporting Systems	• Document Energy and Resource catagories, $E_{TOT} = E_g + E_r \ldots E_n$ E_{TOT} = total energy inputs E_g = power from grid E_r = power from renewables $R_{TOT} = R_g + R_r \ldots R_n$ R_{TOT} = total resource inputs R_g = resources from grid R_r = resources from renewables	• Listing of Energy and Resource catagories for factory • Gaps in factory level data collection or reporting Capability Identified

Phase 1b

	Input	Model	Output
1b	• Time Period selected for Study (t) • Energy unit price (P_e) • Units of Energy consumed (E_u) • Resource unit prices (P_r) • Units consumed for each Resource (R_u)	• Total Energy Consumed: $E_{TOT}{}^1 = P_e.E_u$ • Total Resource Consumed: $R_{TOT}{}^1 = P_r.R_u$	• Cost based Energy consumption history for time period ($E_{TOT}{}^1$) • Cost based consumption history by Resource for time period ($R_{TOT}{}^1$) • Facility Level Metering Capbility Gaps Identified

Phase 1c

	Input	Model	Output
1c	• Energy consumption history for time period (E_{TOT}^{t}) • Consumption history by Resource for time period (R_{TOT}^{t}) • Facility budget total (F_{TOT}^{t}) for time period (t) • Facility budget catagories (F_1, F_2, F_n) Where F_1 = Depreciation, F_2 = Headcount, F_3 = Energy, etc	• Calculate Energy E_F and Resource R_F spend as a proportion of total facility budget for time period defined • $E_F = E_{TOT}/F_{TOT}$ where $F_{TOT}=\Sigma F_1, F_2 \ldots F_n$ • $R_F = R_{TOT}/F_{TOT}$ where $F_{TOT}=\Sigma F_1, F_2 \ldots F_n$	• Pie Chart of facility budget (F_{TOT}) with Energy (E_F) and Resource (R_F) percentages as a function of total facility spend • Pareto of Energy (E_F)and Resource (R_F) consumption

Phase 1d

	Input	Model	Output
1d	• Process Map of System users • Facility Management Data • Vendor or Service Management Data • Building Metering Data	• Document System Level Users (S_1, S_2, S_3 … S_n) Where S_1=Prod Line, S_2=Environmental Control, S_3=water, etc	• System Level Users Identified (S_1, S_2, S_3 … S_n) • Process Map of system level users for E_F or R_F

Phase 1e

	Input	Model	Output
1e	• Process Map of (S_1, S_2, S_3 … S_n) • Time period for analysis (t) • Metering nodes for System Level Users • Design Data (d) or • Implied Data (i) or • Metered Data (m)	For S_1, S_2, S_3 … S_n using d, i or m • $E^t(S_n)_m = P_e.E_u(S_n)$ where $E^t(S_n)$ = Energy consumption of chosen system in time • $R^t(S_n)_m = P_r.R_u(S_n)$ where $E^t(S_n)$ = Resource consumption of chosen system in time	• Quantified system level process map of energy or resource spend for S_1, S_2, S_3 … S_n • Gaps in system level metering capability identified

Phase 1f

	Input	Model	Output
1f	• Quantified system level process map of energy or resource spend for S_1, S_2, S_3 … S_n	• $S_1 = E_{prod\ line} = E^t(S_{prod\ line})/E_{TOT}^t(S_{total})$ or • $S_1 = R_{prod\ line} = R^t(S_{prod\ line})/R_{TOT}^t(S_{total})$ If $E_{prod\ line}$ or $R_{prod\ line}$ >20% continue If $E_{prod\ line}$ or $R_{prod\ line}$ <20% consult management sponsor on view. This is required to ensure appropriate prioritisation.	• Pareto of System Level Users of the Identified Energy/Resource Category for S_1, S_2, S_3 … S_n • Metering gaps defined to quantify system level user consumption for Production Line(s)

Phase 1g

	Input	Model	Output
1g	• $E_{prod\ line}$ or • $R_{prod\ line}$	If $E_{prod\ line}$ or $R_{prod\ line}$ is a top 3 factory facility consumer? Then Prod line a Significant Energy User (SEU) of E_{TOT} or R_{TOT} If $E_{prod\ line}$ or $R_{prod\ line}$ is not Top 3 factory consumer? Then use data for other energy work within factory	Understanding of cost impact of $E_{prod\ line}$ or $R_{prod\ line}$ in terms of •Inclusion in site Energy Management System (EnMS) •Energy Efficiency •Energy performance (EnPI) •Energy Consumption

Phase 2a

	Input	Model	Output
2a	• $E_{prod\ line}$ or • $R_{prod\ line}$	• Production Line Area catagorised into sub-sections of interest. $S_{prod\ line} = T_1+T_2+T_3...+T_n$ Where $T_1, T_2 ... T_n$ are discrete production tools in $S_{prod\ line}$ • If multiple lines exist, the production area is broken down into discrete production lines $S_{prod\ line(TOT)} = S_X+S_Y+S_Z$ $= \Sigma S(x, y, z)$ $S_X= S_{T1}+S_{T2}+S_{T3} ... S_{Tn}$ where T1, T2, etc are discrete prod tools within productions line S_X	• Production Line Area ($S_{prod\ line}$) broken out into discrete tools • Production Line Area broken out into individual lines (S_X, S_Y, S_Z) • Individual Lines broken out into discrete tools (S_{T1}, S_{T2}, S_{T3}, etc)

Phase 2b

	Input	Model	Output
2b	• Target $S_{prod\ line}$ or S_X, S_Y, S_Z broken out into tools of interest - $T_1, T_2 ... T_n$ • Production Line Area broken out into discrete lines - $S_X+S_Y+S_Z$	• Validate $T_1, T_2 ... T_n$ within $S_{prod\ line}$ or S_X, S_Y, S_Z by creating an inventory list • For individual Production Line S_x validate $T_1, T_2 ... T_n$ by creating an inventory list etc • All validation done by going to GEMBA	• Catagorised list of equipment types $T_1, T_2 ... T_n$ for $S_{prod\ line}$ or S_x • Process Map outlining all production equipment in $S_{prod\ line}$ or production line of interest S_x • Metering needs/gaps understood to quantify consumption for Production Line in the area of interest or for the discrete production line

Phase 2c

	Input	Model	Output
2c	• Process Map of production equipment in the area $S_{prod\ line}$ or production line of interest S_x	• Production State(s) identified for each discrete equipment set Productive States (P) and Non Productive (NP) • Individual equipment types $T_1, T_2 \ldots T_n$ evaluated for metering capability to measure tool consumption performance	• Physically verified Process Map outlining all production equipment in the area or production line of interest • Metering needs and gaps understood to quantify consumption for individual equipment production states

Phase 2d

	Input	Model	Output
2d	•Production States defined for study (P or NP) •Metering nodes for Equipment; • Design Data (d) or • Implied Data (i) or • Metered Data (m)	• Metered data collected or Design/Implied used for each defined production state. For a single production line for a defined production state(s) (N or NP) $E_{prod\ line\ (m)}=E(T_1)+E(T_2)+E(T_3)+\ldots+E(T_n)$ where $E(T_1) = E_P+E_{NP}$ etc	• For a targeted Production Line , performance data collected for Energy or Resource Category for the defined Production State(s) • Metering Capability gaps understood to allow study to be completed at a tool level •Production state tracking capability gaps understood

Phase 2e

	Input	Model	Output
2e	• $S_{prod\ line}$ or production line of interest S_x • $E_{prod\ line}$ or $R_{prod\ line}$ • Production State(s) for $T_1, T_2 \ldots T_n$	• For $E(T_{1..n}) = E_P+E_{NP}$	• For a given production state P or NP, $E_{prod\ line}$ pareto of $E(T_1)+E(T_2)+E(T_3)+\ldots+E(T_n)$ Where $E(T_1) = E_P+E_{NP}$

Phase 3a

	Input	Model	Output
3a	• Production Equipment list T_1, T_2 ...T_n for $S_{prod\ line}$ or production line of interest S_x • Production State(s) P or NP • $E_{prod\ line}$ or $R_{prod\ line}$ pareto of $E(T_1),E(T_2),E(T_3),..,E(T_n)$	• ID highest consuming tool (T_1) in prod area I $E(T_1) = E_P+E_{NP}$ •Consult with production engineering to validate choice in case other factors to be considered for example is this tool a factory constraint	• Production State (E_{NP}) identified for specific Production tool for more detailed Energy study I $E_{T1}=E_{NP}$ E_p not part of study • Nonproductive states (NP) are targeted initially to reduce operational concerns

