The energy saving opportunity in targeting non-value add manufacturing activities – a structured approach

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ABSTRACT

With an ongoing increase in industrial energy demand anticipated in Europe, energy efficiency continues to be an important focus within industrial environments. This paper 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 with qualitative workforce input supporting the risk assessment. It also develops an assessment of an organisations capability to manage an energy improvement in order to minimise risk to core Overall Equipment Effectiveness 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. This demonstrates the need to consider the implications of energy change to an organisation in terms of operational metrics. The approach has been applied successfully across a range of manufacturing industries including multinational environments such as information and communication technology, pharmaceutical and medical device as well as Irish small and medium enterprises. The case study presented delivered a 51% reduction in energy consumption for targeted manufacturing states used by discrete part manufacturing equipment.

1. Introduction

An anticipated increase in industrial energy demand across Europe will result in an estimated 30% increase in energy consumption over the next 20 years (EU Director General for Energy, 2009). This will pose further challenges to Europe's commitment of reducing energy consumption by 20% by the year 2020 (European Commission, 2012). Energy efficiency is a key topic within industrial environments as a response mechanism to this challenge. This challenge is broadly being addressed by three different approaches within industry; management led initiatives within companies, energy efficiency technology implementation and adherence to policies/regulations (Abdelaziz et al., 2011). Historically, facilities management and technical building services have championed energy efficiency improvements through a focus on environmentally based management and regulatory compliance (Almeida et al., 2013) and maintaining energy performance through monitoring and targeting programs (Dobes, 2013). Two further issues present challenges in energy efficiency within manufacturing industries;

- There is a lack of data and knowledge of energy consumption within manufacturing processes. Furthermore there is a reluctance to modify process parameters due to perceived risk and cost of change for highly regulated industries such as medical device and aero engine manufacture (Elmualim et al., 2010).
- The increasing complexity of manufacturing equipment and process chains is driving the development of more integrated metrics to ensure compliance. Through measurement, monitoring and control, industries are striving to understand new opportunities for improvement (Hon, 2005). This complexity is also resulting in increased demands for both energy and resource categories within manufacturing equipment as product sophistication evolves (Gutowski et al., 2005).

There has been a growing awareness of the need to promote the examination of energy consumption within manufacturing

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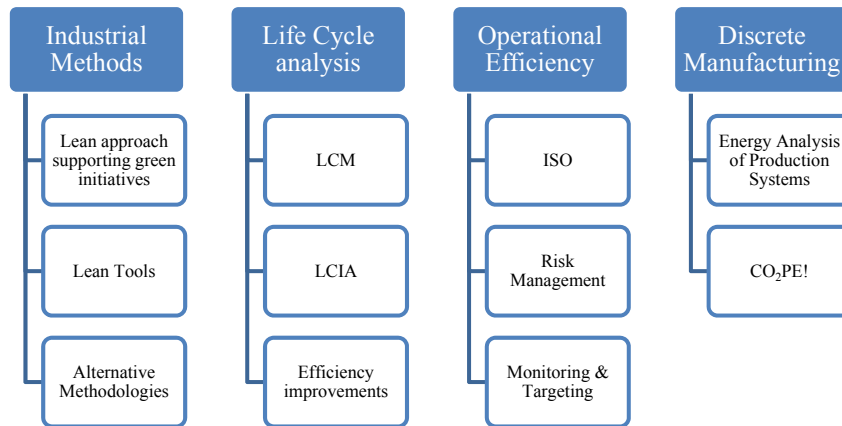 E-mail address: aughneyn@tcd.ie (N. Aughney).

Fig. 1. Pillars used to develop the structured approach towards targeting non-value added energy consuming activities.

