Impact of Productivity on Energy Conservation

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ABSTRACT

Productivity has a major impact on energy use and conservation in manufacturing plants. It is often more significant than the optimization of equipment energy efficiency. This article describes a lean manufacturing, which represents the current state of the art in plant productivity. A significant opportunity for energy savings by transforming production into a single-piece lean flow is demonstrated. The impact from major individual productivity elements on energy is discussed. Simple metrics and models are presented as tools for relating productivity to energy. Simple models are preferred because productivity is strongly influenced by intangible human factors, such as work organization and management, learning and training, communications, culture, and motivation, which are difficult to quantify in factories.

INTRODUCTION

At the time of this writing (2005), the world is experiencing strong contradictory global trends of diminishing conventional energy resources and rapidly increasing global demands for these resources, resulting in substantial upward pressures in energy prices. Since the energy used by industry represents a significant fraction of the overall national energy use, equal to 33 percent in the United States in year 2005, a major national effort is underway to conserve industrial energy [1]. The rising energy prices place escalating demands on industrial plants to reduce energy consumption without reducing production or sales, by increasing energy density.

The optimization of industrial hardware and its uses, including motors and drives, lights, heating, ventilation and cooling equipment, fuel-burning equipment, and buildings, is well understood, has been practiced for years, [2], and is important in practice. However, optimization offers only limited energy conservation opportunities, rarely exceeding a few percent of the pre-optimization levels. In contrast, the impact of productivity on energy use and energy density offers dramatically higher savings opportunities in both energy and other costs. In an extreme case, when transforming a factory from the traditional "process village" batch-and-queue system to the state-of-the-art, so-called "lean" system, the savings in energy can reach 50 percent or more.

The best organization of production known at this time is called "lean," developed at Toyota in Japan, [3]. It is the flow of value-added work through all processes required to convert raw materials to the finished products with minimum waste. Major elements of lean organization include: steady single-piece flow with minimum inventories and no idle states or backflow; flexible production with flexible equipment and operators and flexible floor layout ready to execute an order of any size profitably and just in time; reliable and robust supplies of raw materials; minimized downtime due to excellent preventive maintenance and quick setups; first-pass quality; clean, uncluttered, and well-organized work space; and optimized work procedures. Most importantly, it means an excellent workforce: well trained, well managed, motivated, team-based, and unified for the common goals of market success and efficient communication. The lean organization of production is now well understood among productivity professionals, but it is not yet popular among the lower tier suppliers in the U.S. Its implementation would benefit the suppliers in becoming more competitive, and save energy.

The engineering knowledge of energy conservation by equipment improvements is well understood and can be quantified with engineering accuracy for practically any industrial equipment [2]. In contrast, industrial productivity is strongly influenced by intangible and complex human factors such as management, work organization, learning and training, communications, culture, and motivation. These work aspects are difficult to quantify in factory environments. For this reason, the accuracy of productivity gains, and the related energy savings, are typically much less accurate than the energy savings computed from equipment optimization. Simple quantitative models with a conservative bias are therefore recommended as tools for energy management in plants. This article includes some examples. They are presented in the form of energy savings or energy cost savings that would result from implementing a given productivity improvement, or eliminating a given productivity waste; or as simple metrics measuring energy density.

It is remarkable that in most cases, these types of energy savings occur as a natural byproduct of productivity improvements, without the need for a direct effort centered on energy. Thus, the management should focus on productivity improvements. In a traditional non-lean plant intending to transform to lean production, the first step should be to acquire the knowledge of the lean system. It is easily available from industrial courses and workshops, books such as [3] and [4], and video training materials such as [6]. The next step should be the actual transformation of production to lean. Most of the related energy savings will then occur automatically. Implementation of individual productivity elements, such as machine setup time reduction, will yield some energy savings, but the result will not be as comprehensive as that yielded by the comprehensive implementation of lean production.