Phase 3b

	Input	Model	Output
3b	• $E(T_1)$ •Time period for study (t) • Tool level metering (in situ or stand alone) • Monitor frequency should reflect accurate behaviour of equipment (ms required)	• Monitor Energy or Resource consumption for a defined period of time I $E(T_1)_{(1D\text{->}2days)}$	• Overlayed time trend of consumption with tool behaviour for a given non-prod state • Understanding of tools performance and relationship between production states with respect to consumption

Phase 3c

	Input	Model	Output
3c	• Schematics of tool (T_1) at a modular level • Production engineering operational knowledge • OEM performance data	• $T_1=c_1+c_2+c_{3..}+c_n$ where c=Tool module or subcomponent	• Process level map of equipment divided into modular blocks outlining energy/resource paths • Metering capability or gap understanding at a modular level

Phase 3d

	Input	Model	Output
3d	• Metering capability or gap understanding at a modular level • Non Production state (NP) • Design Data (d): Use tool electrical schmatics or labelling to ID V/I inputs to modules of equipment or • Implied Data (i): Review historical exps or work completed on equipment or use OEM data or • Metered Data (m): Power data from modules or define plan to selectively measure modules in	• For a tool T_1 , with metered data, m, E_{NP} can be defined as: $E(T_1)_m= E(c_1) +E(c_2) +E(c_3) +\ldots+E(c_n)$ where $E(c_1)$is the energy consumed at a subcomponent or module level c_1 in state NP with tool T.	• Module breakdown within equipment of Energy or Resource consumption for the defined state • Gaps understood in capability to collect data • Understanding of breakdown to module level if possible

Phase 3e

	Input	Model	Output
3e	• Module breakdown within equipment of Energy or Resource consumption for the defined state $E_{T1(m)} = E(c_1)+E(c_2)+E(c_3)+\ldots+E(c_n)$ • Time period of study (t) •Energy unit price (P_e) • Units of Energy consumed (E_{CU}) for component/module or • Resource unit prices (P_r) • Units consumed for each Resource (R_u)	• Total Energy E_{NP} consumed by module: $E(c_1)^t = P_e.E_{cu}$ • Total Resource Consumed by module: $R(c_1)^t = P_r. R_{cu}$	• Process level map of equipment divided into modular blocks outlining energy/resource paths with costings for the defined state

Phase 3f

	Input	Model	Output
3f	• Process level map of equipment: $E(c_1),E(c_2),E(c_3),..,E(c_n)$ for state NP	• Create table of tool consumption by module where $E(T_1)_m = E(c_1) + E(c_2) + E(c_3)+\ldots+E(c_n)$	• Breakdown of Production Equipment module costed consumption for $E(c_1), E(c_2), E(c_3),\ldots, E(c_n)$

Phase 4 Functionality (a)

	Input	Model	Output
4F a	• Process level map of equipment divided into modular blocks outlining energy/resource paths with costings for the defined state where $E(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n)$ • Equipment Maintenance Personnel	• Brainstorm ideas with team on how to reduce energy consumption of selected equipment by altering modular or overall equipment energy performance Where $E(T_1)$=Current energy performance of tool and $E_f(T_1)$=Future energy performance • Use current state/future state Value Stream Map process	• Ideas tabulated into 2 columns; Current state performance $E_f(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n)$ Potential future state performance $E_f(T_1)_m = E_f(c_1) + E_f(c_2) + E_f(c_3) + \ldots + E_f(c_n)$

Phase 4 Functionality (b)

	Input	Model	Output
4F b	• Process level map of equipment divided into modular blocks outlining energy/resource paths with costings for the defined state • Equipment Maintenance Personnel • Current state performance and potential future state performance	• Use costings data calculated from the equipment energy map to calculate future savings from potential future state performance I $E_f(T_1)_m = E_f(c_1) + E_f(c_2) + E_f(c_3) + \ldots + E_f(c_n)$ where $E_f c_n = P_e . E_{cu}$ P_e = Energy unit price E_{cu} = Units consumed for component c	• $E(T_1)_m$ • $E_f(T_1)_m$

Phase 4 Functionality (c)

	Input	Model	Output
4F c	• Process level map of equipment divided into modular blocks outlining energy/resource paths • Equipment Maintenance Personnel • $E(T_1)_m$ • $E_f(T_1)_m$	• For $E_f(T_1)_m$, Personnel to understand is the selected equipment functionally capable of performing the future state ideas • Failure Mode Effects Analysis to be completed as required by module $E_f(c_1)$,$E_f(c_2)$, $E_f(c_3)$,…,$E_f(c_n)$	• Future state ideas evaluated for functionality by module-c, If E_fc_1= possible then $E_fc_1=E_fc_1$ If E_fc_1 = not possible then $E_fc_1 = Ec_1$

Phase 4 Functionality (d)

	Input	Model	Output
4F d	• Process level map of $E_f(c_1)$,$E_f(c_2)$, $E_f(c_3)$,…,$E_f(c_n)$ • Equipment Maintenance Personnel • Future state ideas listed for functionality and tabulated in table with current and future state data to support $E_f(T_1)_m$	• Identify Key Perfromance Indicators (KPI's) and/or Overall Equipment Effectiveness (OEE) Indicators that equipment is managed to: Availability (A_1) Quality (A_2) Cost (A_3)	• Tabulated summary of future state ideas on how to alter equipment energy behavior for selected state I $E_f(T_1)_m= E_f(c_1) +E_f(c_2) +E_f(c_3)+\ldots+E_f(c_n)$ • Success Criteria identified for functionality testing (A_1, A_2, A_3)

Phase 4 Functionality (e)

	Input	Model	Output
4F e	• Tabulated summary of future state ideas to support $E_f(T_1)_m$ • Equipment Maintenance Personnel • Single Constraint Criteria (SC_1) • $E(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n)$ • $E_f(T_1)$ = future state performance projects	• Equipment to be targeted is taken out of production for duration of testing • Module behaviour is mapped against single constraint (SC_1) • Testing plan developed for each idea and executed • Safe plan developed to recover equipment in the unlikelihood of an issue	• $E_f(T_1)_m = E_f(c_1) + E_f(c_2) + E_f(c_3) + \ldots + E_f(c_n)$ • Success criteria pass/fail data for (SC_1) to allow project selection

Phase 4 Functionality (f)

	Input	Model	Output
4Fe	• Tabulated summary of future state ideas to support $E_f(T_1)_m$ • Equipment Maintenance Personnel • Multiple Constraint Criteria (MC_1, MC_2, MC_3) • $E(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n)$ • $E_f(T_1)$ = future state performance projects	• Equipment to be targeted is taken out of production for duration of testing • Testing plan developed for each idea and executed • Safe plan developed to recover equipment in the unlikelihood of an issue • Module behaviour is mapped against multi constraint criteria (MC_1, MC_2, MC_3) • Module Risk Measurement is calculated ($RM_{module} = I_{module}.R(t)$) • Operational Impact Measurement is calculated $IR_{module} = \sum_{i=1}^{n} Ioperations \, . w$	• Functionality evaluations completed to support $E_f(T_1)_m$ • Success criteria pass/fail data for (MC_1, MC_2, MC_3) to allow project selection • Plot of RM_{module} vs IR_{module} to support decision making

Phase 4 Functionality (g)

	Input	Model	Output
4Fe	• Tabulated summary of future state ideas to support $E_f(T_1)_m$ • Equipment Maintenance Personnel • Success Criteria (A_1, A_2, A_3)	• Equipment to be targeted is taken out of production for duration of testing • Testing plan developed for each idea and executed • Safe plan developed to recover equipment in the unlikelihood of an issue	• Functionality evaluations completed to support $E_f(T_1)_m$ • Success criteria pass/fail data for (A_1, A_2, A_3) to allow project selection

Phase 4 Risk (a)

	Input	Model	Output
4R a	• Equipment Maintenance Personnel • KPI's/OEE metrics	• Tool metrics broken down into 3 catagories: Availability, Quality & Cost. Based on definitions; • Availability (A_1) – Tool running or ready to run. Infleunced by Down time (PM's), Unscheduled Down Time, Errors, Alarms, People and Material needed to run equipment. • Quality (A_2)– Good product from equipment,Influenced by SPC performance, customer input, scrap or unit yield for batching. • Cost (A_3)– Ongoing cost of maintaining the change identified for implementation.	• 3 categories of equipment performance based on collective experience of personnel working on equipment •Equipment behaviour broken down into performance catagories to allow prioritisation

Phase 4 Risk (b)

	Input	Model	Output
4R b	• Equipment Maintenance Personnel •3 categories of equipment performance based on collective experience of personnel working on equipment • Absolute scale	• Pairwise comparisons completed between A_1,A_2,A_3 • Questions used to compare the importance of categories are; • 'Please rate availability (A_1) relative to quality (A_2) in importance' • 'Please rate availability (A_1) relative to cost (A_3)in importance' • 'Please rate quality (A_2) performance relative to cost (A_3)in importance' • Absolute scale used to score ratings	• Record the results from questions • Evaluation of factory capability to evaluate energy projects identified from this process