environments in more detail, specifically manufacturing process chains (Herrmann et al., 2011) as a base to deriving measures to improve energy and resource efficiency in a structured manner (Duflou et al., 2012b). Recent simulation work has highlighted the impact of production management on energy consumption and further reinforced the potential influence on costs, depending on the use pattern (Herrmann and Thiede, 2009). The complexity of these environments is compounded further as a result of the potentially significant differences that can occur between theoretical energy demand and the actual energy consumed for discrete manufacturing processes (Duflou et al., 2012a). This issue reinforces the need for appropriate metering strategies within energy
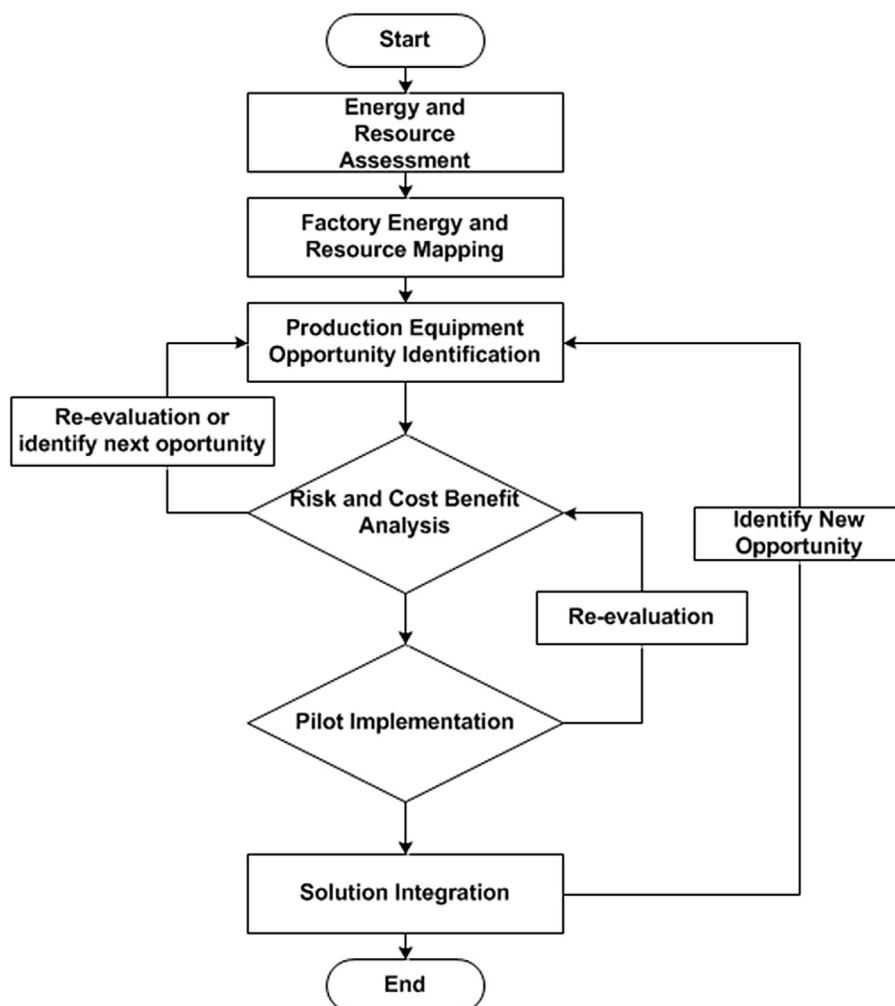

Fig. 2. Overview of the structured approach.

conscious manufacturing environments to deliver transparency in energy consumption (Kara et al., 2011).

When the field of view is opened to consider how structured approaches can be used to integrate energy efficiency into manufacturing systems. The benefits of this approach can be seen through the use of structured environmental assessments for production processes to benefit cleaner production strategies (Jia et al., 2013) through the use of environmental benchmark data. Authors such as Lopes (Lopes Silva et al., 2013) have identified a need to consider the integration of energy improvements with factory based quality tools to support energy performance improvements. This demonstrates how a structured approach and reference performance comparisons can benefit a manufacturing organisations ability to quantifiably verify sustainability and environmental impacts (Aguado et al., 2013). The extensively applied lean principles and methods have also been shown to support a structured approach to industrial environmental improvement (Yang et al., 2011) through the measurement of environmental performance. The versatility of these approaches demonstrates linking the use of these structured methods to environmental performance improvements through waste reduction ranging from production cell applications (Pampanelli et al.) to supply chain optimisation (Dües et al., 2013).

The International Organisation for Standardisation (2011) has focused on outlining a framework known as I.S.O. 50001 to allow organisations structure to improve energy performance with a focus on corporate and organisational set up as well as verifiable gains in improvement. Concurrently, the Cooperative Effort in Process Emission ($CO_2PE!$) outlines a standardised approach to support energy data collection (Kellens et al., 2011), and focuses on understanding energy and resource consumption behaviour within production equipment. It investigates the concept of energy consumption for fundamental operational states for production equipment as a basis for an approach. Other examples of considering a tool state approach have shown the impact of individual tool module consumption and the effect of machine states on this consumption such as set up, power on and energy conversation rates (Rajemi et al., 2010). These approaches have highlighted the opportunity to reduce CO_2 emissions from a generation perspective due to a reduction in demand, and have also forced researchers to critically consider the issue of system boundary definitions. Other work in standards development has considered energy consumption during different production recipes (Avram and Xirouchakis, 2011) and concluded that using a structured approach can support machine energy reduction. The authors suggested that the approach could lead to findings that would be of value and inform future tool design improvements, raising the issue of design for energy efficiency in the DFx paradigms. Further evidence of the modular consumption approach of production tools and how it can inform tool redesign has been demonstrated through its application to model development to directly reduce tool CO_2 emissions (Balogun and Mativenga, 2012). This direct energy consumption model has highlighted the beneficial impact of optimising both the monetary and environmental impact of electricity usage. It has highlighted the benefit of the inclusion of additional manufacturing states, increasing the opportunity to characterise energy demand performance of production tools.