TRADITIONAL VERSUS LEAN PRODUCTION

The traditional organization of production still used frequently in most factories tends to suffer from the following characteristics:

- Supplier selection is based on minimum cost, resulting in low levels of mutual trust and partnership, the need for receiving inspection, and often large inventories of raw materials (RM).
- Work-in-progress (WIP) is moving in large batches from process village to process village, and staged in idle status in queues in front of each machine, while the machine moves one piece at a time. This work organization earned the nickname “batch-and-queue (BAQ)” [3].
- Finished goods (FG) are scheduled to complex forecasts rather than customer orders, resulting in large inventories.
- The floor is divided into “process villages” populated with large, complex and fast similar machines selected for minimum unit cost.
- Minimum or no information is displayed at workstations, and the workers produce to quotas.
- Work leveling is lacking, which results in a random mix of bottlenecks

and idle processes.

- Unscheduled downtime of equipment occurs frequently.
- Quality problems with defects, rework, returns, and customer complaints are frequent.
- Quality assurance in the form of 100 percent final inspections attempts to compensate for poor production quality.
- The floor space is cluttered, which makes moving around and finding items difficult.
- The workforce has minimal or no training, and single skills.
- The management tends to be authoritarian.
- A language barrier exists between the workers and management.
- There is a culture of high-stress troubleshooting rather than trouble prevention.

In such plants, the waste of materials, labor, time, space, and energy can be as much as 50 to 90 percent [3].

The lean production method, developed primarily at Toyota in Japan under the name of just-in-time (JIT) and generalized in the seminal work [3], is the opposite of traditional production in almost all respects, as follows:

- Raw materials are bought from reliable supplier-partners and delivered JIT in the amount needed, at the price agreed, and with the consistently perfect quality that obviates incoming inspection.
- Single-piece flow (SPF) of WIP is steadily moving at a common takt time* from the first to the last process.
- The FG are produced to actual customer orders JIT, resulting in minimum inventories.
- The floor is divided into flexible production lines with small simple machines on casters that can be pushed into position and set up in minutes.
- The labor is multi-skilled, well-motivated, and well-trained in optimized procedures.
- Quality and production status and issue descriptions are displayed on large visible boards at each workstation, making the entire production transparent for all to see.

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*Takt time is the common rhythm time of the pieces moving from workstation to workstation on the production line. It is the amount of time spent on EACH operation. It precisely synchronizes the rate of all production operations to the rate of sales JIT.

- Preventive maintenance assures no unscheduled downtime of equipment.
- All process operators are trained in in-line quality checks and variability reduction.
- No final inspection is needed, except for occasional sampled checks of FG.
- Defects, rework, returns, and customer complaints are practically eliminated.
- The floor space is clean and uncluttered.
- The workforce is trained in company culture and commonality of the plant mission, customer needs, workmanship, and quality.
- The culture promotes teamwork, multiple job skills, supportive mentoring management, and company loyalty.
- The management promotes trouble prevention and "stopping the line" at the first sign of imperfection, so that no bad pieces flow downstream.

According to [3], the transformation from traditional to lean production can reduce overall cost, inventory, defects, lead time by 90 percent, space by 50 percent, and vastly increase plant competitiveness, customer satisfaction, and workforce morale. The resultant energy savings can be equally dramatic. Ref. [4] contains interviews with industry leaders who have succeeded in this transformation.

IMPACT ON ENERGY

The impact of productivity on plant energy falls into the following two broad categories:

1) *Productivity improvements that save infrastructure energy*. These improvements reduce the energy consumed by all plant support systems which tend to be energized regardless of the actual production activities, such as lights, space cooling and heating devices, cooling towers, combustion equipment (boilers, molten metal furnaces), air compressors, forklift battery chargers, conveyors, etc. To the first approximation, the infrastructure energy is reduced in proportion to the production time reductions, which can be huge in the lean system. To perform more detailed estimates of the infrastructure energy savings, the management would have to conduct detailed energy accounting and understand how

much energy is used by each support system under different production conditions. This knowledge is rarely available; therefore the former simplistic approach, combined with conservative estimates, offer useful tools.