Phase 4 Risk (c)

	Input	Model	Output
4R c	• Recorded the results from questions	• Normalisation calculation completed for A_1,A_2,A_3 using the matrix calculation: $\begin{array}{cccc\|c} & A_1 & A_2 & A_3 & \text{Priorities} \\ A_1 & 1 & a_{12} & a_{13} & B_1 \\ A_2 & {}^{1}/_{a_{12}} & 1 & a_{23} & =B_2 \\ A_3 & {}^{1}/_{a_{13}} & {}^{1}/_{a_{23}} & 1 & B_3 \end{array}$	• Normalised value or prioritisation number B_1, B_2, B_3 • Reflection of customer priorities within their factory setting

Phase 4 Risk (d)

	Input	Model	Output
4R d	• Normalised value or prioritisation number B_1, B_2, B_3 • Equipment Maintenance Personnel	• A_1, A_2, A_3 are assessed in terms of subcriteria to understand how capable a factory is to manage a change. Subcriteria are; • Likelihood C_1 = the possibility of a change to a metric due to implementing a project • Detectabilty C_2 = the ability to see a change on a metric due to implementing a project • Severity C_3 = the level or degree to which the change has affected a metric.	• An understanding of what production line personnel value in terms of being able to evaluate a change to their equipment

Phase 4 Risk (e)

	Input	Model	Output
4R e	• Equipment Maintenance Personnel •2 Subcatagories of equipment performance based on collective experience of personnel working on equipment • Absolute scale	• Pairwise comparisons completed between C_1, C_3 for equipment availability performance • Questions used to compare the importance of subcatagories are; • 'Please rate Likelihood relative to Severity in importance'	• Record the results from questions • Allows an understanding of what factory personnel value (importance) in terms of equipment availability performance

Phase 4 Risk (f)

	Input	Model	Output
4R f	Record the results from questions	Normalisation calculation completed for C_1, C_3 for equipment availability performance using the matrix calculation: $\begin{array}{ccccc} & C_1 & C_3 & & \text{Priorities} \\ C_1 & 1 & a_{12} & & I^L_{A1} \\ C_2 & 1/a_{12} & 1 & = & I^S_{A1} \end{array}$	Availability (A1) performance assigned an importance values (***I***) with respect to likelihood (***L***) and Severity (***S***). These reflect factory personnel's experience of production line priorities

Phase 4 Risk (g)

	Input	Model	Output
4Rg	•Equipment Maintenance Personnel •3 Subcatagories of quality performance based on collective experience of personnel working on equipment • Absolute scale	• Pairwise comparisons completed between C_1, C_2, C_3 for equipment quality performance • Questions used to compare the importance of subcatagories are; • 'Please rate Likelihood relative to Severity in importance' •'Please rate Likelihood relative to Detectability in importance' •'Please rate Detectability relative to Severity in importance'	• Record the results from questions • Allows an understanding of what factory personnel value (importance) in terms of equipment quality performance

Phase 4 Risk (h)

	Input	Model	Output
4Rh	Recorded the results from questions	Normalisation calculation completed for C_1, C_2, C_3 for equipment quality performance using the matrix calculation: $\begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & C_2 & C_3 \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} \\ 1/a_{12} & 1 & a_{23} \\ 1/a_{13} & 1/a_{23} & 1 \end{bmatrix} \end{array} \begin{array}{c} \text{Priorities} \\ I^L_{A2} \\ =I^D_{A2} \\ I^S_{A2} \end{array}$	Quality (A_2) performance assigned importance values (*I*) with respect to Likelihood (***L***), Detectability (***D***) and Severity (***S***). These reflect factory personnel's experience of production line priorities

Phase 4 Risk (i)

	Input	Model	Output
4Ri	• Equipment Maintenance Personnel • 2 Subcatagories of equipment performance based on collective experience of personnel working on equipment • Absolute scale	• Pairwise comparisons completed between C_1, C_3 for equipment cost performance • Questions used to compare the importance of subcatagories are; • 'Please rate Likelihood relative to Severity in importance'	• Pairwise comparisons completed between C_1, C_3 • Allows an understanding of what factory personnel value (importance) in terms of equipment cost performance

Phase 4 Risk (j)

	Input	Model	Output
4Rj	• Pairwise comparisons for C_1, C_3	• Normalisation calculation completed for C_1, C_3 for equipment cost performance using the matrix calculation: $\begin{array}{cc} & \begin{matrix} C_1 & C_3 \end{matrix} \quad \text{Priorities} \\ \begin{matrix} C_1 \\ C_2 \end{matrix} & \begin{bmatrix} 1 & a_{12} \\ 1/a_{12} & 1 \end{bmatrix} = \begin{matrix} I^L_{A3} \\ I^S_{A3} \end{matrix} \end{array}$	• Cost (A_3) performance assigned an importance values (*I*) with respect to likelihood (***L***) and Severity (***S***). These reflect factory personnel's experience of production line priorities

Phase 4 Risk (j) Summary

KPI	Likelihood (L)	Detectability (D)	Severity (S)
Availability (A_1)	I^L_{A1}		I^S_{A1}
Quality (A_2)	I^L_{A2}	I^D_{A2}	I^S_{A2}
Cost (A_3)	I^L_{A3}		I^S_{A3}

Phase 4 Risk (k)

<table>
<tr><th></th><th>Input</th><th>Model</th><th>Output</th></tr>
<tr><td>4Rk</td><td>•Equipment Maintenance Personnel
• Energy projects identified
• Scale for scoring project risk based on workforce experience</td><td>• Project(s) scored based on original 3 key metrics: A_1, A_2, A_3 and the probability of a change in these KPI's as a result of the project(s) implementation
•Each metric assessed in terms of likelihood/detectability/severity based on workforce input
<table>
<tr><th>Score</th><th>Detail</th><th>Likelihood/Detectability</th><th>Severity</th></tr>
<tr><td>1</td><td>Certain Fail</td><td>100% certainty</td><td>Major Impact</td></tr>
<tr><td>3</td><td>High Risk</td><td>>80% certainty</td><td>Significant Impact</td></tr>
<tr><td>5</td><td>Med Risk</td><td>≥50% certainty</td><td>Medium Impact</td></tr>
<tr><td>7</td><td>Low Risk</td><td><30% certainty</td><td>Minor Impact</td></tr>
<tr><td>10</td><td>No Risk</td><td>Certain of no issue</td><td>No Impact</td></tr>
</table>
</td><td>• Workforce input into probability of successful implementation of project(s) based on their knowledge of production line and A_1, A_2, A_3 .</td></tr>
</table>

Phase 4 Risk (k)

	Input	Model	Output
4Rk	•Equipment Maintenance Personnel • Energy projects identified • Scale for scoring project risk based on workforce experience	• Questions asked are in terms of the identified projects affecting equipment performance in terms of Availability (A_1)/Quality(A_2)/Cost(A_3). • Availability questions to be asked of the client in support them prioritising: 'What is the likelihood of you seeing a change in availability performance because of this project? $L_{A1}^{Project'}$ 'How severe would the impact likely be availability performance from implementing this project? $S_{A1}^{Project'}$ •Quality questions to be asked of the client in support them prioritising: 'What is the likelihood of you seeing a change in quality performance from implementing this project? $L_{A2}^{Project'}$ 'How easily can you detect a change in quality performance as a result of this project? $D_{A2}^{Project'}$ 'How severe would the impact likely be to quality perofmrance from implementing this project? $S_{A2}^{Project'}$ •Cost Questions to be asked of the client in support them prioritising: 'What is the likelihood of you seeing a change in cost performance from this project? $L_{A3}^{Project'}$ 'How severe would the impact likely be cost perfomance as a result of this project? $S_{A1}^{Project'}$	• Projects scored in terms of factory capability to monitor a change in terms of Likelihood(**L**)/Detectability(**D**)/Severity(**S**) as shown.

