**Low energy production impact on lean flow**

**Dr Peter Ball**

Manufacturing & Materials Department, Cranfield University, Cranfield, UK

p.d.ball@cranfield.ac.uk, +44 1234 750111

**Structured abstract**

*Purpose* - Rising energy costs and potential scarcity are driving energy reduction initiatives in manufacturing companies. The reduction in energy use is complementary to the classic lean production philosophy and the lean and green literature implies that reducing energy waste supports lean objectives. The purpose of this paper is to examine this perceived positive correlation and identify the impact level of energy reduction of lean product flow.

*Design/methodology/approach* - To achieve this, published case studies and practices from interview were gathered and categorised against a waste management hierarchy.

*Findings* - Energy reduction activities implicitly reduce waste which is compatible with the lean waste objective, however, when applying the waste hierarchy principle to energy efficiency practice, lean product flow is progressively constrained or compromised towards the lower levels of the hierarchy.

*Research limitations/implications* - The hierarchical classification seeks to communicate how reported energy efficiency improvements will/will not impact on flow. The research focuses on the modification of existing discrete part production facilities towards greater energy efficiency and neglects alternative production technologies and new build. The results suggest that as manufacturers seeking to be more energy efficient move away from preventative actions to more reduce and reuse actions then production flexibility could become restricted and the design of production facilities make re-think the fast, linear and short flow of product.

*Practical implications -* Examples of industrial practices are provided to show the implications of energy reduction practice on production flow.

*Originality/value* - Categorises the relationship between classic lean and industrial low energy initiatives to provide insight to how higher energy cost could impact on production.

**Keywords**: sustainable manufacture, lean flow, green, low energy production, waste hierarchy

**Article classification**: research paper

**Introduction**

Over many decades more of manufacturing industry worldwide has adopted the principles of the Toyota Production System (TPS) initially through the adoption of Just in Time (JIT) principles and latterly under the umbrella of lean production. The adoption of lean has enabled companies to focus on timely delivery of quality product to the customer with low waste. Setting aside subtle differences in emphasis, the adoption of such principles provides better value to the customer through faster, more flexible flow of product using smaller batches and therefore overall lower inventory.

Attention is now increasingly being given to the environment and how manufacturing can be more sustainable (Jovane *et al.*, 2008) through reducing the use of all resources, not just material resources, so that the current generations do not exceed the ‘carrying capacity’ of the earth. Sustainable manufacturing considers the entire material cycle from material extraction to subsequent disposal beyond the boundaries of a single factory (O’Brien, 1999). Developments have included the switch to more environmentally benign materials, using less material, reusing waste and avoiding harmful emissions. Industry has grown used to energy being cheap over several generations (O’Callaghan & Probert, 1977) and there is now the recognition that the economic design factors for production systems need to be revisited (Karnouskos *et al*., 2009). Pressures to undertake such activities have been driven by economics such as material and energy cost, regulatory requirements and incentives as well as social and consumer pressures. The drive to use less resource is implicitly compatible with lean production.

Energy efficiency activities are increasingly common due to cost and external pressures. Significant benefits from an environmental focus have been shown (Schönsleben *et al.*, 2010), for example Toyota Motor Europe has achieved a 40% reduction in energy per vehicle in recent years (Toyota, 2011). Such work on reducing energy will not only result in lower costs to a business but could also reduce the impact of any punitive or restrictive measures that may be introduced through legislation. These reductions can be achieved through upgrading to more efficient capital equipment or by better management of the existing equipment.

Energy is one of many resource flows in a manufacturing business (Ball *et al.*, 2009). Energy flow and reduction has received less attention compared to production flow and inventory reduction. This has been due to a number of factors including: low cost, perceived free-issue in production where areas are not accountable for use, lack of measurement, lack of accountability as well as the absence of obvious visual clues to its provision and then disposal of the waste heat that results. Activities to reduce energy consumption are inherently compatible with the lean focus on waste reduction. When examining the flow principle of lean and applying it to energy, potential savings could be made by looking not just at the point of consumption of energy but at its lifecycle, for example waste heat from one process could be reused elsewhere.

The wider view of energy can present challenges as this could conflict with production flow, for example better management of an oven could result in more efficient operation but not necessarily maintain smooth flow. The lean literature contains a wealth of examples of improvements in flow and reduction in waste. There are fewer examples of compromises. For example, a fabrication shop which was struggling to reduce changeover times decided to increase batch size which resulted in higher inventory but enabled the adjoining assembly shop to operate without shortages and overall better factory level performance.

This paper examines the relationship between energy efficiency and its impact on production flow at factory level in discrete manufacturing. Cases are collected from literature, available databases and industry direct to collate activities being undertaken and, in particular, identify cases where compromises between energy efficiency and production flow are encountered. The waste management hierarchy (EC 2008) has the potential to categorise distinctly different ways of handling resource waste, whether in the form of materials or energy. Thus cases are collated against the waste hierarchy modified for energy and the implications of the findings on what improvements can be achieved and their impact is presented.

**Methodology**

This work seeks to uncover the relationship between energy and lean flow which have been extensively examined in isolation but significantly less work has been carried out considering both together. Examination of this aspect lends itself better to exploratory research and associated methods. Data was captured through a combination of literature search and industrial case (by interview). Whilst the search for energy efficiency actions and practices was neutral towards the impact on lean, particular emphasis during the analysis was given to those practices that could compromise lean flow and scheduling.

The unit of analysis is the factory. Scope is bounded by the factory fence to include the factory buildings as well as separate utilities. The focus is discrete part and product manufacture and the process plant that supports discrete production such as painting and surface treatment. The scope excludes continuous processes and any building or facility improvement that could not be linked to production impact such as building insulation or boiler upgrade. Resource flows to the factory were also out of scope. Whilst product flows in the supply chain between factories and may attract significant attention for improvement, energy efficiency opportunities are more significant within factories as both buildings and production equipment are the major energy consumers. Similarly resource flows to the factory were not considered such as the energy (e.g. fossil fuel or renewable), however, the impact of peak load restrictions was in scope.