The ongoing focus on energy based tool characterisation work demonstrates the impact of appropriate metering, standards application and manufacturing states to manufacturing process design and equipment selection. It has been further recognised with process optimisation and tool design now being seen as a fundamental part of the approach for cleaner production (Klemeš et al., 2012) and should be enforced by all industrial and business facilities. The aim of this research is to examine the potential of targeting non value adding manufacturing activities as potential energy saving opportunities in complex manufacturing process chains. This research work considers the development of a method to gather the appropriate data in order to correlate energy saving opportunity, risk and cost benefit. The approach outlined considers energy and state/operational behaviour of discrete production equipment. Risk factors are examined using appropriate consideration of human factors to develop risk models.

2. The need for a structured approach

A structured approach is necessary in order to study and analyse factory energy efficiency opportunities given the complexity of multiple stakeholders spanning management to the operator on the factory floor. The approach developed has been influenced by a number of areas, highlighted in Fig. 1 which up to now have been operating in isolation as individual pillars of research or application. The development of structured approaches build on existing momentum of lean methods (Womack, 1996) which is being adopted to focus on energy through governmental organisations (Sustainable Energy Authority of Ireland, 2009; United States Environmental Protection Agency, 2011). Structured approaches work to support furthering the characterisation of manufacturing within the product life cycle (Westkämper et al., 2000) to understand the impact of discrete manufacturing (Duflou et al., 2011). This will support ongoing efforts to integrate energy based change into organisations (International Organisation for Standardisation, 2012), support risk management (Wu et al., 2013) and metric development (Feng et al., 2014). The approach also builds on work already recognised (Despeisse et al., 2012; Devoldere et al., 2007) as making a contribution to energy characterisation within manufacturing environments. In terms of application within industrial environments, the structured approach will facilitate enterprises assessing their capability to undertake this type of work. In particular through considering the appropriate risks, mitigation steps can be considered to support implementation.

3. Method and structure

A structured approach towards undertaking an energy efficiency initiative within a complex manufacturing facility is outlined below.

It can be seen from Fig. 2 that a logical study and analytical approach has been developed in order to build an appropriate data base of information that will enable energy efficiency in the selected process or process chain. The structured approach outlined above provides clear visibility to all stakeholders on the process of data gathering and subsequent analysis. The output includes energy profiles at various hierarchical levels within the factory and the identification of the production related components of energy within the overall factory energy consumption. The process identifies gaps within factory energy performance which sets direction for improvements and allows this data to be used for future project improvement evaluations and implementations. Underlying this study and analysis is a focus on using measurement data, risk and cost benefit consideration. It also considers the organisational management structure and workforce knowledge to understand and deliver energy improvement opportunities.

3.1. Energy and resource assessment

The purpose of this phase is to formally identify and collate the energy (E_{tot}) categories consumed within the factory of study as considered in equation (1).

$$E_{tot} = E_g + E_r + \ldots + E_n \tag{1}$$

where,

E_g = power from the grid network.

E_r = power from the grid through renewable sources.

A system level map as shown in equation (2) can then be generated comprehending the main system level users of E_{tot} such that

$$E_{tot} = S_{prod\ line}, S_{env\ control}, S_{Chilled\ water}, \ldots, S_n \tag{2}$$

The approach allows for the identification of the highest energy consuming systems and in particular how significant the production energy ($S_{prod\ line}$) is within factory consumption. A baseline characteristic of energy consumption is recorded and monetised which can be used to engage factory support. This data drives a sense of urgency to support the assembly of appropriate skills to support further characterisation and improvement efforts as argued by Kotter (2006) in his assessment of 'Why Transformation Efforts Fail' where the author cites management engagement and empowerment to act as key to change initiatives.

3.2. Factory energy and resource mapping

The purpose of this phase is to understand consumption behaviour of targeted manufacturing chains. This involves generating an overall consumption map of how the selected energy category is being 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 ($T_1 \ldots T_n$) outlined in equation (3).

$$S_{prod\ line} = T_1 + T_2 + T_3 + \ldots + T_n \tag{3}$$

where T_{1-n} = Tools 1 to n in the production line.

This allows an energy consumption profile to be created using equation (4) such that

$$E_{prod\ line} = E(T_1)_m + E(T_2)_m + E(T_3)_m + \ldots + E(T_n)_m. \tag{4}$$

where $E(T_1)_m$ is metered performance for individual discrete production tool T_1.

Equation (5) considers this metered performance

$$E(T_n) = E_p + E_{np} \tag{5}$$

where, E_P = energy consumption in a productive state and E_{NP} = energy consumed in a non productive state.

This approach will highlight potential relationships between manufacturing states and energy consumption within the manufacturing process chain, $S_{prod\ line}$.

3.3. Production equipment opportunity identification

In order to facilitate a deeper level of understanding on how energy is consumed within these users ($T_1 \ldots T_n$), equipment energy maps with principle components or modules identified ($c_1 \ldots c_n$) are developed using equation (6) such that;

$$T_n = c_1 + c_2 + c_3 + \ldots + c_n \tag{6}$$

where, c = Tool module or subcomponent 1 to n.

