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Developing a start-stop production system concept

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Abstract

Our cars have known energy efficiency. We take for granted they are efficient at different speeds, some are able to reuse energy and many have start-stop engine functionality. Critically they do not consume energy when they are not moving. This paper explores the challenges of working towards a start-stop production system concept. The base load energy and other resource consumption (whether during breaks or at night) are known to be a significant proportion of total consumption and attempts to reduce consumption span behavioural aspects through to technology limitations. The impact on switching off machines and supporting utilities has a major impact on the response time to starting full production as well as confidence in the quality that can be achieved. The situation is further compounded by the fact that most production systems are configured with technology that means running at less than full production rate has a serious impact on energy efficiency; there are rarely alternative energy efficient operating speeds.

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Keywords: start-stop production system; energy efficiency; energy value-add

1. Introduction

The need for industrial energy efficiency is well understood and many companies have made significant reductions in their resource use [1, 2]. It is not uncommon for companies engaging in energy efficiency initiatives to achieve double digit savings year on year [3]. Practices that companies have implemented include upgrading drives, upgrading lighting and managing compressed air systems better as well as switching off equipment when not needed and implementing more resource efficient production schedules [4]. Such changes can be technologically or organisationally driven. Often these eco-efficiency changes are within the boundaries of the current production system and factory system design and ultimately the improvements will be limiting.

More radical changes to production systems are required to make significant improvements. Changes could come from reusing energy within the factory or changing production technologies (e.g. moving from steam to direct gas and water in paint plants). Critically there is the need to challenge the fixed cost of production in which companies typically do not see a dramatic reduction in energy at end of production. The significant fixed component of energy consumption of factories affects not just the reduction at end of shift but also within shift whereby there is typically a loose relationship between energy consumed and product produced. The significant fixed energy use means the energy value-add varies according to production volume. Most factories become more efficient as production rises and lower production rates seriously impact on energy efficiency [5].

Research into resource efficiency has resulted in the development of the waste hierarchy [6], tools [7], technologies [8] and methodologies [9] to support industrial improvement. Examples include the use of monitoring [10] to guide operational improvements as well as modelling and simulation tools for examining the production system, the utilities and the surrounding factory building [11, 12]. The latter work at factory scale recognises the independencies and the multi-scale nature of the energy efficiency challenge. It has been observed that the energy spent on production processes is small compared to total energy spent [13]. All these developments enable energy efficiency to be tackled from both technical and organisational standpoints.

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Energy use in production will vary at different production rates [14, 15] and it is notable that the consumption is only weakly related to production with a significant amount of base load, fixed consumption. Whilst there has been some work to align consumption with output on specific technologies [16] and overall system performance [17] work is still needed to understand how whole factories can dramatically reduce energy consumption when production stops. Additionally, many of the barriers to energy reduction relate to organisational issues rather than technology alone [18]. Additionally, greater understanding of the correlation between energy efficiency and production volume is needed to work towards energy efficient production flexibility. Such developments would enable a move from eco-efficient to eco-effective factories.

The paper takes work from reviews from literature in the area of production systems and energy efficiency to assess key constraints that prevent us approaching the concept of the start-stop production system by categorising these constraints according to technology, organisation/people behaviours and overall system operation. Additionally, the work shows examples of industrial practice that could form building blocks of a fuller production system design. The paper concludes with an agenda for future research to address challenges to work towards significant factory energy reduction.

2. Methodology

This work seeks to uncover the technological and structural design features of production systems that enable point resource efficiency and global resource efficiency within a factory, in particular, the features relating to energy. Whilst the focus on energy could be seen as limiting, its relationship with all other resource flows such as use of water, use of compressed air, processing of materials, etc. means that the reduction in use of power will reduce other resource consumption (or identifying the use of power will challenge the use of other resources). Additionally, energy unlike many other resources it is difficult to store.

The work drew on peer reviewed and other literature on sustainable manufacturing, eco-efficiency, eco-factory and energy efficiency. The literature provided both the principles for the concept development as well as practices, good or otherwise. Through review, analogy and argument the beneficial features of eco-efficient factories are used to challenge current design and operational thinking. A set of requirements is developed around a start-stop production system concept. The requirements are grouped around technology, organisation/people and systems. As a result of the development of requirements a number of challenges arise are reviewed.