2) *Process energy savings*. In this category, the energy savings of process equipment are obtained by improving the process productivity. Examples include the reduction of unscheduled machine downtime or setup time, and the elimination of process variability, defects, rework, scrap, excessive labor time, etc.

SINGLE PIECE FLOW

Changing the traditional BAQ production to lean production is by far the most effective productivity transformation a plant can undertake, creating dramatic savings in the overall throughput time, cost, quality, and energy. The example shown in Figure 1 compares just one aspect of the transformation, namely a reduction of batch size from five to one, i.e., the SPF. In both cases, four processes of equal one-minute takt time are assumed. The benefits of the SPF alone are dramatic, as follows:

1) In BAQ, the batch is completed in 20 min., in SPF in only 8 min., a 60 percent reduction.

2) In BAQ, only one machine at a time produces value, while three others are idle. If the idle machines remain energized, as is the case with injection molding, three of the four machines (75 percent) would be wasting energy, and doing it for 16 minutes each, adding up to 64 minutes of machine-energy wasted. In the SPF system, no machine energy is wasted as no machine would be idle, except for the lead and tail of each process of four minutes, adding up to 16 minutes of machine energy wasted, a savings of 75 percent from BAQ.

3) Reducing the batch throughput time by 60 percent reduces the infrastructure energy by the same amount, assuming the production is completed faster and the plant de-energized. Alternatively, the freed 60 percent time and energy could be used for additional production and profits.

4) An important additional benefit: In SPF, a defect can be detected on the first specimen, as soon as it reaches the next process, while in the BAQ the entire batch may be wasted before the defect is discovered and a corrective action undertaken, with the energy used for making

the batch wasted.

This simple example clearly illustrates the dramatic impact of SPF on both overall productivity and energy consumption. Typically, as the factories transform to lean systems, their sales, production, profits, and energy used increase simultaneously. A convenient metric to track the overall benefit is the gross energy density, ED_1 or ED_2:

$$ED_1 = EC_{T/}P \qquad (1a)$$

$$ED_2 = EC_{T/}AC \qquad (1b)$$

where EC_T is the overall annual cost of energy in the plant, P is the number of products produced per year, and AC is the total annual costs (sales minus net profit). ED_1 should be used if similar products are made most of the time, and ED_2 if the plant has a wide menu of dissimilar products. The ED ratios will decrease as progress is made from BAQ to SPF. If the volume of production remains constant during the transformation, energy savings and energy cost savings alone may be more convenient metrics to track plant energy efficiency.

INVENTORY REDUCTION

All inventories, whether in RM, WIP, or FG, beyond the immediate safety buffers, are detrimental. Inventory means that company capital is "frozen" on the floor. This has several negative aspects: cutting into the cash flow; wasting labor for inventory control, storage and security; wasting infrastructure energy for lights, forklift energy, and possible cooling or heating of the inventory spaces if the goods require temperature or humidity control; wasting space and the associated lease/mortgage fees and taxes; and becoming scrap if not sold (a frequent waste in large inventories). Inventory and inventory space reductions lead to infrastructure energy savings. Process energy can also be saved by not making the FG that end up in inventory, cannot be sold, and become scrap. Ref. [3] and [4] contain case studies for, among others, inventory reductions. A convenient nondimensional metric to track the overall impact of all inventories on energy savings is

$$EC_T * I_T/AC \qquad (2)$$

where I_T is the number of inventory turns per year.

