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INTRODUCING SUSTAINABILITY EARLY INTO MANUFACTURING PROCESS PLANNING

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ABSTRACT: In response to the global trend towards implementing sustainable manufacturing practices, we put forth an exploratory approach that uses energy monitoring as a means to introduce sustainability criteria early into manufacturing process planning and scheduling. Typically cost, quality and time are the indices for manufacturability assessment in generating manufacturing process plans. In this paper, we propose the idea of introducing sustainability to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes. To be sustainable, it is pertinent that manufacturing firms understand the energy consumption of different manufacturing equipment used to produce products. This will enable industry to implement energy reduction processes in a more effective manner and pave the way for improved and alternate manufacturing solutions. The paper presents the potential utility of energy usage readings in the interest of continuing dialogue and collaboration.

Keywords: *sustainability index, manufacturing, energy mapping, efficiency, process planning, scheduling*

1. INTRODUCTION

In recent years, sustainable manufacturing has become a strategic move as industries begin to seek novel ways to make efficient use of resources, ensure compliance with regulations related to environment and health, and enhance the marketability of their products and services. It may be of relevance to note that, "Americans represent merely 5 percent of the world's population, yet they consume 40 percent of Earth's nonrenewable resources and produce nearly 30 percent of its total waste…" [1]. In continued interest, the US Department of Commerce (DOC) reported to have received a great deal of individual feed back from the US industry at a recent public-dialogue event [2], supporting sustainable manufacturing as an area where the US must continue to increase its global competitiveness. Accordingly, the International Trade Administration (ITA) has identified four major topics of sustainable manufacturing: 1) establishing an interagency task force on sustainable manufacturing, 2) creating a central online clearinghouse of USG programs and resources that support sustainable business, 3) domestic trade missions to promote sustainable manufacturing and 4) the creation of metrics for sustainable manufacturing. Further details on each topic are available at [2].

In the pursuit of sustainable manufacturing, this paper aims to create awareness on an inherent need to understand the energy consumption and requirements of different manufacturing equipments used to produce products. In manufacturing process planning or scheduling where cost, quality and lead time are the typical indices for manufacturability assessment we propose introducing sustainability in terms of energy efficiency to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes. We believe that this effort will enable companies to implement improved energy reduction practices and calculate/control their carbon production.

For purposes of introducing the idea, the scope of the paper is limited to our discussion on sustainability in terms of energy efficiency to aid sustainable manufacturing of a product and does not cover the entire product lifecycle. The rest of the paper is organized as follows: section 2 presents a brief overview of sustainable manufacturing, industrial statistics and related government efforts. Section 3 introduces the role of energy in manufacturing followed by Section 4 presenting the efforts towards sustainable manufacturing. Section 5 presents the idea of sustainability in terms of energy efficiency and section 6 briefly presents the role of environmental management standards. Section 7 presents the plan of action and finally in section 8 we present our conclusions and recommendations. The appendix presents a list of definitions relevant to the paper for purposes of reference.

2. OVERVIEW

The importance of the term *sustainability* internationally can be attributed to its first use in the Brundtland Commission's report [3], which linked the term to development. The Brundtland report emphasized the economic aspects of sustainability by defining sustainable development as "economic development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [3]. Today with respect to industrial manufacturing and production, sustainability issues are growing exponentially. The following subsections briefly present the US industrial energy facts and the Government's sustainability efforts in terms of energy efficiency.

Industrial Energy Facts

According to the Energy Information Administration (EIA), Annual Energy Review 2006, Figure 1 presents the US primary energy consumption by the source sector.

Of the industrial usage the manufacturing consumes 70 percent based on the manufacturing energy consumption data [4]. Note that the industrial sector includes manufacturing, agriculture, forestry, fishing, and hunting, mining (including oil and gas extraction), and construction sectors. The industrial sector consumed 21.6 quadrillion Btu of the total 99.9 quadrillion Btu consumed nationwide in 2006.
For detailed and updated energy statistic please see EIA [5] and the International Energy Agency (IEA) [6].

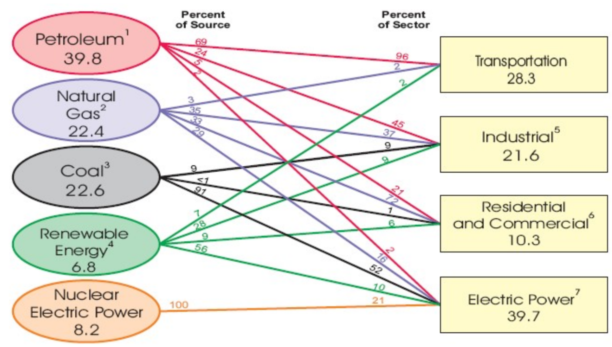

Figure 1 U.S. Primary Energy Consumption by Source and Sector, 2006 (in Quadrillion Btu) Source: EIA [5]

Government Sustainability Efforts

According the US Environmental Protection Agency (EPA) [7], sustainability is a long term effort to environmental protection and process improvements. Sustainable design prevents pollution and energy inefficiencies and calls for a systems level thinking, acknowledging the inter-connections between the economy, the environment and social responsibility [8].