3. Concept development

Factory energy reduction is driven by multiple factors, especially cost and CO2 reduction. Factories can often have a weak link between energy consumption and production output due to the fixed overhead of supporting utilities, ancillary equipment, heating, lighting, etc. Additionally production systems have either not being designed with energy efficiency in mind or have been optimised at full output. By analogy, this contrasts with cars that have start-stop engine control so energy is not consumed at idle as well as gearing for efficiency at multiple speeds. The ability of production systems to ramp-up and ramp-down quickly as well as operate efficiently according to the actual production rate would mean that the energy consumption would be proportional to output rather than having a significant fixed element linked to factory opening hours.

There are subtle qualifiers to the analogy to be made here. Cars do need to be warm to take advantage of start-stop and there are distinct speeds for best efficiency so there is not a linear continuum. Hence factories would need both 'start-stop' and 'gearing' as thermal stability is required to achieve quality and production areas need to produce according to the customer demand efficiently.

This section has taken examples of industrial practice as components for extracting principles. Using theory, principles and practices from the literature for the components of technology and people consideration was made of how to achieve efficiency at factory system level. Using the themes of technology, people and systems identified earlier, the components were collated and these are presented in table 1. Each theme is now briefly described and then the following section then discusses the challenges to progress.

Table 1. Themes, principles and remarks for the concept of start-stop production system

Theme	Principle	Remark
Technology	Variable not fixed energy consumption	Additionally equipment must be efficient
	Sized for task	Avoiding over specification
	Fast ramp-up/down	IT as well as tooling
	Ramp-down phased	Recognises next start time due
	Thermal stability	Achieve quickly
	Point efficiency	At multiple rate/takt
	Maintenance simplicity	Includes cleaning
	Longevity	May limit frequent start-stop
	Quality	Not impacted by start-stop
People	Actively conserve energy	Core organisation values
	Incentivised to minimise consumption	Visual metrics
	Organised to minimise consumption	No intra-department barriers
	Comfort and safety	Cannot compromise safety
System	Consumption aligned to value add	Variable not fixed
	Low overall system interdependence	Production, despatch, office, etc weakly linked
	Low production area interdependence	Technology/cells weakly linked
	System efficiency at multiple rate/takt	Balances with technology & people

The technology theme is the basic building block of components on which to build wider system functionality. Technology is the consumer of the power and other resources, whether it is the production tooling or the supporting utilities. Aside from the need for energy efficient equipment, it is important the equipment is sized for the task and not over-specified. Sizing would be either as a fixed resource or an array of resources that can be gradually brought in according to demand.

In ramping up and ramping down the equipment (production, IT, utilities, etc) is illustrated in Figure 1. It must be recognised that equipment may be needed again soon so it may not fully hibernate to ensure quick, stable resumption (as illustrated by the dotted line). Finally it is recognised the stress that powering off and on can cause equipment and so the life expectancy of equipment must be balanced with the efficiency savings overall.

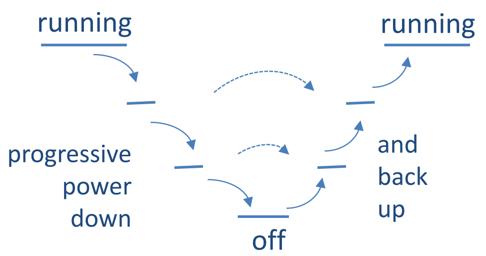

Fig 1. Graph based energy saving at machine level (adapted from [16])

The people theme is related to the organisational structure and the behavioural characteristics within that structure. Training and education may be needed to help staff understand the benefits as well as understand the quality and reliability impacts. Barriers to change must be understood and actions taken to remove them.

The system theme builds from the technology and people themes, recognising the constraints as well as building on the principles and scaling them. The ability to step down power consumption during periods of idle and to run at lower rates of production according to demand with proportionally lower energy use are important goals to aim for (see Figure 2). The ability to de-couple production areas from one another and from the rest of the factory activities enables lower consumption through lower heating, lower lighting, etc.