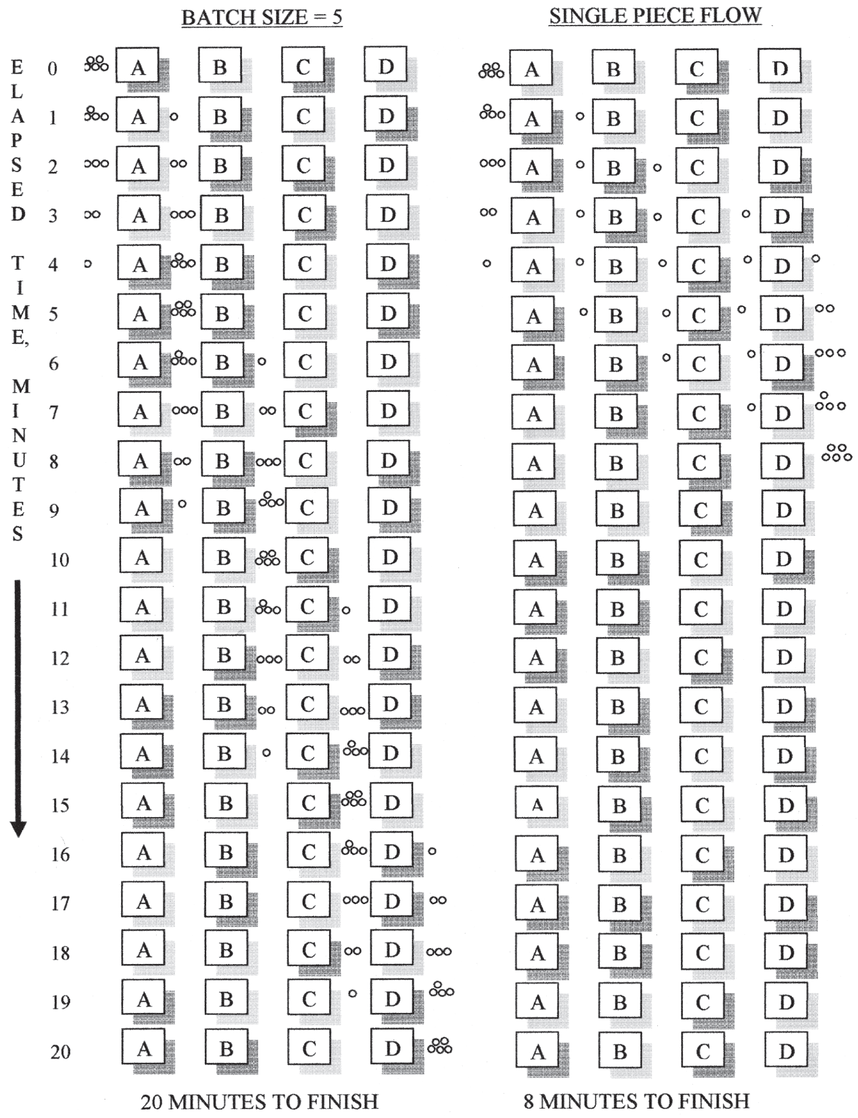

Figure 1. BAQ with batch size of five versus SPF

WORKMANSHIP, TRAINING AND QUALITY ASSURANCE

In the ideal lean system, the processes, equipment, procedures, and training are perfected to the degree that guarantees consistent and robust production with predictable effort, timing, quality and cost; with no variability, defects, or rework; and with maximum ergonomics and safety. This is accomplished by a consistent long-term strategy of continuous improvement of all the above elements, including intensive initial training of the workforce, and subsequent retraining in new procedures. A procedure must be developed for each process until it is robust and predictable, optimized for minimum overall cost, required quality, maximum ergonomics, and safety. Process operators must be trained in the procedures, as well as in the process quality assurance, and they must be empowered to stop the process and take corrective action or call for help if unable to avoid a defect. Management culture must be supportive of such activities. Any departure from this ideal leads to costly penalties in quality, rework, delays, overtime or contract penalties, crew frustrations, and customer dissatisfaction. These, in turn, have negative impacts on energy as follows:

1) Defects require rework, which requires additional energy to re-make or repair the part. The best metric to use here is the energy or energy cost per part used in the given defective process, multiplied by the number of bad parts produced per year.