This can be carried out through metering (m) each component or module of interest. This allows an understanding of how energy

is consumed within the identified equipment: $E(T_1)_m$ as shown in equation (7) where,

$$E(T_1)_m = E(c_1) + E(c_2) + E(c_3) + \ldots + E(c_n) \tag{7}$$

The results in a complete energy profile defined for particular usage mode(s) of operation (P or NP) for both productive and nonproductive states on identified discrete production equipment.

3.4. Risk and cost benefit analysis

This phase focuses on comprehending targeted production equipment and its ability to be optimised with respect to energy consumption. Risk to equipment functionality is considered. A FMEA process supports risk identification in terms of tool and component behaviour. From this exercise a future state energy consumption profile reflected in equation (8) can be generated $E_f(T_1)_m$, such that

$$E_f(T_1)_m = E_f(c_1) + E_f(c_2) + E_f(c_3) + \ldots + E_f(c_n) \tag{8}$$

If current equipment capability cannot realise $E_f(T_1)_m$, the Net Present Value (NPV) tool in equation (9) can be used to appraise the time value of capital requirements necessary to achieve $E_f(T_1)_m$ where

$$NPV(i) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} \tag{9}$$

such that

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).

3.5. Pilot implementation

Due to potential impacts energy based change can have in terms of production line material for example scrap rate or loss of product functionality. An extended testing and characterisation period is required to validate targeted process performance. Detection of performance issues at the equipment level is prioritised to ensure minimal impact to production line operations. This will ensure integrated effects within a manufacturing process chain are comprehended.

3.6. Factory integration

The solution or control path decided upon can utilise three potential paths which reflect the legacy factory constraints;

- Automated solution: Either s/w or h/w changes.
- Semi-automated: Manufacturing run rules.
- Manual: GMP documentation.

4. Organisational capability

Due to the complexity of a modern factory and the output focus that drives factory based performance, improvement activities must show equivalency to current compliance performance and standards. Therefore, the impact of energy based improvements to Key Performance Indicators (KPIs) or Overall Equipment Effectiveness (OEE) metrics should be considered. This will allow organisations to objectively and proactively assess current metric capability to monitor potential changes in operational performance. This will ensure mitigation plans such as monitor changes

Table 1
Importance scale for KPI prioritisation.

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

or operational adjustments can be comprehended. Workforce experience of operations can support this understanding through assigning importance values to performance metrics such as availability (A_1), quality (A_2) and cost (A_3) which are critical to factory equipment performance. Pair wise comparisons can be performed between A_1, A_2, A_3 to assess how these indicators are prioritised (Saaty, 1987, 1994). This prioritisation reflects how work load and equipment indicators are managed to maintain these priorities. A scale used to assign a value is shown in Table 1.

This will result in normalised or prioritised values generated: B_1, B_2 and B_3 using equation (10). These values reflect an understanding of how a work force manages equipment performance in terms of factory KPIs. This highlights which KPIs must be considered in terms of subsequent testing of energy efficiency opportunities.

$$
\begin{array}{c}
\quad\quad A_1 \quad A_2 \quad A_3 \\
\begin{array}{c} A_1 \\ A_2 \\ A_3 \end{array}
\left[\begin{array}{ccc}
1 & a_{12} & a_{13} \\
1/a_{12} & 1 & a_{23} \\
1/a_{13} & 1/a_{23} & 1
\end{array} \right]
= \begin{array}{c} B_1 \\ B_2 \\ B_3 \end{array}
\end{array}
\quad\quad (10)
$$

Workforce access to historical factory KPI information can also support an assessment of KPI effectiveness in managing manufacturing process chains. For example, is a dip in manufacturing chain availability metric reflected in a change in tool availability? This assessment will involve understanding why a KPI was initially put in place and requirements at time of creation as factory conditions may have changed over time introducing a level of ineffectiveness. As a result, it is necessary to formally understand what value individual performance metrics deliver in terms of the production line performance. This can be achieved by reviewing each KPI in terms of the following categories; Likelihood (L), Detectability (D) and Severity (S). This will allow the workforce to understand in more detail the ability of individual performance metrics to monitor potential changes in tool performance. By engaging the workforce through their experience of historical performance, as previously undertaken, pair wise comparisons can be completed for the categories (L, D, S) outlined. This will allow the

development of an importance value (I) for each KPI. 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 can be seen in Table 2.

For both availability (A_1) and cost (A_3), pair wise comparisons are completed for both likelihood and severity as historically these metrics are extensively tracked within production environments resulting in highly detectable monitoring. Due to the high degree of variability that can occur in terms of quality performance (A_2), detectability is considered.

By considering monitoring capability, a more effective analysis in subsequent phases can be achieved. The interaction with the workforce up to this point has allowed their experience to support a formal review of a factory's priorities and what aspects of the KPIs are seen as valuable. This ensures a thorough understanding of a factories ability to engage in energy related projects within a production environment.