The JIT, TPS and lean production literature (hereafter referred to collectively as lean) and the energy efficiency literature typically documents and generalises industrial practice rather than drives it. So whilst it is necessary to review academic literature in general, particular emphasis must be placed on retrieval of industrial cases. Academic databases including Scopus, Web of Science and Google Scholar were used for searching. Keywords used for the searches included sustainable + manufact\*, green + production, energy + efficiency, lean + green. The year of publication was not constrained. Tables of contents of journals such as Manufacturing Technology Management, Production Planning and Control, Journal of Cleaner Production and International Journal of Production Research were also browsed in an attempt to identify relevant papers not using the above keywords. The references within the relevant papers identified were also used. Of those papers identified, those included for further analysis had the detail of both the energy efficiency improvement and the context in the production system operation.

Secondary industrial case data is available at a general level in peer reviewed literature and global industry support databases. Support databases, commercial websites and trade journals were viewed to check that the peer reviewed publication lag was not significant, for example identifying industrial practices documented in trade journals that would take time to be identified, collated and published in the peer reviewed literature. Support organisation databases searched included the U.S. Department for Energy’s Energy Efficiency and Renewable Energy (EERE) and the EU’s Benchmarking and Energy management Schemes in SMEs (BESS). Selection of such repositories was based on the ability to gather detail on the industrial practice that would be absent from a corporate website of a manufacturer. This search was complemented by a database search of a sustainable manufacturing practices (Despeisse *et al.*, 2012) available to the author (containing many hundreds of sustainable manufacturing practices drawn recently from global public sources and primary data collection from mainly UK companies) for entries that contained reference to energy and production flow. Trade journals included the UK’s Institution of Engineering and Technology (IET) Engineering and Technology magazine and The Manufacturer magazine.

Primary industrial case data was sourced from western, mainly UK, manufacturers. Examples of energy efficiency projects were sought to ascertain if positive improvements to energy management resulted in positive lean production impacts. Convenience sampling was based on manufacturers known to be making significant advances in the area of energy reduction, either publically known or recommended through contacts. The companies can be categorised as Original Equipment Manufacturers (OEMs) or tier 1 suppliers in the aerospace, automotive, Fast Moving Consumer Goods (FMCG) and industrial equipment supply.

The data collected lends itself to textual analysis against an established framework. The analysis section justifies the adaption of the material waste management hierarchy into a simplified energy waste hierarchy to categorise the practices found and establish any relationship between energy efficiency and lean flow. Whilst energy efficiency activity could be generically described as waste reduction, specific attention was given to production flow impact. This resulted in a significant number of practices being discounted. The remaining practices were used in the categorisation but, given the low number, no attempt was made to apply any numerical analysis and infer meaning from it, e.g. comparing the number of prevention practices compared to energy reduction practices. Similarly, because of the difficulties of establishing robust benchmarking metrics, no attempt was made to compare the financial benefit of practices. The practice implemented could be financially quantified but comparison would have been difficult and would not have provided valuable insight for generalisation.

The categorisation of efficiency practices is reviewed both specifically for the information contained as well as the implications. The practices are gathered from industry and most explicitly state cost benefit. Of particular interest is the impact of the practices on lean production, both in terms of the product flow as well as the waste reduction, where waste includes the classic lean view of waste as well as resources generally so as to include energy.

**Literature**

*Lean production*

Just-in-time (JIT) (Monden, 1983), where production is synchronised with customer demand, and later lean production (Womack *et al.*, 1990) have received significant attention in literature and practice. Implementations are pervasive and the quoted benefits to cost, quality and delivery are significant. Toyota is the classically quoted implementer of flow principles that lean is based on and many other companies have their own adaptations of their production system. The approach is sharply different from work on technology and earlier work on time study that focused on improving the value-adding activities rather than the overall ‘lifecycle’ of the product through the factory. The focus of lean is to deliver value to the customer by focusing on flow of product and information thereby removing waste (Womack & Jones, 2005). Whilst some define lean as primarily about waste, lean is taken here as encompassing flow due to the lesser use of terms like flow and pull alone in the literature and the manufacturing community.

A reduction in waste can lead directly to cost savings and in turn “bottom line” cash savings. The classic seven wastes (muda) of transport, inventory, motion, waiting, over production, over processing and defects (Ohno, 1988) provide focus on what may detract from the value adding activities of an enterprise. These wastes can be identified and tackled using a range of tools such as value stream mapping (VSM) and cause and effect (Ishikawa) diagrams (Bicheno, 2000). Such analysis can lead to faster movement of stock from location to location, shorter changeover times and fewer defects. Whilst the list of wastes has been extended (e.g. to include human talent) it is widely interpreted as wastes relating to the primary materials and does not include waste of other resources such as energy and water.

Flow is a central principle of lean. Ideals of single piece flow and kanban control systems contribute to flowing product to customer quickly on demand. Production systems can be designed for small batch size from the outset or can be modified to reduce batch size. The Single Minute Exchange of Dies (SMED) implementation process reduces the change over time from one product to another thereby allowing cost effective reduction in batch size that permits smoother flow. The trade-off between batch size and change over time is commonplace (Monden, 1994) and idealised one piece continuous flow is rare to achieve. The trade-off in flow is typically a balance between cost and delivery. There is little literature or anecdotal evidence of companies compromising flow once a certain level has been achieved.