Phase 4 Risk (k) Summary

KPI	Project	Likelihood (L)	Detectability (D)	Severity (S)
A_1	Z_1	L_{A1}^{Z1}		S_{A1}^{Z1}
	Z_2	L_{A1}^{Z2}		S_{A1}^{Z2}
A_2	Z_1	L_{A2}^{Z1}	D_{A2}^{Z1}	S_{A2}^{Z1}
	Z_2	L_{A2}^{Z2}	D_{A2}^{Z2}	S_{A2}^{Z2}
A_3	Z_1	L_{A3}^{Z1}		S_{A3}^{Z1}
	Z_2	L_{A3}^{Z2}		S_{A3}^{Z2}

Phase 4 Risk (l)

	Input	Model	Output
4Rl	• Factory priority scores • Subcriteria scores • Project scores	• Each project scored based on all input collected • Project Z_1 score illustrated: $Project\ Z_1 = \left[\begin{matrix} B1\left((L_{A1}^{Z1} \times I_{A1}^{L}) + (S_{A1}^{Z1} \times I_{A1}^{S})\right) + \\ B2\ \left((L_{A2}^{Z1} \times I_{A2}^{L}) + (D_{A2}^{Z1} \times I_{A2}^{D}) + (S_{A2}^{Z1} \times I_{A2}^{S})\right) + \\ B3\left((L_{A3}^{Z1} \times I_{A3}^{L}) + (S_{A3}^{Z1} \times I_{A3}^{S})\right) \end{matrix}\right]$	• Value which indicates the capability of a company to monitor and manage an energy based change identified by this process through their production line

Phase 4 Risk (m)

	Input	Model	Output
4Rm	• Project scores	• Team to reviewing scoring by project • The scores are relative to each other. • A high score indicating a capability to monitor a change based on energy projects identified • A low score indicates lack of capability to monitor a change based on energy projects identified	• High scoring projects represent projects which are functionally possible and factory is capable of effectively managing • Highlights gaps for factory to close in terms of improved change management

Phase 4 NPV (a)

	Input	Model	Output
4NPVa	• High scoring projects represent projects which are functionally possible and factory is capable of effectively managing • Equipment Maintenance Personnel • Energy Manager	• Factory’s have multiple priorities. The high scoring projects identified through this process must be selected and compared to other overall factory prioritity in terms of •Cost •Timing •Suitability based on factory priorities •Resource support	• Selected project(s) identified for investment analysis

Phase 4 NPV (b)

	Input	Model	Output
4NPVb	• Selected project(s) identified for investment analysis • Energy Manager • Project Owner	• From equipment study completed in this process, project owner understands if the energy improvement project can be completed • With the existing capability of the equipment through adjustment or optimisation (then continue to the subsequent phase) or • Does the capability of the equipment need to be upgraded	• Evaluation of performance adjustment to deliver energy improvement complete • Upgrade requirement defined to deliver performance: hw or sw capability

Phase 4 NPV (c)

	Input	Model	Output
4NPVc	• Upgrade requirement defined to deliver performance: hw or sw capability	• Cost of upgrade understood • Yearly savings calculated: (Reference – improvement) unit price x units used of utility x time • Payback calculated: Initial investment/Average yearly saving • Rate of return of investment: -100 x (Av savings over 5 yrs- Av expenditure over 5 yrs)/Up front investment	• Investment costings • Simple Payback for investment • Rate of return for investment

Phase 4 NPV (d)

	Input	Model	Output
4NPVd	• High scoring projects representing projects which are functionally possible and factory is capable of effectively managing • Simple Payback for investment for each project	• Project scores plotted on a 2D plot with project capability scoring on the Y axis and payback value on the X axis	• Visual plot of project(s) scorings highlighting relative differences in capability by project and payback

Phase 5 a

	Input	Model	Output
5a	• High scoring functionally possible project(s) with acceptable payback • Production Engineering • Energy Manager	• Project(s) evaluated over an agreed time period to understand project performance against production line OEE or KPI's. The following data is suggested as appropriate: •Project/Component (populated from previous table) – Test Details-Critical to Quality Indicator-Type of test(GRC/1σ)-Point of Detection (Tool/in line/End of Line)-Data (Baseline)-Data (Test)-Statistical Success Criteria – Test complete (Pass/Fail)	• Defined extended test plan with appropriate success criteria metrics that are production line based for project(s) identified • Gaps identified in capability which must be closed/explained before proceeding

Phase 5 b

	Input	Model	Output
5b	• High scoring functionally possible project(s) with acceptable payback • Defined extended test plan with appropriate success criteria metrics • Production Engineering • Energy Manager	• Project(s) evaluated individually or where appropriate as a grouping. The purpose of the extended testing is to monitor the project(s) over time to ensure production metrics within acceptable criteria	• Defined extended test plan with appropriate success criteria metrics that are production line based for project(s) identified • Gaps identified which must be closed/explained before proceeding

Phase 5 c

	Input	Model	Output
5c	• Extended test data for project(s) • Production Engineering • Energy Manager	• Project(s) data evaluated based on success criteria (OEE/production line KPI's). Equipment functionality testing may not detect or highlight changes within the prodction line itself. As a result extended testing is required • Data to be used to reflect on 'Phase 4 Functionality' if testing reveils issues or not meeting success criteria	• Documented data recording project(s) success • Documented data highlighting issues • Gaps identified which must be closed/explained to proceed to next phase

Phase 5 d

	Input	Model	Output
5d	• Documented data recording project(s) success • Production Engineering • Energy Manager • Quality Engineer or Change Control Board owner	• Project(s) data documented within factor's existing Change Control Process (CCP) • Requires cooperation of quality systems owners to review and validate data • By inputing into CCP system indicates formal factory acceptance of desire to implement change	• Project(s) data collected meets CCP • Requirements • Gaps identified which require further collection or analysis

Phase 5 e

	Input	Model	Output
5e	• Project(s) data collected meets CCP requirements • Gaps identified which require further collection or analysis • Production Engineering • Energy Manager • Quality Engineer or Change Control Board owner	• Factory's have multiple priorities. The project(s) identified through this process must be selected and compared to other overall factory prioritity in terms of • Cost • Timing • Suitability based on factory priorities • Resource support	• Project(s) selected with CCP sponsorship • Project(s) prioritised appropriately based on factory priorities

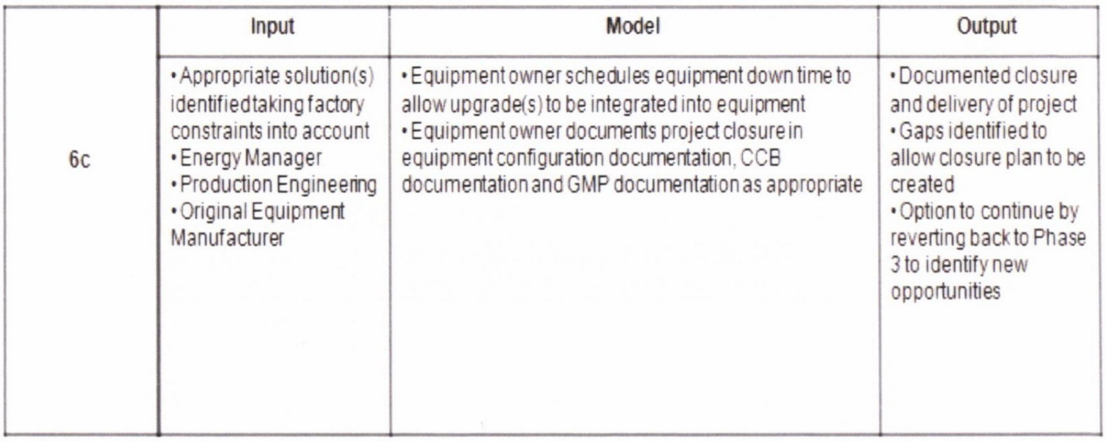
Phase 6 a

	Input	Model	Output
6a	• Project(s) selected with CCP sponsorship • Energy Manager • Engineering Management • Production Management	• Project(s) prioritised appropriately based on factory priorities • Define implementation schedule with stakeholders ie equipment owners, production owners, energy manager • Content detail for implementation to outline owner, change detail, data from Phase 3 and 5 evaluations, schedule.	• Documented and management approved implementation plan for project(s)

Phase 6 b

	Input	Model	Output
6b	• Project(s) selected with CCP sponsorship • Energy Manager • Production Engineering • Original Equipment Manufacturer	• Equpment personnel (engineering and maintenance) identify the most appropriate option to deliver the equipment improvement project. Catagories to be investigated: • Automated solution: •Optimisation of tool mode of operation ie production state or non production state • Equipment control sequence • Appropriate parameter change • Upgrade – sw or hw as appropriate • Semi-automated: • Manufacturing control system • Defined new mode of operation with project improvement included • Manual: • Training • Good Manufacturing Practice documentation • Response flow chart •SOP Documentation	• Appropriate solution(s) identified taking factory constraints into account

Phase 6 c



	Input	Model	Output
6c	• Appropriate solution(s) identified taking factory constraints into account • Energy Manager • Production Engineering • Original Equipment Manufacturer	• Equipment owner schedules equipment down time to allow upgrade(s) to be integrated into equipment • Equipment owner documents project closure in equipment configuration documentation, CCB documentation and GMP documentation as appropriate	• Documented closure and delivery of project • Gaps identified to allow closure plan to be created • Option to continue by reverting back to Phase 3 to identify new opportunities

A1.1 Publications

Aughney, N., O'Donnell, G.E., "The energy saving opportunity in targeting non-value add manufacturing activities – a structured approach", Journal of cleaner production (2014) DOI: 10.1016/j.clepro.2014.05.044

Aughney, N., O'Donnell, G.E., "Investigating the cost considerations of implementing energy based improvements within manufacturing process chains", under construction for the Journal of cleaner production

Ken Bruton, Paul Raftery, Peter O'Donovan, Niall Aughney, Marcus M. Keane, D.T.J. O'Sullivan, "Development and alpha testing of a cloud based automated fault detection and diagnosis tool for Air Handling Units" Automation in construction, Vol (39), April 2014, pp70-83. DOI: 10.1016/j.autcon.2013.12.006

N. Aughney, G.E. O'Donnell "Implementing energy efficiency in manufacturing – overcoming the risk and cost perception barriers". 11th Global Conference on Sustainable Manufacturing (CIRP). Berlin, September 2013.