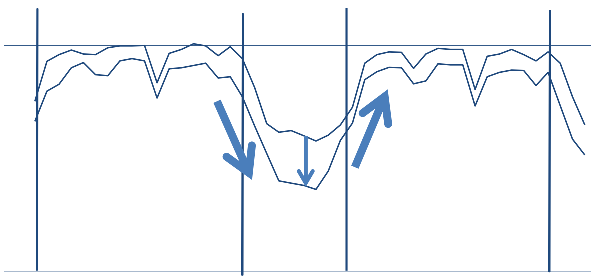

Fig 2. Illustrative energy consumption variable according to production volume at factory level

4. Challenges

Considering the lean production philosophy [19], the challenge of coupling energy consumption to production output could be considered analogous to striving to minimise waste and focus all activities on adding value to the product that is only produced when needed. Indeed, elements of lean thinking have been applied to energy efficiency, for example the energy Value Stream Mapping (VSM) [20]. Energy efficiency improvements can also draw from the lean philosophy of making organisational improvements coupled with supporting technology changes.

With a significant element of factory energy and other resource consumption currently being largely independent of production, approaches must be found to enable a greater alignment so that when production is lower, energy consumption is proportionally lower. The ideal would be for 'fixed' consumption (as illustrated in Figure 3) to become variable. At factory scale there are challenges with compressed air, heat and lighting systems to name a few. Compressed air systems consume a significant amount of energy maintaining pressure during shift and breaks as well as overnight and during weekends. Shutting such systems down when not in use has to recognise the significant time required to re-pressurise as well as the equipment operation problems this could bring. For example, one company locks down their clean room at shift end to allow the air handling to be powered down without loss of system integrity but with lower energy consumption.

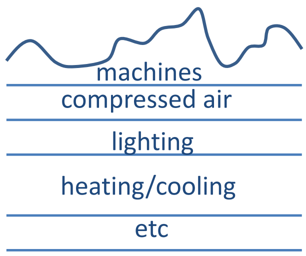

Fig 3. Illustrative fixed and variable energy consumers at factory level

Other large scale consumers, e.g. heating and lighting, suffer the problems of a different type since reducing consumption at times of low occupancy compromises health and safety. Currently, few factories can be dynamically resized according to need, hence the near fixed burden of heating, lighting, etc. is difficult to address. For example, one UK factory currently at the design stage is seeking to exploit zoning of the shop floor for flexibility and resource efficiency.

A key principle for energy efficiency is the need for energy consumption to vary according to production value-add rather than be fixed according to production hours. At a technological level, such as machine tools, the peripherals are significant fixed energy consumers (as illustrated in Figure 4); however, with new machine tool design thinking and better management of machines the fixed burdens are being reduced. At a system level, there is anecdotal evidence of companies challenging themselves to minimise energy consumption at end of shift but there is insufficient published accounts of these to derive more detailed procedures and principles for easy adoption by others. For example, a confectionery factory requires staff to reduce energy consumption to base load before they can leave the shop floor at end of shift.

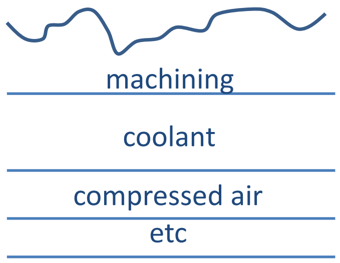

Fig 4. Illustrative fixed and variable energy consumers at machine level

The technology level receives most consideration at the specification stage and improvement kaizens whilst the system level is the focus due the overall production operation. It is difficult to link the two. If the means by which individual processes could start and stop quickly and their most efficient operating speeds could be identified then efficient overall system operation could be more flexible. For example, during period of low output, perhaps during an overtime shift, the production flow could be batched or set at a specific takt to allow multiple machines to operate efficiently. Hence the overall production system could operate in an energy efficient way.