It is argued that lean is one of the key enablers for business sustainability (Thomas *et al.*, 2012). Whilst lean production have provided significant benefit by moving from optimising point technology to examining the overall flow in a system, from an environmental sustainability perspective they address a narrow area and do not cover all resource flows from a lifecycle perspective.

*Energy efficiency*

Gas, oil and electricity are key forms of industrial energy and significant quantities are consumed, e.g. 27% of UK grid electricity was supplied to industry in 2010 (DUKES, 2011). With most energy supply being derived from finite resources and predicted long term cost inflation there is a significant amount of interest in energy efficiency. International research initiatives include CO2PE (2012), industry support groups include UK’s Carbon Trust (2012) and ES KTN (2012) and many corporate websites cite significant energy reduction.

Descriptions of energy efficiency practices are numerous in the literature and in available public repositories, especially those that relate to technology change, for example using more efficient compressors (EERE 2012a), recovering steam concentrate (El-Haggar, 2007) or using more energy efficient technology (Seliger, 2007). Improvements may, however, come from how the technology is used through effective maintenance such as repairing leaks in air systems (EERE 2012a) or energy management techniques such as reducing load during non-productive periods (Herrmann *et al*., 2008a).

The risk of significant rises in energy cost over the long term is widely acknowledged, leading to higher costs in industry which in turn drive activities to reduce energy consumption and therefore cost. Energy has always been a cost to a business, but it has not always been recognised as a direct cost in production. It is commonplace for energy to be seen as free issue, on demand resource at a local level in batch and flow environments. In continuous environments it is more common to see shop floor reporting and targets expressing energy consumption as a proportion of product produced. Facilities staff and production staff typically are grouped separately (Melnyk *et al.*, 2001) and their behaviour is guided by different performance metrics. Barriers (Murillo-Luna *et al.*, 2011) can therefore arise in the move towards lower energy production. Perhaps because energy for production is provided by the supporting facilities function it is seen as a “supplier” responsibility rather than the user responsibility whose focus is to deliver product on time.

There are some important characteristics of energy to be noted once it has been converted from its primary form (e.g. gas). After conversion to another form it becomes difficult to capture, store and reuse. Additionally it can be released to the environment safely and unseen (e.g. heat or pressure release). Some forms of contained energy can be temporarily buffered (e.g. compressed air or steam) but almost all will eventually result in the form of heat that is not easy to retain or reuse due to issues of location, quality and timing. Given the technical challenges of controlling and storing energy it may be preferable to balance energy efficiency with others aspects of a factory, such as production flow.

*Production system design*

The design of discrete part production systems has traditionally been based around production system metrics such as cost, quality, flexibility, time, dependability and customer satisfaction (Skinner, 1969, Wheelwright 1984). Improvement approaches are little different. The dominant basis for improvement and design approaches such as continuous improvement (or Kaizen), design of a factory with a future (Black, 1991), Toyota Production System (Monden, 1994) and manufacturing system design (Parnaby, 1986) were developed at a time when energy cost was small compared to material and other costs. As energy costs rise, companies will make changes to reduce those energy costs through actions such as switching off equipment when not in use or installing more efficient devices. There is little systematic guidance to improve the design of a discrete production system accounting for energy use.

It may seem counter-intuitive that production systems design for best product flow may not be designed for best energy consumption as smoothing flow will smooth utilisation of capacity and therefore should remove peaks in energy demand through continuous operation. However, smoothing utilisation does not mean maximising utilisation, especially with older production systems that are not sized according to current demand. A furnace may be running to allow smooth flow of product but this may not be at continuous maximum output and therefore maximum efficiency. The same may be true for clean rooms or whole production lines. Analogous to the SMED example earlier, there is a trade off between cost of running time and the cost of storage through down time. It is possible that making production “lumpier” through batching could reduce energy cost which may or may not in turn impact on production timeliness or volume. The trade off between energy use with the waste of inventory or the waste of waiting could be considered; however, most published examples of energy improvements do not compromise production performance. For example, layout and technology modifications are addressed by Deif (2011) with the explicit intention not to affect production.

*Lean and green*

Traditional lean methods and tools have been extended to green manufacturing. Bergmiller & McCright (2009) carried out research to ascertain if there was a correlation between those manufacturers recognised for their lean practices and a natural move towards greater environmental progress. They established a clear correlation across a number of green factors such as process design and waste segregation. Herrmann *et al* (2008b) highlight coherences and conflicts of lean production and environment. They align lean wastes to environmental wastes and, whilst generally non-specific on trade-offs, they cite the compromises such as between environmental impact and delivery frequency. Through their simulation modelling of lean implementation they present results that show higher quality assurance, andon and pull frequency resulting in potentially slightly higher direct energy (machines, transport, quality) consumption. Miller *et al* (2010) also use modelling to examine lean and sustainable manufacturing objectives in several industrial cases concluding that lean implementations result in green transformations too.

More in depth studies between lean and green uncover a generally positive correlation (e.g. Hajmohammad *et al.*, 2013) but present a more complex picture. King & Lenox (2001) examine lean and environmental performance through analysis of publicly available data on US firms. They established a positive correlation between lean and environmental performance with respect to reduction in waste at source, however, lean companies still engage in end-of-pipe solutions to reduce the environmental impact of emissions by focusing on the treatment of emissions rather than the cause of emissions. They initially cite examples where lean practices such as changeovers may result in more waste due to the use of cleaning and the disposal of unwanted material but their data is too coarse to provide further insight. Rothenberg *et al* (2001) use survey and interview to gain insight into the relationship between lean, green and environmental performance. They found positive correlations between lean areas of inventory, work systems and people, and environmental performance. Additionally lean adoption and energy conservation are positively correlated. They also identified areas of trade-off where leaner companies could have poorer environmental performance due to focus on longer term avoidance rather than expensive end-of-pipe abatement solutions. On examining energy, examples of switching off equipment and substituting for more efficient equipment were cited.