2) Variability in the process time, or delays caused by defects, mean that the production takes more time and more infrastructure and process energy for the same amount of value work and profits when compared with the ideal non-variable process. Example 1 illustrates cases 1) and 2).

3) Defective processes usually require a massive final inspection to sort out the good products. Finding the finished goods defective is the most inefficient means of quality assurance because often the entire batch must then be re-made, consuming the associated energy. The inspection space, labor, and energy represent a direct waste and should be replaced with in-line quality assurance (ILQA) that detects the first bad piece* and immediately undertakes a corrective action. Typically,

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*Governmental, medical, etc., orders usually require a 100 percent final inspection. In the lean system, this is performed as a formality, because everybody in the plant knows that all pieces will be perfect because all imperfections have been removed in real time before the inspection process.

The ILQA can be implemented in a few days of operators' training, and has the simple payback period measured in days or weeks [5].

Example 1: Energy waste from poor workmanship

A plant with $20,000,000 in sales and $2,000,000 in profits spends $1,000,000 on energy per year. The typical order requires 10 processes of roughly equal energy consumption. The production equipment consumes 60 percent and the supportive infrastructure 40 percent of the plant energy. Sequential process #5 has the defect rate of 10 percent. To compensate for the defects, the first five processes must produce 10 percent extra pieces. The annual waste of energy cost (and the energy cost savings, if the defective process is fixed) is then:

($1,000,000/yr) (5/10 processes) (60 percent process energy)
(10 percent defect rate) = $30,000./yr (3)

The additional production time of 10 percent wastes not only the cost of the process energy computed in (3) but also the infrastructure energy cost of:

($1,000,000/yr) (40% infrastructure energy)
(10% defects) = $40,000./yr (4)

Such delays also extend the promised delivery time and reduce customer satisfaction and factory competitiveness. Adding (1) and (2) together (not counting the direct productivity losses), the wasted energy cost alone of $70,000/yr represents 3.5 percent of the annual profits and 7 percent in annual energy costs. Based on the author's experience [5], these numbers are not infrequent in industry. Fixing the productivity of process #5 would eliminate these wastes.

OVERAGE REDUCTION

Many a plant compensates for its notorious defects by routinely scheduling production in excess of what the customer orders. Some minimum overage is usually justified for machine setups, adjustments, and QA samples. In a lean plant, this rarely exceeds a fraction of one percent. In a traditional plant, the value of 5-15 percent is not infrequent. A 5 percent overage means that the plant spends 105 percent of the necessary costs. If the profit margin is 5 percent, the overage alone may consume the entire profit. The overall energy waste (and the opportunity to save energy) is simply proportional to the overage amount. Overage is one of the most wasteful ways of compensating for defective processes. The best remedy is to simply identify the defective process with ILQA, find the root cause*, and repair it.

Unintentional overage can also be destructive to profits and energy use. Example: A worker is asked to cut only a few small pieces from a large sheet of metal, but instead he cuts the entire sheet thinking that "my machine is already set up, and soon they will ask me to cut the rest of the sheet anyway, so I might as well do it now." The excessive pieces then move through all the processes, unknown to the management, consuming energy, labor, and fixed costs, to end up as excessive FG inventory and, in the worst case, find no buyer and end up as scrap. Uncontrolled and careless overage can easily consume all profits, and, of course, waste energy proportionately to the overage amount.

DOWNTIME

Equipment downtime and idleness may occur due to scheduled maintenance, unscheduled breakdowns, machine setups, and poor process scheduling. The downtime may cause proportional loss of both profits and energy. The downtime may have four-fold impact on energy use, as follows:

1) When a process stops for whatever reason during an active production shift, the plant infrastructure continues to use energy, loosing money as in equation (4). A good plant manager should understand what fraction of the infrastructure energy is wasted during the specific equipment downtime. With this knowledge, the energy waste can be estimated as proportional to the downtime.