Production volumes are in constant flux. Activities vary across shifts due to external demand requirements and within shifts because of scheduling complexity or production issues. Efficient and effective technology is required for future production system design that responds to changing requirements. Efficiency is required for running at a given rate, and that rate could be variable. For example, a main shift may operate fully manned whereas an evening shift, weekend shift or overtime could operate at a slower takt time either because flow is slower or because fewer areas are in use.

There are challenges for production equipment to ramp up and ramp down quickly according to production needs. Large production plant, e.g. paint plants, require a separate operating plan to bring the plant up to operating conditions starting many hours in advance. For example, an automotive plant is currently examining ways to delay the start of their operating plan to begin closer to the start of the production plan through changes to staffing hours and technology. Other plant such as ovens for food baking struggle to maintain quality if there are gaps in production. Designing plant that can start up quickly and hibernate quickly would result in considerable energy savings and offer flexibility benefits to production operations. There is potential to use principles being developed for machine tools, e.g. for start-up and shut-down sequencing [16], for other equipment and whole factories. This in turn can be used to identify key factory-wide technological and organisation constraints to energy efficiency to be targeted.

Faster cleaning and maintenance could enable faster production resumption or faster overall factory shutdown. Cleaning often requires significant use of resource, e.g. hot water in food production or air handling in paint plants. The disposable production system principle used in some pharmaceutical production to minimise cleaning by using disposable reactor linings could be of interest here, however, reduced energy and water waste have to be balanced with other waste generation.

Constraints to improvement could be driven by material and product issues. Some processes are fixed in their speed either for reasons of physical material properties required or that the production process has been certified under specific conditions and flexibility is limited. Additionally, there may be linkages between production processes, e.g. for food or very high volume production, whereby once processing has started all stages must be completed. It is important to capture such constraints and if they cannot be challenged directly then they are recognised in the wider system design and operation.

Organisational behaviours can have a significant impact on the drive for energy efficiency and work has been carried on removing barriers to promote improvement progress [18, 21]. On a day-to-day basis there is also the challenge of the authority and confidence to switch off machines during production hours. For example, one UK aerospace factory made significant improvements to a process by switching off equipment when no product was present, however, significant analysis was required to give production staff confidence that quality would not be affected. Whilst some factories may demand energy consumption is minimised before the end of shift, many machines will be left idling during shifts due to operators' lack of confidence that the machines can be brought back to capable operating conditions quickly. Finally, in many factories (particularly those with discrete production) the energy metrics are not combined with production operations metrics hence the shop floor who consume the energy is not incentivised to reduce consumption. Greater consideration of how to incorporate energy metrics with shop floor production metrics is required.

On small scale, peripherals supporting machine tools are significant consumers but one machine tool is typically independent of another and this can be exploited. The independence of sub-systems enables machines to be progressively powered down according to when they are next needed. This principle of independence has potential to be extended to other areas, for example with building zone heating and lighting. The application of such thinking could trigger the development of ways in which large open factory space that is typical of current factories could be flexibly zoned to physical separate areas to operate heating, lighting, etc independently.

5. Conclusion

This paper has drawn an analogy between the fuel efficiency of cars and the resource efficiency, in particular energy efficiency, of production systems. There is a significant contrast between factories that are significant consumers of energy when there is no output and the performance of cars with start-stop technology, gears for efficiency at different speeds that only consume energy when occupied. No start-stop production system concept exists with defined efficiency at multiple production rates.

The contribution of this paper is to propose the concept of a start-stop production system, develop the features of the concept and identify the challenges to achieving it. The paper presents the factory scope necessary to define the concept and the features that span technology, people and systems. The challenge is multi-scale from the technology within a machine tool to the integration of building and production systems. Some of the challenges relate to legacy technology whilst others relate to how machines and people are organised for reliable commencement of production shift.

Challenges for future work can be identified spanning systems, technology and organisation. Four key challenges became apparent in the work. Firstly enabling independence of sub-systems within the factory so shut down can be achieved independently. Next is the change in design approach to move fixed consumption to variable consumption so use changes according to need. Thirdly, the development of technology that can start up quickly, run efficiently according to demand and then quickly shut down. Finally, the promotion of organisational behaviour, guided by incentives, that results in technology being used effectively.

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