These views of industry show positive links between lean and green, they show potential trade-offs between lean and environment but not lean flow and energy consumption. Florida (1996) used survey and interview to understand the link between lean and green. He found a clear positive link between work to improve manufacturing processes and increased productivity on opportunities for environmental improvement. It was acknowledged by respondents that the environmental benefit was frequently an unintended consequence of the wider efforts, so whilst lean may benefit green the reverse of this was not examined. Yang *et al* (2011) again used large samples to understand the relationship between lean and environmental practices and how these impact on performance. A strong correlation was found between lean and environmental practices through the reduction in wastes. Overall, at the level of survey and analysis of firm performance through available public data there is general agreement that lean (waste reduction practices in particular) positively impact on environmental practices, however, the reverse of environmental practices on lean, and particularly flow, is absent from the literature. Dües *et al* (2013) consider the compatibility of lean and green and map out the differences and similarities between the two with a particular reference to wastes.

More focused work on energy and lean suggests lean approaches only lead to energy improvements if energy is specifically targeted. Seryak *et al* (2006) show the effect of lean on energy and interestingly argue that lean promotes more effective use of capacity but as overall capacity remains the same then energy use may stay the same. Heilala *et al* (2008) combine the traditional view of economics based manufacturing system design with ecological objectives. Their simulation based SIMTER tool models factors such as utilisation, peak load, queuing, storage and material handling to examine different layouts, however, it is non-specific on the resulting impact on performance or lean objectives. Whilst they do not address lean flow principles explicitly they examine load shifting to avoid peaks to reduce energy purchase cost. Load shifting is also addressed by Solding & Thollander (2006) who demonstrate the change in energy consumption according to the changes in production plan by scheduling to reduce peaks without reducing output. This is also addressed by buildings services, production flow and production management simulation modelling software from Hesselbach *et al* (2008) who also consider flow lot sizing and physical flow and non-specific lean production principles.

The literature shows there is significant emphasis on the positive correlation between lean production and energy efficiency, either because lean improvements reduce waste and hence energy or because energy reduction aligns to the lean principle of reducing waste. Trade-offs are raised in the literature with lean are typically associated with environmental effects (polluting emissions). The emphasis is on value through flow of the product with significantly less attention given to the enabling resource flow such as energy.

**Impact of low energy on production flow and scheduling**

*Use of waste hierarchies for analysis*

The link between lean production and environmental and sustainable manufacturing actions is generally a positive one, with exceptions related to end-of-pipe abatement requiring additional resources to minimise emissions. The examples generally given for energy reduction support the principle of lean waste reduction and in turn flow. However, many of the common examples for energy reduction are focused on avoidance actions such as switching off equipment when not required (e.g. Herrmann *et al.*, 2008a) or replacing equipment for more energy efficient types (EERE, 2012b). Energy reduction actions that go beyond housekeeping and upgrades are not commonly cited despite having significant potential, for example batching energy intensive operations or synchronised production schedules to minimise net energy consumption.

The waste management hierarchy (EC 2008) is a well understood and well used concept for categorising waste management strategies (see Figure 1a). The waste hierarchy is typically depicted as a pyramid containing a number of levels. These levels progress from most favoured to least favoured strategies of prevent, reduce, reuse, recycle, recover (energy) and dispose. This categorisation implicitly refers to materials (product, packing, etc) resources rather than energy resources. The hierarchy can be adapted to focus on energy (see Figure 1b) with strategies that include prevent, reduce, reuse and dispose. There are few published energy hierarchies of this type, although Toyota has made presentations referring to this type of hierarchy. For example, waste heat from one process can be harvested for *reuse* to provide pre-heating for another process or could be *disposed* by expelling to atmosphere. The hierarchy is similar to that of Lunt & Levers (2011) with slight differences, e.g. that the disposal step relates more to the removal of equipment rather than to the removal of energy itself.



Figure 1 Waste management hierarchies for (a) materials and (b) energy

An alternative approach would have been to use Total Productive Maintenance (TPM) (Jones & Rich, 2001) which would take a loss related view and is a foundation on which many companies build their improvement work. This could address the area of efficient energy and material utilisation (or energy productivity), such as production start up and production running. Another choice could also be the classic seven wastes identified earlier. Some of those wastes can be directly related to energy such as over-processing, waiting or defects, however, many do not have significant impact or relevance such as motion or inventory. The waste hierarchy was the favoured option for examination of the practices observed as it was considered a more generic view of energy as a resource, it is a widely accepted robust categorisation of physical resource and this phase of the work was concerned with categorisation rather than deployment.

A distinction could be made between reuse and recycle depending on whether the energy medium is used directly or changes form. Waste hierarchies are helpful in categorising changes to resource use within an existing system. Hence, neglecting the less common design of new production systems, an energy waste hierarchy can be used to categorise energy reduction actions in an existing production system and relate them to lean production impact.

Changes to energy use could include:

* Equipment level: reducing energy input through energy efficiency
* Process level: maintaining flow of product to reduce energy loss between processes
* System level: reducing loss at system level by reusing outputs from one process as an input to another.

Many of the examples in the public domain fall in the first category above. The latter categories give emphasis to the lifecycle of energy rather than local use. Focus on the energy lifecycle has potential to impact on other lifecycles, namely production flow.