P. Harris, G.E. O'Donnell, N. Aughney, T. Whelan "Energy usage and efficiency in Non-Conventional Micromachining". 11th Global Conference on Sustainable Manufacturing (CIRP). Berlin, September 2013.

N. Aughney, G. E. O'Donnell, "Lean Energy: A Methodology to Characterise and Optimise Energy and Resource Consumption within Manufacturing Process Chains" *Proceedings of the 10th Global Conference on Sustainable Manufacturing (CIRP). Istanbul, October 31st to November 2nd pp. 718-723, 2012.*

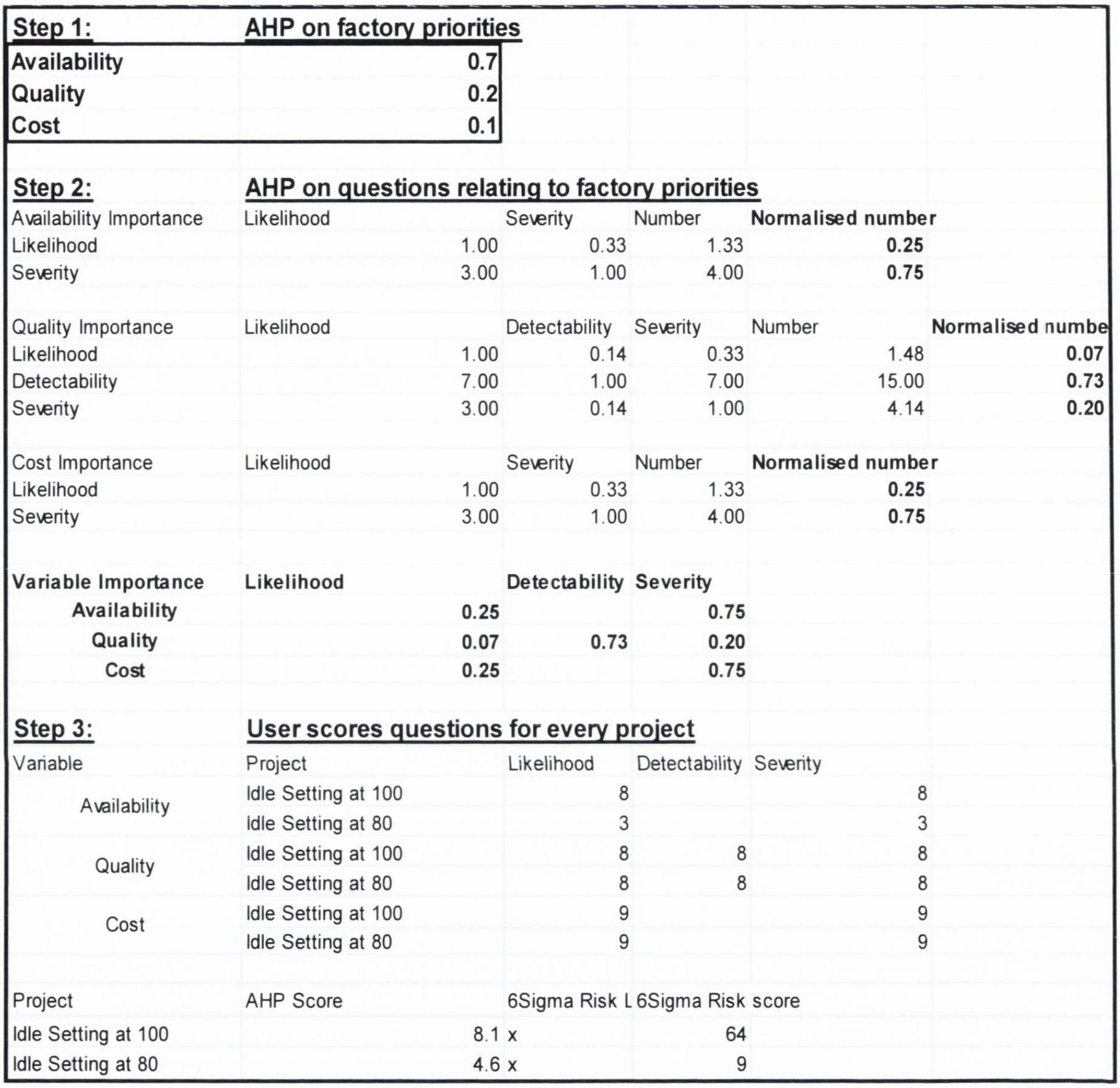
N. Aughney, G.E. O'Donnell, "Lean Energy – The practical route to competitiveness". Dublin Castle 10th May 2011.

N. Aughney, *"A view on the 2020 vision and challenges",* keynote speaker at ICM, 20th October, 2011.

N. Aughney, G.E. O'Donnell, "Lean optimisation of fab tools", keynote speaker at Energy Symposium, Seagate, Derry, 23rd April 2013.

N. Aughney, "Optimisation of energy consumption within compliant environments", keynote speaker at the TEMPO seminar, Cork, 25th July 2013.

A1.2 AHP evaluation & NPV templates



Step 1:	**AHP on factory priorities**
Availability	**0.7**
Quality	**0.2**
Cost	**0.1**

Step 2: **AHP on questions relating to factory priorities**

Availability Importance	Likelihood	Severity	Number	**Normalised number**
Likelihood	1.00	0.33	1.33	**0.25**
Severity	3.00	1.00	4.00	**0.75**

Quality Importance	Likelihood	Detectability	Severity	Number	**Normalised numbe**
Likelihood	1.00	0.14	0.33	1.48	**0.07**
Detectability	7.00	1.00	7.00	15.00	**0.73**
Severity	3.00	0.14	1.00	4.14	**0.20**

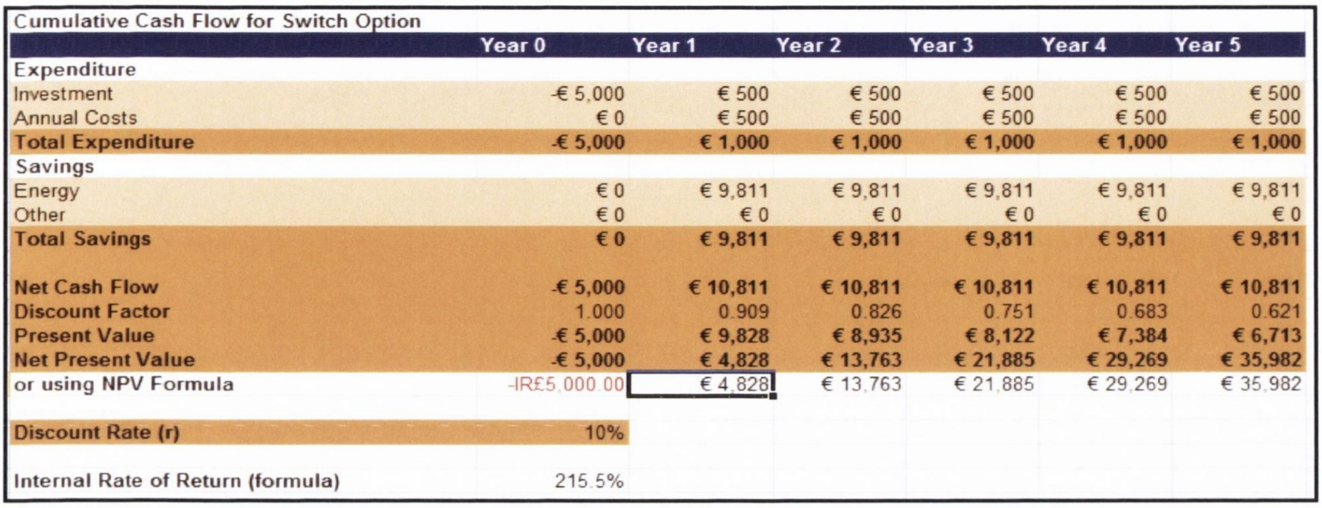
Cost Importance	Likelihood	Severity	Number	**Normalised number**
Likelihood	1.00	0.33	1.33	**0.25**
Severity	3.00	1.00	4.00	**0.75**