By using the projects selected from the output of the previous functionality evaluations, workforce experience can also be utilised to obtain an understanding how successful these projects will be in terms of impact to KPIs. A table of relevant values assigned through workforce experience is shown in Table 3.

For projects identified, for example Z_1 and Z_2, a value can be assigned by the workforce based on their experience, to the possibility a change in performance of selected KPIs (A_1, A_2, A_3) in terms of Likelihood (L), Detectability (D) and Severity (S). For example a

Table 3
Scoring chart for project(s) by workforce.

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
Normalised prioritisation values by KPI.

KPI	Project	L	D	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 2
Normalised prioritisation values by KPI.

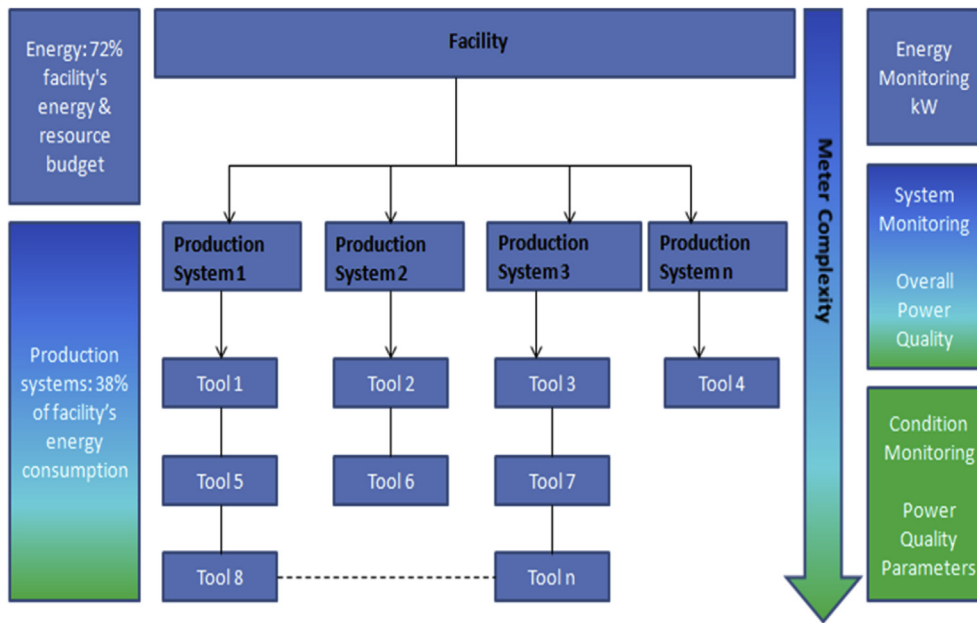| KPI	Likelihood (L)	Detectability (D)	Severity (S)
Availability (A_1)	I_{A1}^{L}		I_{A1}^{S}
Quality (A_2)	I_{A2}^{L}	I_{A2}^{D}	I_{A2}^{S}
Cost (A_3)	I_{A3}^{L}		I_{A3}^{S}

Fig. 3. Production system influence on energy consumption adopted from O'Driscoll and O'Donnell (2013).

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 is denoted as;

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

The values attributed by the workforce 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. Workforce knowledge of these issues is captured using FMEA templates and maintenance data bases reflecting historical equipment issues.

A capability score can then be calculated by project (Z_1), as shown in equation (11) which reflects a factory's ability to monitor and manage a change based on a company's priorities and capabilities.

$$\text{Project } Z_1 = \begin{bmatrix} B1\left(\left(L_{A1}^{Z1} \times I_{A1}^{L}\right) + \left(S_{A1}^{Z1} \times I_{A1}^{S}\right)\right) + \\ B2\left(\left(L_{A2}^{Z1} \times I_{A2}^{L}\right) + \left(D_{A2}^{Z1} \times I_{A2}^{D}\right) + \left(S_{A2}^{Z1} \times I_{A2}^{S}\right)\right) + \\ B3\left(\left(L_{A3}^{Z1} \times I_{A3}^{L}\right) + \left(S_{A3}^{Z1} \times I_{A3}^{S}\right)\right) \end{bmatrix}$$
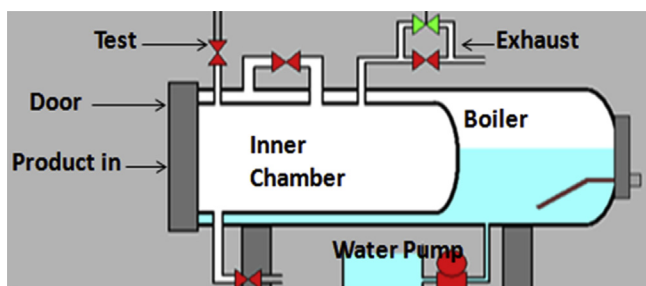
(11)

Fig. 4. Autoclave layout.