*Sourcing energy waste management examples from practice*

The data collected, as described in the methodology, was aligned to major categories of the waste hierarchy (prevent, reduce, etc). Analysis of the data sought to discover if there were practices that had a negative impact on product flow rather than derive statistical observations on the popularity of particular activities or the proportion which had positive effects. Energy efficiency activities that had no impact on production flow or improved production flow were included. Actions were developed to describe the sub-categories of the waste hierarchy based on the data collected. For example, prevent has sub-categories of permanent prevention by decommissioning or temporary prevention by hibernation. Where possible, the primary data collated was reviewed by practitioners to verify the categorisations. It was noted that changes aligning to higher levels of the waste hierarchy tended to be operational whilst changes to the lower levels tended to require equipment modification. The collated data is shown in Table 1. The table entries are ordered first according to the waste hierarchy strategies and then by actions of increasing impact on flow within each strategy. Whilst the database and primary data analysis generated numerous examples, only one instance of each type was included and no attempt was made to quantify frequency of citation.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Hierarchy** | **Action** | **Effect on flow & schedule** | **Effect on energy** | **Examples** |
| Operational | Prevent | Switch off | None | Use only when required | Switch off equipment at end of shift |
| Prevent | Hibernation | Processes not available on demand | Conserve energy  | CNC machines e-stop during shiftClean room air handling reduction at night |
| Prevent | Decommission | Concentrate flow in less processes (higher utilisation) | Concentrate energy in processes (and building space) | Production line improvement enabled decommission of another with same output, less energy |
| Reduce | Smooth (facilities) energy demand | None. Offset operational plan (same production plan) | More efficient energy production | Phased facilities start up to reduce peaks with no production impact/more integrated facilities operations plan |
| Reduce | Reduce users | None | Lower energy cost | Reduce number of active users (lights, pumps, etc) |
| Reduce | Change set points | None | Lower energy cost | Relax tolerances on temperature, etc. settings without impacting on product quality |
| Reduce | Change technology | None | Lower energy cost | Replace drives for more efficient onesUse lower cost drying techniques |
| Reduce | Cluster batches | Increase (short term) utilisation, lumpier flow | Minimum losses between production runs / enable processes to run closer to design loads (efficiency) | Batching and sequencing Scheduling for smoothing |
| Reduce | Increase utilisation | Dependent on capacity management policy | Lower energy per unit of production | Higher output: Utilisation of spare capacity for sub-contractSame output: Slow rate to lower oven operating temperatures |
| Reduce | Smooth (production) energy demand | Delays production until energy available | More efficient energy production | Constant supply of steam, avoid peaks of demand from production |
| Reduce | Manage demand level | Schedule production according to external effect | Lower energy input | Avoid operations that require cooling at hottest part of day |
| Reduce | Manage demand timing  | Flexibility of production schedule | Lower energy cost through supplier efficiency | Energy intensive industries manage demand |
| Reduce | Change technology (consolidate)  | Greater sensitivity to machine breakdown | Reduces energy consumption for operations | Multiple operation machine replaces several single operation machines |
| Design | Reduce | Maintain product velocity | Flow driven by product push rather than demand pull | Reduce thermal loss from product | Faster transportation of hot (cold) product, e.g. minimise transport delay of ceramic tiles between operations |
| Reuse | Harvest energy direct | None | Production energy captured | Maximise use of product test, e.g. engine test generates electricity |
| Reuse | Harvest energy and reuse locally | Constraints in production schedule | Production energy captured and reused | One process waits on another to reuse its waste energy (intent) |
| Reuse | Integrate facilities and production  | Reduces flexibility as result of increased schedule dependency | Net reduction | Reuse of process heat for facility (e.g. to cleaning water)Reuse of facility heat for production processes |
| Reuse | Integrate energy intensive processes | Compromises physical product flow | Shorten path closed-loop energy flows | Production line design co-locates of energy intensive processes (intent) |
| Dispose | Environment used as sink | None | Vent heat to atmosphere | Passive ventilation of heat |
| Dispose | Environment as substitute | Slower/longer (move and/or store) | Less energy required for production | Cooling coatings via long conveyors. Slower curing.Cool to atmosphere |

Table 1. Categorisation of energy efficiency activities against the energy waste hierarchy that impact on product flow.

The examples here cover energy saving through to energy efficiency. They relate well to those found in the literature, such as greater use of a single line or the avoidance of peak loads and have been analysed using modelling techniques (Herrmann & Thiede, 2009). Additionally, Bunse *et al* (2010) support the examples on batch size and sequencing in their review of manufacturing execution systems for energy efficiency. Other authors cite the recovery of heat (e.g. Schönsleben *et al.*, 2010) or provide examples of dynamic scheduling to reduce net energy consumption including scheduling to avoid cooling operations at the hottest part of the day (e.g. Karnouskos *et al.*, 2009).

The results, obtained from the database as well as practice, contained more examples towards the top of the hierarchy. The higher level actions can be observed to be generally simpler and requiring less capital investment than those lower in the hierarchy. Within each level of the hierarchy there are actions that reduce energy without impacting on production. Such actions may be more readily recognisable compared to other actions listed and it is easier to find instances of these in public sources. However, this could be considered as overly simplistic as actions that could require relatively low levels of capital investment are not necessarily easy to implement, e.g. the prevent action of decommission would require significant work on flexibility, process capability and training to move production to new areas. Additionally, those actions towards the top of the hierarchy could be considered to be challenging in that cultural shifts in working practices may be required to ensure changes are maintained.

Those actions lower in the hierarchy have greater impact on production flow in terms of schedule flexibility due to schedule dependencies. The observation that the more radical actions lower in the hierarchy could constrain further development resonates with the observation of Lewis (2000) that those companies that pursue lean may constrain future innovation. Changes towards the top of the hierarchy can be seen as relating more towards short to medium term housekeeping by running current facilities better. Hence prevent and reduce actions align more to *operational* changes. Changes towards the bottom of the hierarchy allow less flexibility in production as changes incorporate capital investment that more closely couple (energy) resource flows, potentially slowing the flow of product or disrupting the linear flow.