Variable Importance	**Likelihood**	**Detectability**	**Severity**
Availability	**0.25**		**0.75**
Quality	**0.07**	**0.73**	**0.20**
Cost	**0.25**		**0.75**

Step 3: **User scores questions for every project**

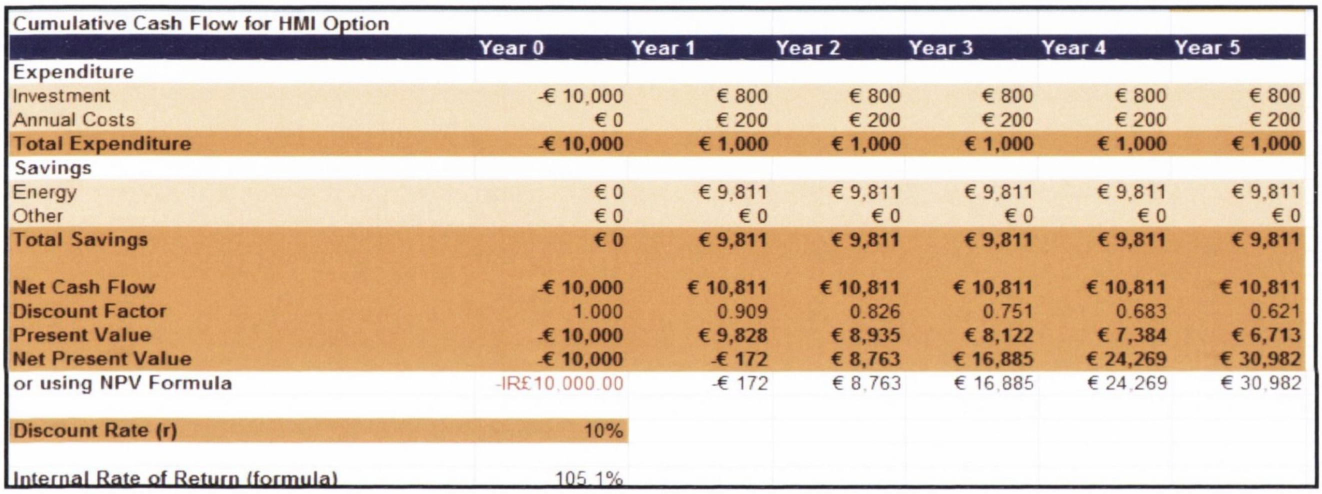
Variable	Project	Likelihood	Detectability	Severity
Availability	Idle Setting at 100	8		8
	Idle Setting at 80	3		3
Quality	Idle Setting at 100	8	8	8
	Idle Setting at 80	8	8	8
Cost	Idle Setting at 100	9		9
	Idle Setting at 80	9		9

Project	AHP Score	6Sigma Risk L	6Sigma Risk score
Idle Setting at 100	8.1	x	64
Idle Setting at 80	4.6	x	9



Cumulative Cash Flow for Switch Option

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Expenditure						
Investment	-€ 5,000	€ 500	€ 500	€ 500	€ 500	€ 500
Annual Costs	€ 0	€ 500	€ 500	€ 500	€ 500	€ 500
Total Expenditure	**-€ 5,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**
Savings						
Energy	€ 0	€ 9,811	€ 9,811	€ 9,811	€ 9,811	€ 9,811
Other	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
Total Savings	**€ 0**	**€ 9,811**	**€ 9,811**	**€ 9,811**	**€ 9,811**	**€ 9,811**
Net Cash Flow	**-€ 5,000**	**€ 10,811**	**€ 10,811**	**€ 10,811**	**€ 10,811**	**€ 10,811**
Discount Factor	1.000	0.909	0.826	0.751	0.683	0.621
Present Value	**-€ 5,000**	**€ 9,828**	**€ 8,935**	**€ 8,122**	**€ 7,384**	**€ 6,713**
Net Present Value	**-€ 5,000**	**€ 4,828**	**€ 13,763**	**€ 21,885**	**€ 29,269**	**€ 35,982**
or using NPV Formula	-IR£5,000.00	€ 4,828	€ 13,763	€ 21,885	€ 29,269	€ 35,982
Discount Rate (r)	10%					
Internal Rate of Return (formula)	215.5%					



Cumulative Cash Flow for HMI Option

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Expenditure						
Investment	-€ 10,000	€ 800	€ 800	€ 800	€ 800	€ 800
Annual Costs	€ 0	€ 200	€ 200	€ 200	€ 200	€ 200
Total Expenditure	**-€ 10,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**	**€ 1,000**
Savings						
Energy	€ 0	€ 9,811	€ 9,811	€ 9,811	€ 9,811	€ 9,811
Other	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
Total Savings	**€ 0**	**€ 9,811**	**€ 9,811**	**€ 9,811**	**€ 9,811**	**€ 9,811**
Net Cash Flow	**-€ 10,000**	**€ 10,811**	**€ 10,811**	**€ 10,811**	**€ 10,811**	**€ 10,811**
Discount Factor	1.000	0.909	0.826	0.751	0.683	0.621
Present Value	**-€ 10,000**	**€ 9,828**	**€ 8,935**	**€ 8,122**	**€ 7,384**	**€ 6,713**
Net Present Value	**-€ 10,000**	**-€ 172**	**€ 8,763**	**€ 16,885**	**€ 24,269**	**€ 30,982**
or using NPV Formula	-IR£10,000.00	-€ 172	€ 8,763	€ 16,885	€ 24,269	€ 30,982
Discount Rate (r)	10%					
Internal Rate of Return (formula)	105.1%					

Figure A1.2 – (a) AHP template and (b) NPV templates

A1.3 Industrial survey

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1	Total Energy Inputs	Plant Manager, Facilities Manager, Facilities/Energy Engineers

1.1 What was the total energy consumed (GWh) for the calendar year 2010?

……………………………………………………………………………………………

1.2 What was the total energy consumed (GWh) for the calendar year 2006?

……………………………………………………………………………………………

1.3 Is historical data available for the total energy consumed for the last 5 years (2006 to 2011)? Yes / Partial / No

Calendar Year	Total Energy Consumed	Comment
2011		
2010		
2009		
2008		
2007		
2006		

1.4 Comment on any significant shifts in production / facilities that have occurred in the last 5 years?

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……………………………………………………………………………………………

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……………………………………………………………………………………………

1.5 Does your organisation participate in any demand side management (DSM) opportunities? If so, please outline:.

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

1.6 Quantify the primary energy sources and resources supplied to the facility?

		Value and Units	Average price per unit
Net Electricity	Purchased		
	Transferred in		
	Onsite Generation from Non-combustible Renewable Energy		
	Sales and Transfers Offsite		
Fuel Oil	Kerosene, Petrol, Diesel		
Gas	Natural Gas (NG)		
	Liquefied Petroleum Gases (LPG)		
	Other industrial gases		
Coal	Coke, Peat,		
Biomass	Agricultural Waste		

	Wood Harvested Directly from Trees		
	Wood Residues and By-products		
Other	Solar		
	Water		
	Oil, Lubricants		

1.7 Outline what tariff structures are utilised for electricity usage?

....

....

1.8 Outline what tariff structures are utilised for natural gas usage?

....

....

2	Energy Utilisation	Facilities Manager, Facilities/Energy Engineers

2.1 Does the organisation analyse the breakdown of final energy usage into sub-sectors such as HVAC, Lighting, IT, Process Heat, Mechanical Energy etc.?

....

2.2 Outline the sub-sectors and their relative size?

....

....

....

2.3 For the reference year 2010, please breakdown the relative percentages of total energy usage and cost, under the following standardised categories?

		% of Total	Cost
Facilities	HVAC		
	Lighting		
	C.A.		
	Chilled Water		
	Waste		
	Other		
Production	Thermal Processes (Chilling/Heating)		
	Cleaning Processes		
	Other Production Energy		

2.4 Outline the Organisation strategy for identifying direct versus indirect energy usage?

....

....

2.5 Identify the significant energy users (SEUs) by the relevant primary supply?

(Tick the relevant box on the matrix and provide the relative % and/or Units)?

	Electricity	Fuel Oil	Gas	Coal	Biomass	Other
Indirect Uses - Boiler Fuel						
Conventional Boiler Use						
CHP and/or Cogeneration Process						
Direct Uses – Process						
Process Heating						
Compressed Air						
Process Utilities						
Process Cooling and Refrigeration						
Machine Drive						
Electro-Chemical Processes						
Other Processes						
Direct Uses - Non-Process						
Facility HVAC						
Facility Lighting						
Other Facility Systems						
Onsite Transportation						
Conventional Electricity Generation						
Other Non-process Use						
End Use Not Reported						
Totals						

Energy Monitoring Systems (EMS)

2.6 Describe the energy monitoring systems? (Types of sensors, network points, number of sensors, level of distribution and sub-distribution board monitoring)

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....