The capability score is a function of the collective experience of the workforce team which has 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 ten, 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 KPIs. 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 KPIs 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. For example, would they be detected and if so how severely could the issue impact production line KPIs. Detectability and severity 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.

5. Case study

A discrete manufacturing medical device facility supported an evaluation of the approach outlined previously. This facility operated five production lines on a continuous manufacturing basis. Within this facility, there is an ongoing continuous improvement culture in terms of reducing environmental impact through the adoption of ISO14001/50001 management systems and resource consumption reduction.

5.1. Energy and resource assessment

A detailed study of both energy and resource categories used within the manufacturing site was completed. This included mapping the significance of production system consumption through both in-situ metering and stand alone measurements as seen in Fig. 3. It involved using the factory BMS to get a profile of individual
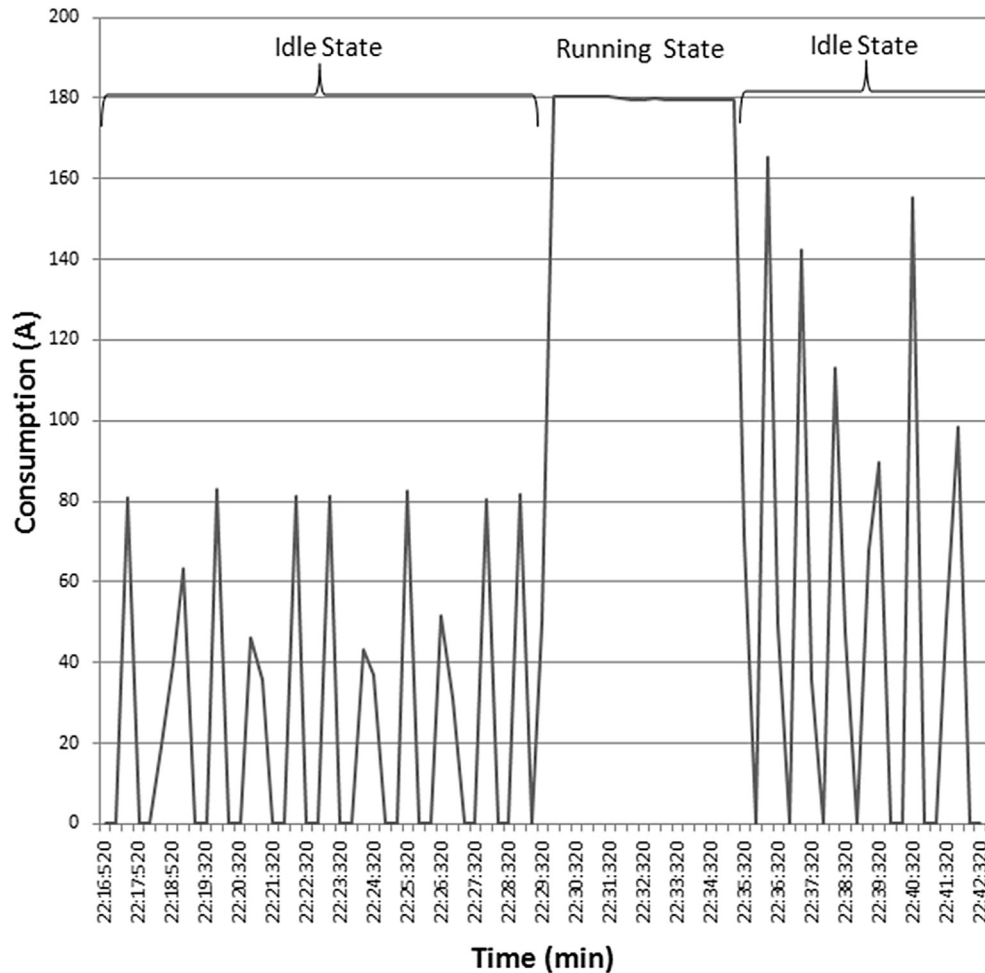
Fig. 5. Autoclave energy behaviour.

tool energy usage. A higher degree of sampling resolution was then undertaken manually using a fluke 1735 power logger at a sample rate of 1 s to study individual tool energy behaviour over a 2 day period. Due to the scale of the production system involved this resulted in a 6 month exercise to collect the appropriate individual tool characterisation data. This exercise was completed to ensure an accurate consumption baseline was collected to reference any potential improvement opportunities.

Fig. 3 demonstrates that the study highlighted the production system as being the predominant consumption category.

5.2. Factory energy and resource mapping

Within the production system, the significant energy user was targeted to understand consumption with respect to manufacturing states. This highlighted both running and idle state energy consumption of an autoclave system being the same, at 108 kW. The significance of idle energy consumption was reinforced through an annual utilisation rate of 20% highlighting an area for further characterisation.