2) Some machines continue using energy during maintenance, repair or setup, in proportion to the downtime, (e.g., the crucible holding molten metal for a die casting machine remains heated by natural gas while the machine is being set up or repaired). Reducing the setup time or eliminating the repair time saves the gas energy in direct proportion to the downtime saved. To calculate energy savings in such situations,

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*Typically the lack of training, excessive work quotas, or bad process or material.

it is necessary to understand the energy consumption by the equipment per unit time, multiplied by the downtime reduction.

3) When a particular machine is down, additional equipment upstream or downstream of that machine may also be forced into an idle status but remain energized, thus wasting energy. In an ideal single-piece flow, the entire production line* will stop. To estimate the energy saving opportunity from reducing this cumulative downtime, the energy manager must understand which equipment is idled by the downtime of a given machine, and how much energy it uses per unit time, while being idle.

4) Lastly, energized equipment should be well managed. A high-powered machine may be left energized for hours at a time when not scheduled for production. A good practice is to assign each such machine to an operator whose duty it is to turn the machine off when not needed for a longer time, if practical, and to turn it back on just in time to be ready for production exactly when needed.

Preventive maintenance and setup time reduction have a particularly critical impact on both productivity and related energy use, as follows:

Preventive maintenance: Practical, routine preventive maintenance should be done during the hours free of scheduled production (e.g., during night shifts, on weekends, or during layover periods). The maintenance should be preventive rather than reactive. Well-managed "total" preventive* maintenance involves not only oiling and checking the machines per schedule, but also ongoing training of the mechanics; developing a comprehensive database containing information on the particular use and needs of various machines; preparing a schedule of parts replacement and keeping inventory of frequently used spare parts; and well-managed ordering system for other parts, including vendor data so that when a part, if needed, can be ordered immediately and shipped by the fastest possible means. Industry leaders have demonstrated that affordable preventive maintenance can reduce the unscheduled downtime and associated energy waste to zero. This should be the practical goal of well-run factories.

Setups: Modern market trends push industry towards shorter series and smaller orders, requiring, in turn, more, and shorter, setups.

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*As in the saying "In lean either everything works or nothing works."

Industry leaders have perfected routine setups to take no more than a few minutes. In poorly managed plants, routine setups can take as much as several hours. In all competitive modern plants, serious efforts should be devoted to setup time reductions. The effort includes both training and hardware improvements. The training alone, with only minimal additional equipment (such as carts), can yield dramatic setup time reductions (e.g., from hours to minutes) [6]. Further gains may require a change of the mounting and adjustment hardware and instrumentation. Some companies organize competitions between teams for developing robust procedures for the setup time reductions. In a plant performing many setups, the opportunity for energy savings may be significant, both in the process and infrastructure energy, as shown in Example 2.

Example 2: Energy savings from setup time reduction

A plant operates on two shifts, 260 days per year, performing on average 20 two-hour setups per day on their electrically heated injection molding machines. Each machine consumes 20kW when idle but energized. By a focused continuous improvement system and training, the crew reduces the routine setup time to 0.5 hour, with few, if any expenses for additional hardware, thus saving:

(260 days/yr) (20 setups/day) (1.5 hr saved/setup)
= 7,800 machine hrs/yr.

The resultant process energy saved will be:

(7,800 hr/year) (20kW) = 156,000 kWh/yr (5)

In addition, infrastructure energy will be saved because of the reduced downtime. Using the data from Example 1, if the work is done on two shifts for 260 days per year (4160 hrs/yr), the plant infrastructure uses 40 percent of the plant energy, and each machine consumes 2 percent of the plant infrastructure energy during the setup, the additional energy cost savings due to the setup time reduction will be:

(7800 hr/yr) (0.02) (0.04) ($1,000,000)/
(4160 hr/yr) = $15,000. (6)

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*The term "preventive" tends to be replaced with "productive" in modern industrial parlance.