....

....

....

2.7 Describe the monitoring of non-electrical energy networks? (Number of sensor Points, types, etc.)

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....

2.8 Describe the temporal resolution of the meters, sampling frequency etc.

....

....

2.9 What metering plan is in place for your factory and does it include the production line(s)?

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3	Production / Energy Data	Production Manager, Production Engineers, Plant Manager, Automation/IT Engineers

3.1 Are there discrete, continuous or both manufacturing flows in operation?

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....

3.2 Outline the production processes.

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....

....

....

3.3 What are the value streams/business units and what is their relative size?

....

....

3.4 How do you define your unit of production within each value stream?

....

....

....

3.5 What is the normal product range and variation?

....

....

3.6 What key metrics are currently used to track production?

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....

....

3.7 What are the significant drivers of the production metrics?

....

....

3.8 Is 'energy-consumed' embedded into the calculation of the production metrics?

....

....

3.9 Are energy costs allocated to value streams and how?

....

....

....

3.10 How is production metric information gathered (manually or auto) and at what interval? (E.g. milliseconds, seconds, minutes, hours, days)

....

....

....

3.11 What type of statistical analysis is performed? (E.g. raw data, mean, standard deviation, regression analysis, etc.)

....

....

....

3.12 What is the general work schedule for production? (Days/shifts/24/7)

....

....

....

3.13 What manufacturing paradigms are applied (LEAN / Agile / OEE)?

....

....

3.14 What production management and monitoring software is used?

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....

3.15 Is energy consumption by equipment type broken down?

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....

3.16 How do you identify opportunities for improvement?

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3.17 Outline what formal processes are used for the identification, prioritisation and management of change?

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3.18 Are production machines uploading data onto a network or stand alone?

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....

3.19 Which type of data is captured (e.g. tool parameters, production data, and environmental variables)?

....

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3.20 Is the production machine state data (idle, working, standby) correlated to energy behaviour?

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3.21 Outline the overall factory Automation/ICT systems - what technologies, platforms and networks are in place?

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3.22 Outline the overall factory Automation/ICT systems infrastructure / architecture?

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3.23 Is there access to the organisations IT Systems relating to production? Y / N If so, is access based on Database Structures or Application Programming Interfaces (API). .

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……………………………………………………………………………………………………

3.24 Is the organisations IT System hosted locally or corporately?

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3.25 Are facilities and manufacturing operations linked on the same IT /building energy management system (BEMS)

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……………………………………………………………………………………………………

3.26 Can energy usage data be linked to operations metrics/management tools?

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……………………………………………………………………………………………………

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3.27 Is tighter linkage of facilities control to factory control desirable?

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……………………………………………………………………………………………………

3.28 Does the production facility have wireless capability that could support sensors as well as networks?

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……………………………………………………………………………………………………

3.29 Are there any Wi-Fi networks currently and successfully deployed in the facility?

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……………………………………………………………………………………………………

……………………………………………………………………………………………………

3.30 Are there any radio networks currently and successfully deployed in the facility?

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3.31 Outline the organisation's security protocols relating to wireless data? (Security, encryption, redundancy)

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3.32 What visualisation systems (Info-Graphic Boards) are there in place for production data?

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3.33 What visualisation systems (Info-Graphic Boards) are there in place for energy usage?

....

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....

3.34 What is the organisation's overall maintenance strategy for production equipment? (In-house / contract)

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....

3.35 What is the organisation's overall maintenance strategy for facilities?

(In-house / contract)

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3.36 Is there an energy performance aspect to external maintenance/service contracts?

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A1.4 Autoclave electrical schematics