5.3. Production equipment opportunity identification

The autoclave tool, outlined in Fig. 4, is designed to deliver reliable, repeatable and risk-free de-waxing of castings resulting from self steam regulation. It is an adiabatic process as there is no heat transfer into or out of the autoclave system. It is a constant volume process. Heat transfer within the boiler can be considered in the context of equation (12) below:

$$dQ = nC_v \ dT \tag{12}$$

where:
dQ = Quantity of heat flowing into the boiler.
n = moles of gas at temp T.
C_v = Molar heat capacity at constant volume.
dT = Temperature change.

It can be seen from Fig. 4 that the system has 2 chambers. The system itself generates steam within a boiler chamber under constant conditions of 453 K and 937 kPa. Product is exposed to these conditions during processing within the inner chamber.

Through undertaking a physical map of energy consuming devices with the tool, it was found that 95% of the electrical consumption of the system was due to heating elements. The energy characteristic resulting from the control cycle to handle the parts is shown in Fig. 5. It can be seen that the energy usage within the boiler chamber is constant irrespective of the presence of product.

5.4. Risk and cost benefit analysis

The operational KPI metrics identified; availability (A_1), quality (A_2) and cost (A_3) were prioritised using the workforce supporting
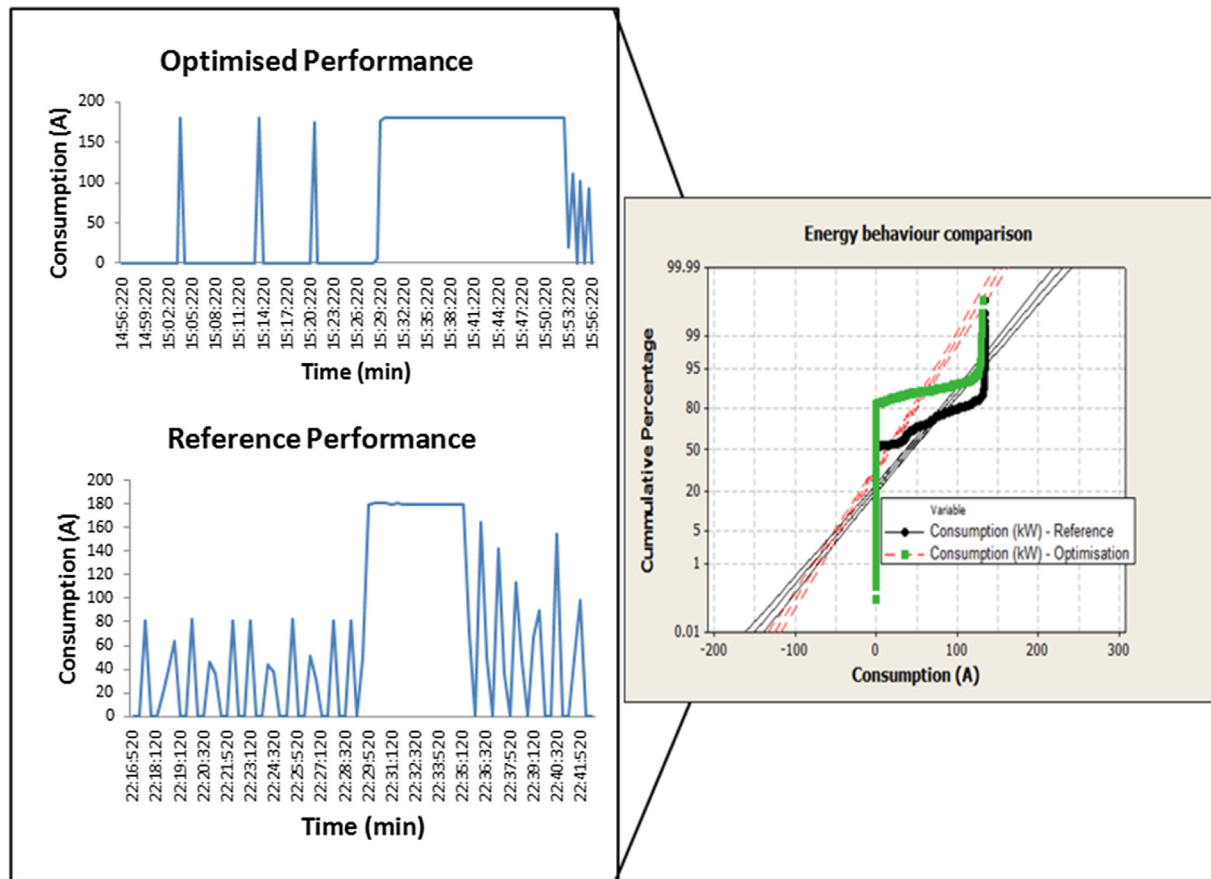
Fig. 6. Autoclave electrical behaviour over time.

autoclave operations. This highlighted availability as being the predominant priority with a normalised value of 70%, as outlined in Table 1 A.1. A critical recovery time of 600 s was identified through the prioritisation process which reflected the 'one of kind' single point of fail constraint that existed with the autoclave. Subsequent experimentation focused on characterising the impact of idle energy reduction and recovery times which highlighted an idle energy setting of 14 kW with a tool recovery time of 360 s, documented in Table 2 A.1.