FLEXIBILITY

Production flexibility, also called agility, is an important characteristic of competitive plants. A flexible plant prefers small machines, if possible on casters, that are easy to roll into position and plug into adjustable quick-connect electrical and air lines, and easy to set up and maintain, over the large fixed machines selected with large batches and small unit costs in mind*. Such an ideal plant will also have trained a flexible workforce in multiple skills, including quality assurance skills. This flexibility allows for the setup of new production lines in hours or even minutes, optimizing the flow and floor layout in response to short orders, and delivers the orders JIT. The energy may be saved in two important ways, as follows:

- Small machines processing one piece at a time use only as much energy as needed. In contrast, when excessively large automated machines are used, the typical management choice is between using small batches JIT, thus wasting the large machine energy, or staging the batches for the large machine, which optimizes machine utilization at the expense of throughput time, production flow, production planning effort, and the related infrastructure energy.
- Small machines are conducive to flexible cellular work layout, where 2-4 machines involved in the sequential processing of WIP are arranged into a U-shaped cell, with 1-3 workers serving all processes in the cell in sequence, the last process being quality assurance. This layout can be made very compact, occupying a much smaller footprint in the plant compared to traditional "process village" plants, roughly a reduction of 50 percent, [3], [4], and is strongly preferred by workers because it saves walking and integrates well the work steps. Such a layout also saves forklift effort and energy, and infrastructure energy due to the reduction of the footprint.

OTHER PRODUCTIVITY ELEMENTS

A complete list of productivity elements is beyond the scope of this article, and all elements have some leverage on energy use and conser-

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*Such machines are called "monuments" in [3].

vation. In the remaining space, only the few most important remaining aspects are mentioned, with their leverage on energy. Descriptive details can be found in [7] and numerous other texts on lean production.

Visual factory: Modern factories place an increasing importance on making the entire production as transparent as possible to make any problem visible to all, which is motivational for immediate corrective actions and continuous improvements. Ideally, each process should have a white board displaying short-term data such as current production status (quantity completed versus required), rate of defects or rejects and their causes, control charts, information about the machine condition or maintenance needs, and a brief list and explanation of any issues, all frequently updated. The board should also display long-term information such as process capability history, quality trends, operator training, etc. Such information is most helpful in the optimization of, among others, process time and quality, which leads to energy savings, as discussed above.

"Andon" signals: The term refers to the visual signals (lights, flags, markers, etc.) displaying the process condition, as follows: "green=all OK," "yellow=minor problem being corrected," and "red=high alarm, stopped production and immediate assistance needed." The signals are very useful in identifying the trouble-free and troubled processes, which is conducive to focusing aid resources to the right places in real time, fixing problems immediately, and not allowing defects to flow downstream on the line. These features, in turn, reduce defects, rework, delays, and wasted costs, which improve overall productivity and save energy, as described above. It is also useful to display the estimated downtime*. Knowing the forecasted downtime frees other workers to perform their pending tasks which have waited for such an opportunity, rather than wait idle. This leads to better utilization of the plant resources, including infrastructure energy.

"5S's": The term comes from five Japanese words that begin with the "s" sound and loosely translate into English as: sorting, simplification, sweeping, standardization, and self-discipline*. These terms describe a simple but powerful workplace organization method. The

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*Toyota and other modern plants have large centrally located Andon boards that display the Andon signal, the workstation number, and the estimated downtime.