Changes lower down in the hierarchy would be for the upgrade and redesign of existing facilities or only for new facilities in the case of the lowest actions. The reuse and dispose actions align more to *design* changes, however, there is a transition and overlap of *design* and *operational* changes around reduce actions. For the reuse actions, the word ‘harvest’ is used to describe energy reuse with the current layout whilst ‘integrate’ implies more significant changes to capital whilst still using the harvesting principle.

Against the tactics classification developed by Despeisse *et al.* (2012) (manage resource, manage technology, change resource, change technology), the practices found from published case studies appear to cluster in the area of the management of resources. Whilst there could be potential bias in the collection of practices from the databases, it appears that most of the impacts of energy on production flow fall into particular sub-categories of ‘mange resource’: aligning resource use with production schedules, optimising production schedules to improve efficiency and optimising resource input profile to improve efficiency. It was the latter that had most effect on production flow. These are operational rather than design or technology related changes. There were fewer published examples of practices that could be considered changing technology or changing resources.

**Discussion**

The results have shown a range of energy efficiency actions from industry from primary and secondary sources. The collection of data was open to any actions whether they had a positive, neutral or negative impact on lean production, in particular flow. The categorisation against the derived energy waste hierarchy drew all actions that could compromise product flow and included samples of other actions but did not seek to repeat the many examples available in the literature. The perspective adopted is that of production (the consumer) and generally excludes the generation source and the intermediary transformation.

The collation of actions showed that energy reduction actions in existing facilities can compromise lean flow and scheduling. Without specific reference to the contrary, it was assumed that all these industrial practices resulted in a cost benefit, hence companies would implement changes that could constrain flexibility to reduce cost. As expected, there were no cases reported where overall output was compromised. The impacts on material flow can be summarised as layout and timing related. For the layout impacts the ideal of the straight line or u-shaped production layout well documented in the lean literature may be changed to bring energy intensive processes closer to facilitate efficient reuse of waste energy of one process in another. For the timing related impacts the smooth, on-demand flow as pulled by the (internal) customer could become ‘lumpier’ and slower as parts and groups of parts are batched together to maximise machine efficiency or sequenced in a way that improves the opportunity for energy reuse or smoothes the demand for energy.

The data collection focused on production related energy consumption and ignored non-production energy consumption. General building services were ignored. Additionally production maintenance was ignored. For example, the use of teams rather than individuals to clean down individual painting booths is more efficient as the booth air handling is running for a shorter period but this is during planned downtime and does not impact on the production schedule. Another, commonly cited, example of maintenance is to reduce demand by ensuring correct operation such as repairing compressed air leaks. Whilst this could have been included in the analysis, the maintenance activities will have no production impact in general and therefore were ignored. Lastly the cost and benefit were not compared as the low sample size would not have allowed meaningful comparison of the return on investment against the position in the hierarchy.

The assumption within this work is that the factory operation was independent of external effects. It was assumed that material and energy are available on demand with no issues of intermittency even though costs could vary for high energy users. Additionally energy consumed by logistics operations was ignored and no consideration was given to ensuring full loads, changing delivery quantities and frequencies, etc. Finally, the sharing of material and energy wastes beyond the factory fence with other factories in the form of industrial symbiosis (Graedel & Allenby, 2010) was beyond the scope of the data collection.

Changes that would align to the top of the hierarchy are those that are favoured most and are commonly cited, for example, prevention of waste by turning off equipment when not needed or repairing leaks in compressed air systems. Housekeeping tasks such as these do not require new technologies (O’Callaghan & Probert, 1977). Examples of reduction strategies of sizing compressed air systems according to needs or replacing inefficient motors with more efficient ones do appear in the public domain and typically require capital spend (often with short payback). Available examples of strategies of reuse are far less common. The mapping shown in Table 1 of the changes to the operation of a production system to an energy waste hierarchy brings out generalised effects. The examples shown towards the top of the hierarchy are typically low cost, quick to implement and have a greater visual impact compared to examples lower down. Towards the lower part of the hierarchy the capital investments needed for change become more significant and tend to reduce flexibility.

There is an element of lock-in with the actions to achieve the lower strategies due to the need to achieve the return on investment and the implied physical restrictions that result; lower in the hierarchy the production system operation becomes more closely coupled. This could result in less linear flow to bring together energy intensive processes or slower as production is delayed to exploit energy reduction opportunities. Whether focusing on the lower level actions that result in production system design changes or the higher level operational changes there is the need to better understand the impacts through procedures and metrics. Overall there is a lack of guidance on how to address such improvement or design tasks. The mapping of practices against the waste hierarchy presents the results of changes and does not guide what change to make in the first place.

**Conclusion**

This paper sought to examine if the positive link between lean and green still holds for lean flow principle. Industrial practice was investigated to understand the link between lean production and green production, particularly on the impact of energy efficiency activities. Literature commonly cites the complementary nature of lean production on green or environmental improvements, particularly as energy and other resource reductions can be linked to the objective within lean to reduce waste. Given the strong likelihood of significantly higher energy costs as the demand for finite energy resources broadens, the challenge to make more significant energy reductions within production systems becomes greater.

The research gathered publicly available case data as well as primary data collection with manufacturers known to leaders in sustainable, environmentally friendly, green production. The data collection was categorised against a waste management hierarchy adapted to energy waste management. The analysis particularly focused on actions where there was an impact on both flow of energy and flow of product.

The analysis developed actions that showed a range of energy efficiency practices that varied according to the perceived ease of implementation and the investment required to implement. Some of the practices found could affect the production layout and production control that in turn compromise the existing product flow. There were instances of product flow being linked less to (internal) customer demand and more to other constraints such as the flow of other products or the availability of energy.