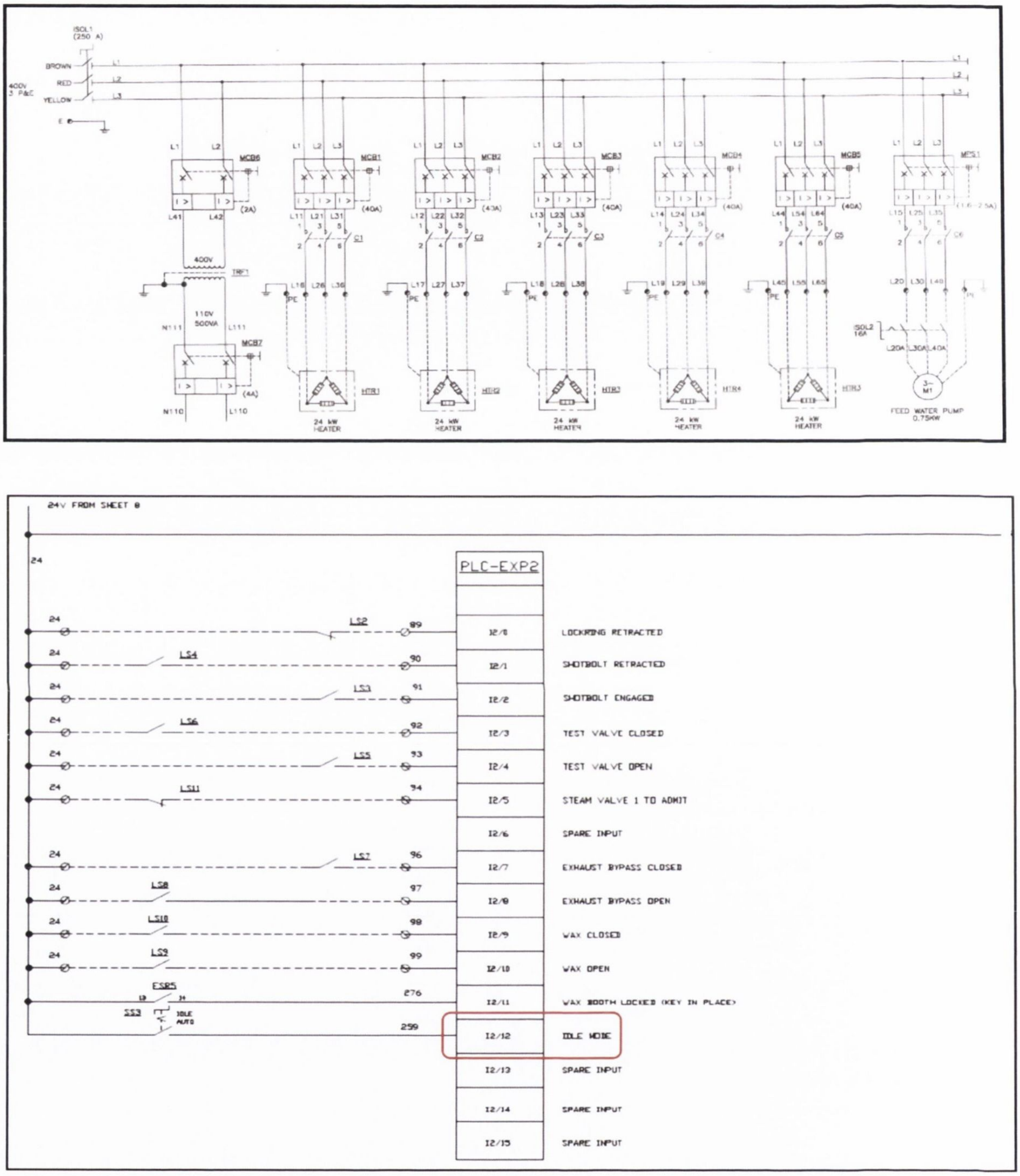


Figure A1.4 – (a) Autoclave electrical schematics and (b) PLC Modification

A1.5 ICT tool module schematics

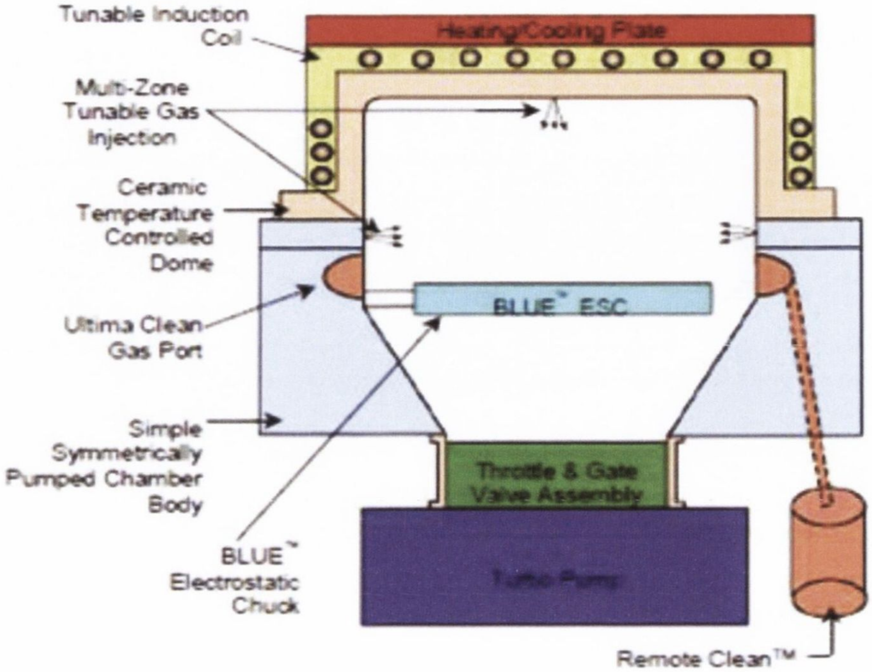


Figure A1.3 – Process chamber of high density CVD tool

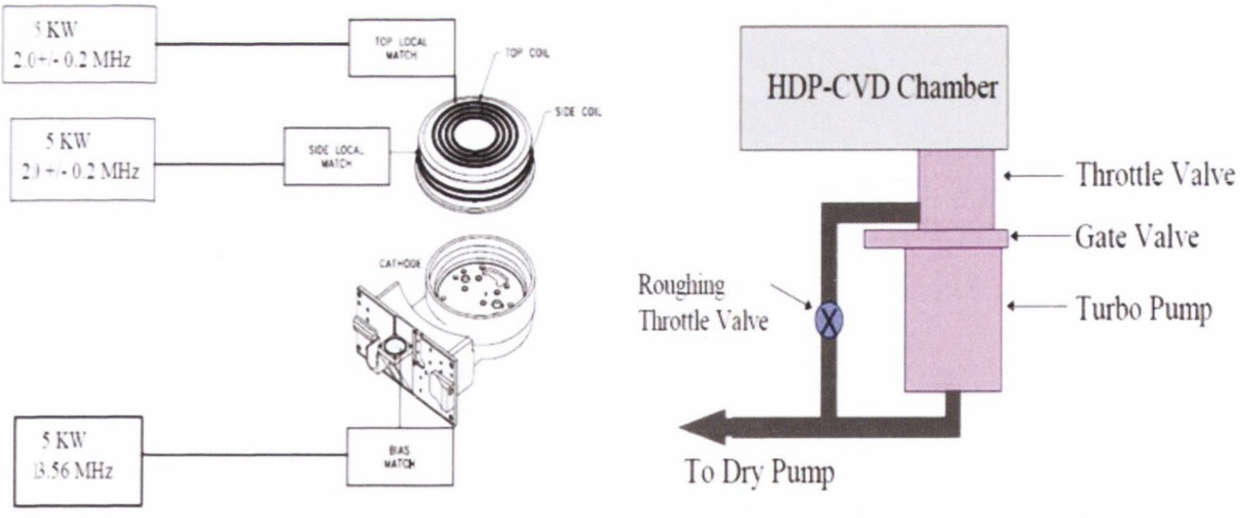


Figure A1.4 – Modules: RF (a) and (b) turbo molecular pump

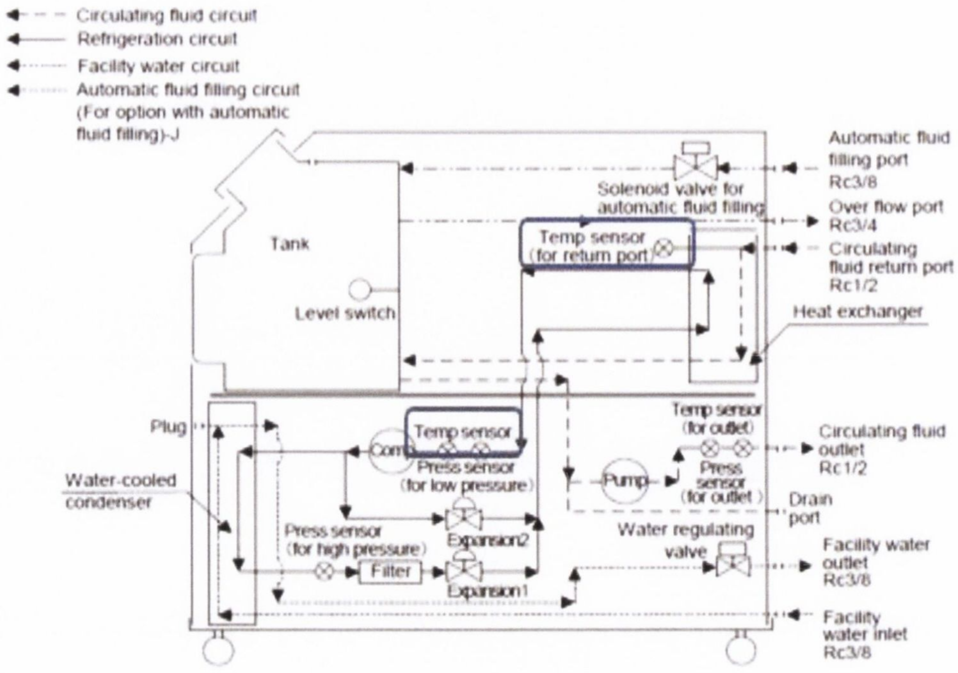
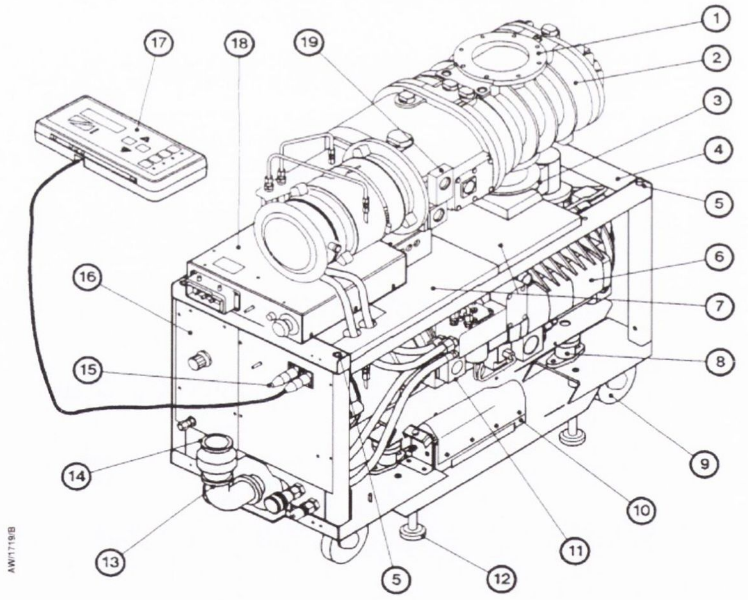


Figure A1.5 – Chiller configuration



1. iQMB pump * inlet
2. iQMB pump *
3. iQDP pump inlet
4. iQDP pump frame
5. Lifting-bolt hole
6. iQDP pump
7. Acoustic panels (part of the Acoustic Enclosure *)
8. Vibration isolator
9. Castor
10. Sensor Monitoring Module
11. iQDP Oil-Level Monitor *
12. Levelling foot
13. Check-valve
14. Check-valve outlet
15. Terminator plug #
16. Gas Module
17. Pump Display Module *
18. Electrics Module
19. iQMB Oil-Level Monitor *

Figure A1.6 – Dry pump configuration for process/transfer/cassette chambers

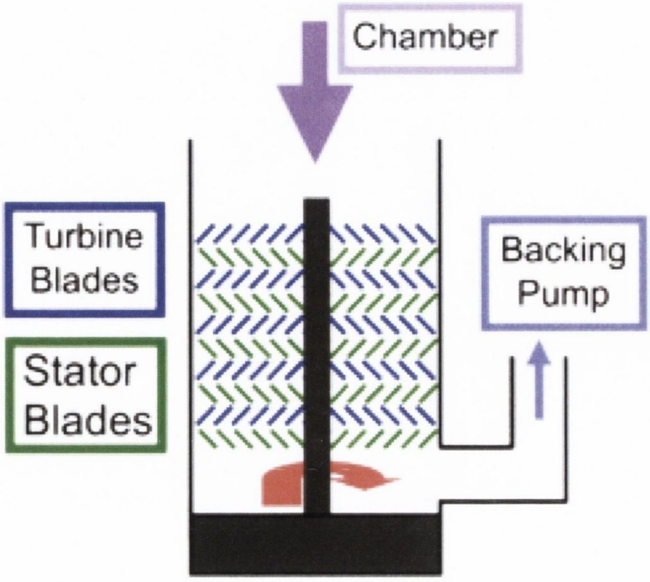


Figure A1.7 – Schematic of turbo molecular pump