underlying principle of the method is that only the items needed for the immediate task (parts, containers, tools, instructions, materials) are kept at hand where they are needed at the moment, and everything else is kept in easily accessible and well organized storage in perfect order, easy to locate without searching, in just the right quantities. All items have their designated place, clearly labeled with signs, labels, part numbers, and possibly bar codes. The minimum and maximum levels of inventory of small parts are pre-defined and are based on actual consumption rather than the "just in case" philosophy. The parts, tools, and materials needed for the next shift of production are prepared by a person in charge of the storage during the previous shift and delivered to the workstation before the shift start. The floor is uncluttered and marked with designated spaces for all equipment. The entire factory is spotlessly clean and uncluttered. Walls are empty except for the visual boards. In consequence of these changes, the searching for parts, tools, and instructions, which can represent a significant waste of labor and time, is reduced, and this, in turn saves energy. Secondary effects are also important: In a well-organized place, fewer mistakes are made, fewer wrong parts are used, less inspection is needed, quality, throughput time, and customer satisfaction are increased, and costs and energy are decreased. Figure 2 illustrates a fragment of a messy factory, where the average worker was estimated to waste 20 percent of his shift time looking for and scavenging for parts and tools. Multiplied by the number of workers, this yields a significant amount of wasted production time, also wasting plant energy in the same proportion. Sorting, cleaning, and organizing the workplace is one of the simplest and most powerful starting points on the way to improved productivity and energy savings.

CONCLUSION

Large savings in energy are possible as an inherent byproduct of improving productivity. The state-of-the-art lean productivity method can yield dramatic improvements in productivity. In the extreme case, when converting from the traditional batch-and-queue and "process village" manufacturing system to lean production, overall costs, lead

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*Many other translations of the words are popular in industry.

Figure 2. In this messy plant the workers waste close to 20 percent of their time looking for items and scavenging for parts and tools, also wasting the plant energy.

times, and inventories can be reduced by as much as 50-90 percent, floor space and energy by 50 percent, and energy density can be improved by 50 percent. The amount of energy that can be saved by productivity improvements often radically exceeds the savings from equipment optimization alone, thus providing a strong incentive to include productivity improvements in energy-reduction efforts.

Productivity strongly depends on human factors such as management, learning and training, communications, culture, teamwork, etc., which are difficult to quantify, making accurate estimates of the cost, schedule, and quality benefits from various productivity improvements and the related energy savings difficult to estimate with engineering accuracy. For this reason, simple metrics and models are recommended, and some examples have been presented. If applied conservatively, they can become useful tools for energy management in a plant. The prerequisite knowledge includes an understanding of lean flow and its various productivity elements, and a good accounting of energy use in the plant, including the knowledge of the energy used by individual machines and processes both when in productive use and in the idle but energized state, as well as the energy elements used by the infrastructure (various light combinations, air-compressors, cooling and heating devices, combusting systems, conveyers, forklifts, etc.). In these times of ferocious global competition and rising energy prices, all industrial plants should make every effort to improve both productivity and energy use.

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References

(1) U.S. Dept. of Energy, Energy Efficiency and Renewable Energy, http://www.eere.energy.gov/industry/(accessed Dec. 2005).
(2) U.S. Dept. of Energy, http://eereweb.ee.doe.gov/industry/bestpractices/plant_assessments.html, (accessed Dec. 2005).
(3) Womack, P. James; Jones, Daniel, T.; Lean Thinking Second Edition, Lean Enterprise Institute (www.lean.org), ISBN: 0-7432-4927-5, Boston, Massachusetts, 2005.
(4) Liker, Jeffrey, Becoming Lean, Inside stories of U.S. manufacturers, Productivity Inc., Portland, OR, service@productivityinc.com, 1998.
(5) Bohdan W. Oppenheim, Selected Assessment Recommendations, unpublished, Industrial Assessment Center, Loyola Marymount University, Los Angeles, (boppenheim@lmu.edu), 2005.
(6) Setup Reduction for Just-in-Time, Video/CD, Society of Manufacturing Engineers, Product ID: VT90PUB2, http://www.sme.org/cgi-bin/get-item.pl?VT392&2&SME& 1990, (accessed Dec. 2005).
(7) Ohno, Taiichi, Toyota Production System: Beyond Large Scale Production, Productivity Press, New York, NY, 1988, info@productivityinc.com.
(8) Hirano, Hiroyuki, Five pillars of the visual workplace, the sourcebook for 5S implementation, Productivity Press, New York, NY, 1995, info@productivityinc.com.

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