The work considered existing discrete production facilities and has potential to be extended to process industry as well as greenfield design. There is potential to explore actions which may favour CO2 reduction over economic metrics as well as whether manufacturers at the different stages of their sustainability journey favour energy efficiency actions at different levels of the waste hierarchy. Additionally there is scope to review the fast, short and linear flow production system design thinking that favours fast and efficient customer over minimising factory energy use.

**Acknowledgements**

The author would like to thank those manufacturers and individuals who contributed to the data referenced in this paper including: MD, SE, SH, AL, PL, SR, RW.

**References**

Ball, P.D., Evans, S., Levers, A. and Ellison, D. (2009), “Zero Carbon Manufacturing Facility – towards integrating material, energy and waste process flows”, *Proceedings of the IMechE Part B Journal of Engineering Manufacture*, Vol. 223 No. B9, pp. 1085-1096.

Bergmiller, G.G. and McCright, P.R. (2009), “Lean Manufacturers’ Transcendence to Green Manufacturing”, *Proceedings of the 2009 Industrial Engineering Research Conference,* 30 May - 3 June, Miami, FL.

Bicheno, J. (2000), *The Lean Toolbox*, 2nd ed., Picsie Books, Buckingham.

Black, J.T. (1991), *The Design of the Factory with a Future,* McGraw-Hill, New York.

Bunse, K., Vodicka, M., Schönsleben, P. , Brülhart, M. and Ernst, F.O. (2010), “Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature”, *Journal of Cleaner Production Volume*, Vol. 19 No. 6-7, pp. 667-679.

Carbon Trust (2012), *Carbon Trust*, http://www.carbontrust.co.uk (Accessed 17 December 2012)

CO2PE! (2012), *Cooperative Effort on Process Emissions in Manufacturing*, http://www.co2pe.org/ (Accessed 25 October 2012).

Deif, A.M. (2011), “A system model for green manufacturing”, *Journal of Cleaner Production,* Vol. 19 No. 14, pp. 1553-1559.

Despeisse, M., Mbaye, F., Ball, P.D. and Levers, A. (2012), “Emergence of sustainable manufacturing practices”, *Production Planning and Control*, Vol. 23 No. 5, pp. 354-376.

Dües, C.M., Tan, K.H. and Lim, M. (2013), “Green as the new lean: how to use Lean practices as a catalyst to greening your supply chain”, *Journal of Cleaner Production*, Vol. 40, pp. 93-100.

DUKES (2011), *Digest of UK Energy Statistics 2011*, Department for Energy and Climate Change, London, UK. ISBN 9780115155277.

EC (2008), “Directive 2008/98/EC of the European Parliament and of the Council on waste”, *Official Journal of the European Union*, L312/3.

EERE (2012a), *Compressed Air System Improvements Increase Production at a Tin Mill*, Energy Efficiency and Renewable Energy, U.S. Department of Energy (accessed 25 October 2012) http://www.compressedairchallenge.org/library/casestudies/weirtons.pdf.

EERE (2012b), *Case study – the challenge: Improving ventilation system energy efficiency in a textile plant*. Energy Efficiency and Renewable Energy, U.S. Department of Energy, Industrial Technologies Program, from http://www1.eere.energy.gov/manufacturing/tech\_deployment/case\_study\_ventilation\_textile.html (accessed 25 October 2012).

El-Haggar, S. (2007), *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable Development*, 1st ed, Elsevier Academic Press, Boston, USA.

ES KTN (2012), *Environmental Sustainability Knowledge Transfer Network*, https://connect.innovateuk.org/web/sustainabilityktn (accessed 17 December 2012).

Florida, R. (1996), “Lean and green: The move to environmentally conscious manufacturing”, *California Management Review*, Vol. 39 No. 1, pp. 80-105.

Graedel, T.E. and Allenby, B.R. (2010). *Industrial ecology and sustainable engineering*, Pearson Education, Upper Saddle River, NJ.

Hajmohammad, S., Vachon, S., Klassen, R.D. and Gavronski, I. (2013). "Lean management and supply management: their role in green practices and performance", *Journal of Cleaner Production*, Vol. 39, pp. 312-320.

Heilala, J., Vatanen, S., Montonen, J., Tonteri, H., Johansson, B., Stahre, J. and Lind, S. (2008), "Simulation-Based Sustainable Manufacturing System Design”, *Proceedings of the 2008 Winter Simulation Conference,* Miami, Florida, USA.

Herrmann, C. and Thiede, S. (2009), “Process chain simulation to foster energy efficiency in manufacturing”, *CIRP Journal of Manufacturing Science and Technology*, Vol. 1, No. 4, pp. 221–229.

Herrmann, C., Zein, A., Thiede, S., Bergmann, L. and Bock, R. (2008a), "Bringing sustainable manufacturing into practice: The machine tool case”, *Global Conference on Sustainable Product Development and Life Cycle Engineering*, Busan (Korea): p. 272.

Herrmann, C., Thiede, S., Stehr, J. and Bergmann, L. (2008b), "An Environmental Perspective on Lean Production”, *41th CIRP International Seminar on Manufacturing Systems*, Tokyo, Japan, pp. 83–88.

Hesselbach, J., Herrmann, C., Detzer, R., Martin, L., Thiede, S. and Ludemann, B. (2008), "Energy Efficiency through optimized coordination of production and technical building services”, *Proceedings LCE2008 - 15th CIRP International Conference on Life Cycle Engineering*, 17-19 March, The University of New South Wales, Sydney, pp. 624-628.

Jones, D.T. and Rich, N. (2001). *Total Productive Maintenance*, 2nd Ed, Liverpool Business Publishing, Wirral, UK.