In order to understand can the identified KPIs support appropriate data collection for energy based change, workforce experience was again used to assess KPI capability. This leverages their experience of historical factory KPI performance and determined that although availability, a KPI monitor was designed only to monitor severe changes with a weighting of 0.75, performance testing against the 600 s recovery would be a sufficient evaluation. The factory quality metrics were noted to be sensitive enough to support evaluating with a prioritised weighting of 0.73 as shown in Table 3 A.1. Workforce experience was again used to assess the probability of a successful implementation of both idle settings outlined in Table 4 A.1 using their knowledge of the production line. A capability score was then calculated highlighting the idle setting of 690 kPa as being optimal in terms of energy savings on tool recovery, as documented in Table 5 A.1. Both hardware and software upgrade options were assessed to realise the savings identified with both demonstrating favourable payback period of less than one year as noted in Table 6 A.1.

5.5. Pilot implementation & factory integration

A pilot test was completed utilising the optimised idle energy setting confirming a 51% reduction in idle energy consumption. The pilot was completed to verify repeatability of performance with predictable recovery. Fig. 6 highlights the electrical behaviour of reference and optimised performance completed to verify previous experimental results as well as cumulative performance over time.

A review of potential solution paths was completed to evaluate the most appropriate avenue to ensure a controlled solution was identified. These included

- Automated solution: PLC enabled optimised pressure setting.
- Semi-automated solution: Manufacturing defined event allow optimisation.
- Manual checklist: Documented procedure to activate solution.

The integrated solution identified and implemented was the automated solution path which avoided any human factor dependence. This involved PLC modification to allow the integration of the optimised idle setting into the autoclaves operational control logic.

6. Discussion

The approach and the evidence from the test case demonstrated the significance of production systems on factory energy consumption. The structure outlined allows engagement with the

appropriate skill sets within an organisation that can influence energy usage at a manufacturing level. This was necessary as the factory BMS used a sample rate of 15 min to collect energy data. In order to ensure an appropriate consumption baseline at an individual tool level, data was collected a 1 s sample rate. This resulted in an extensive collection period which was a highly manual exercise. This however did identify appropriate discrete production equipment to be targeted for optimisation and experimentation. The use of energy mapping allowed an initial understanding of the energy behaviour through defined manufacturing states namely production and idle states and is in agreement with existing literature highlighted in Sections 1 and 2. The benefit to the organisation was an enhanced understanding of energy consumption within their operations. By focussing on non-value added manufacturing states such as idle, the approach allowed production personnel the opportunity to understand how energy improvements can be delivered without impacting manufacturing operations. The reduction opportunity identified within the test case was comparable to similar literature studies found however there was limited data available due to the I/P sensitivities of industrial data.

7. Conclusions

The method outlined demonstrates an approach to understanding an organisations capability to support energy based change and the need to consider the appropriate risks to operations. By leveraging workforce knowledge of factory systems such as FMEA's and maintenance databases, a capability score can then be developed which assesses this ability. This informs the organisation of its ability to manage an energy based change through its factory. The study documented highlights the significance of production systems in terms of energy consumption. As manufacturing systems become more complex this research suggests a path to supporting energy savings and comprehending impacts to operational performance. As manufacturing complexity grows, it will be necessary to consider optimal metering strategies for production lines in terms of infrastructure and sampling to ensure effective decision making when comprehending operational impacts. This also has implications for equipment design in terms of energy efficiencies and reinforces the need for ongoing work in these areas.

Acknowledgements

Appendix 1

Table 1
Normalised values reflecting priorities of area.

KPI	Prioritisation
Availability	0.7
Quality	0.2
Cost	0.1

Table 2
Experimental summary of idle settings investigated.

Experiment	Pressure setting (kPa)	Mean power (kW)	Recovery time (secs)
Reference	937	27	0
Exp#1 (Z_1)	690	14	360
Exp#2 (Z_2)	551	7	767

Table 3
Normalised values reflecting KPI attribute importance to the workforce.

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

Table 4
Workforce input on ability on monitor autoclave energy projects.

Variable	Project	Likelihood	Detectability	Severity
Availability	Idle Setting at 690	8		8
	Idle Setting at 551	3		3
Quality	Idle Setting at 690	8	8	8
	Idle Setting at 551	8	8	8
Cost	Idle Setting at 690	9		9
	Idle Setting at 551	9		9

Table 5
Project capability scores.

Project	Capability
Idle Setting at 690	8.1
Idle Setting at 551	4.6

Table 6
Install price and cost benefit of upgrades.

Option	Upgrade	Install price (€)	NPV (€)
1	HMI upgrade	10,000	58,635
2	Switch installation	5000	88,635

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