Jovane, F., Yoshikawa, H., Alting, L., Boer, C.R., Westkamper, E., Williams, D., Tseng, M., Seliger, G. and Paci, A.M. (2008). “The incoming global technological and industrial revolution towards competitive sustainable manufacturing”, *CIRP Annals - Manufacturing Technology*, Vol. 57, No. 2, pp. 641–659

King, A.A. and Lenox, M.J. (2001). “Lean and Green? An empirical examination of the relationship between lean production and environmental performance”, *Production and Operations Management*, Vol. 10 No. 3, pp. 244-256.

Karnouskos, S., Colombo, A.W., Lastra, J.L.M. and Popescu, C. (2009). “Towards the energy efficient future factory Industrial Informatics”, *INDIN 7th IEEE International Conference,* pp. 367-371.

Lewis, M. (2000), “Lean production and sustainable competitive advantage”, *International Journal of Operations and Production Management*, Vol. 20 No. 8, pp. 959-978.

Lunt, P. and Levers, A. (2011), “Reducing Energy Use in Aircraft Component Manufacture - Applying Best Practice in Sustainable Manufacturing”, *SAE AeroTech Congress*. Warrendale, PA: SAE International.

Melnyk, S.A., Sroufe, R.P., Montabon, F.L. and Hinds, T.J. (2001), “Green MRP: Identifying the material and environmental impacts of production schedules”, *International Journal of Production Research*, Vol. 39 No. 8, pp. 1559-1573.

Miller, G., Pawloski, J. and Standridge, C. (2010), “A case study of lean, sustainable manufacturing”, *Journal of Industrial Engineering and Management*, Vol. 3 No. 1, pp. 11-32.

Monden, Y. (1983), *Toyota Production System: Practical approach to production management*, Industrial Engineering and Management Press, Norcross GA USA.

Monden, Y. (1994), *Toyota Production System: An Integrated Approach to Just-In-Time*, Chapman & Hall, London.

Murillo-Luna, J.L., Garcés-Ayerbe, C. and Rivera-Torres, P. (2011), “Barriers to the adoption of proactive environmental strategies”, *Journal of Cleaner Production*, Vol. 19 No. 13, pp. 1417-1425.

O’Brien, C. (1999), “Sustainable production – a new paradigm for the millennium”, *International Journal of Production Economics*, No. 60-61, pp. 1-7.

O’Callaghan P.W. and Probert, S.D. (1977), “Energy management”, *Applied Energy*, Vol. 3, No. 2, pp. 127–138.

Ohno, T. (1988), *Toyota Production System: Beyond large-scale production*, Productivity Press: Portland, Oregon, USA.

Parnaby, J. (1986), “The design of competitive manufacturing systems”, *International Journal of Technology Management*, Vol. 1 No. 3/4, pp. 385-396.

Rothenberg, S., Pil, F.K. and Maxwell, J. (2001), “Lean, green and the quest for superior environmental performance”, *Production and Operations Management*, Vol. 10, No. 3, pp. 228–243.

Schönsleben, P., Vodicka, M., Bunse, K. and Ernst, F.O. (2010), “The changing concept of sustainability and economic opportunities for energy-intensive industries”, *CIRP Annals - Manufacturing Technology*, Vol. 59 No. 1, pp. 477-480.

Seliger, G. (2007), *Sustainability in manufacturing: recovery of resources in product and material cycles*, Springer, Berlin.

Seryak, J., Epstein, G. and D’Antonio, M. (2006), “Lost Opportunities in Industrial Energy Efficiency: New Production, Lean Manufacturing and Lean Energy”, *Proceedings of the Twenty-Eighth Industrial Energy Technology Conference*, New Orleans, LA, 9-12 May.

Skinner, W. (1969), “Manufacturing – missing link in corporate strategy”, *Harvard Business Review*, Vol. 47 No. 3, pp. 136-145.

Solding, P. and Thollander, P. (2006), “Increased energy efficiency in a Swedish iron foundry through use of discrete event simulation”, *Proceedings of the 2006 Winter Simulation Conference*, pp. 1971-1976.

Thomas, A., Francis, M., John, E. and Davies, A. (2012), “Identifying the characteristics for achieving sustainable manufacturing companies”, *Journal of Manufacturing Technology Management*, Vol. 23 No. 4, pp. 426-440.

Toyota (2011), *Toyota European Sustainability Report 2011*. Toyota Motor Europe, Brussels.

Womack, J.P., Jones, D.T. and Roos, D. (1990), *The machine that change the world*. London, Simon & Schuster Ltd

Wheelwright, S.C. (1984), “Manufacturing Strategy: Defining the Missing Link”, *Strategic Management Journal,* Vol. 5, No. 1, pp. 77-91.

Womack, J.P. and Jones, D.T. (2005), *Lean solutions: how companies and customers can create value and wealth together*, Simon & Schuster, London.

Yang, M.G., Hong, P. and Modi, S.B. (2011), “Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing ﬁrms, *International Journal of Production Economics*, Vol. 129, No. 2, pp. 251-261.

**Biography**

Dr Peter Ball is a Reader in Manufacturing Operations in the Sustainable Manufacturing Systems Centre at Cranfield University.  As a mechanical engineering graduate he undertook a PhD in manufacturing simulation at Aston University before joining the University of Strathclyde as a lecturer.  Peter’s work focuses on manufacturing simulation and its support for manufacturing system design and sustainable manufacturing. Research projects have ranged from production improvement to systems implementation and from supply chain diagnostics to sustainable manufacturing. He is investigator for TSB/EPSRC THrough Life Energy and Resource Modelling (THERM) and the EPSRC Centre for Innovative Manufacturing (CIM) in Industrial Sustainability. He is a chartered member (CEng) of the Institution of Engineering and Technology (IET) and a Fellow of the Higher Education Academy (HEA). Peter is the Course Director for the MSc in Engineering and Management of Manufacturing Systems. He is also the academic lead for the Manufacturing & Materials Doctoral Training Centre (DTC).