The EPA and Department of Energy (DOE) [9] jointly established the ENERGY STAR Label to achieve two main objectives: 1) prevent air pollution, including emissions of greenhouse gases, caused by the inefficient use of energy and 2) to promote businesses and consumers who identify and purchase products, homes, and buildings with enhanced efficiency. The Industrial Technologies Program (ITP) leads national efforts to improve industrial energy efficiency and environmental performance [10].

ENERGY STAR Label: In its simplest definition ENERGY STAR [11] means energy efficient. The label results in savings on utility bills while maintaining or enhancing conventional features and comfort. To ensure that the ENERGY STAR label remains an effective consumer tool, EPA and DOE strive to ensure that the resulting performance-based specifications identify energy-efficient products, the usage of which results in reasonable financial return without sacrificing product performance or features. EPA and DOE have identified a set of guidelines for the ENERGY STAR label: 1) Significant energy savings can be realized on a national basis, 2) Product performance can be maintained or enhanced with increased energy efficiency, 3) Purchasers will recover their investment in increased energy efficiency within a reasonable period of time, 4) Energy-efficiency can be achieved with several technology options, at least one of which is non-proprietary, 5) Product energy consumption and performance can be measured and verified with testing and 6) Labeling would effectively differentiate products and be visible for purchasers. Further details on the guidelines can be found in [11].

Industrial Technologies Program: ITP is part of the U.S. DOE Office of Energy Efficiency and Renewable Energy and contributes to its efforts to provide reliable, affordable, and environmentally sound energy for America today and in the future. ITP's mission is to improve the energy intensity of the U.S. industrial sector through a coordinated program of research and development, validation, and dissemination of energy efficiency technologies and operating practices. ITP's efforts towards developing software tools for industrial energy systems can be found in [12]. Related information on the US government's energy saving initiative can be found in [13, 14].

In cooperation with ENERGY STAR, companies like Toyota, General Motors, California Portland cement company, Allergan Inc., and Walt Disney world have in different ways contributed to the sustainability initiatives. Toyota, for example has established a metering standard stating that all plants should record hourly electric data broken down by process equipment. Toyota now requires all plants to meter large energy-consuming equipment hourly and analyze energy use trends throughout the day and during downtime for appropriate actions [15].

EPA and DOE have jointly identified products in over 50 categories that are eligible for the ENERGY STAR Label. They use less energy, save money, and help protect the environment. Considering manufacturing equipment as products by themselves, in this paper we propose to embrace and extend the concept of ENERGY STAR and ITA guidelines for different categories of manufacturing equipment and their energy usage for a diverse set of manufacturing operations.

3. THE ROLE OF ENERGY IN MANUFACTURING

Manufacturing processes utilize energy to transform raw materials and intermediates into final products. Raw materials typically pass through a sequence of intermediate stages that consume the bulk of the industrial energy consumption. From an economic viewpoint, energy enables the manufacturing operations that add value to intermediate products as they are progressively transformed into final consumer goods. This work is directed at identifying energy efficient alternatives that provide opportunities for industries to improve energy efficiency of manufacturing operations executed during various manufacturing processes. Energy efficient manufacturing equipment saves energy without reducing levels of service. Through innovative design, new technologies and the use of advanced materials, efficient products perform equally well as their counterparts but with less energy input. In this aspect energy decisions play a crucial role in the industry. The following subsection briefly presents the factors affecting the industrial energy decisions.

Factors affecting industrial energy decisions

A combination of factors like the impact of technology, regulations and market forces influence industrial decisions. Further, depending on the complexity of manufacturing operations, decisions on energy usage largely depends on the production goals like production targets, the amount of energy consumed per unit of production which again is largely dictated by the plant assets, work procedures and the integrity of equipment affecting per-unit energy requirements, a facility's fuel choices primarily reflecting fuel availability and the nature of the facility's process, as well the capabilities of the facility's powerhouse and fuel procurement activities [16]. Besides this, today environmentally friendly manufacturing practices are additionally seeking major attention during industrial decisions.

Energy efficiency is largely determined by the technologies and the standard operating procedures that are in place to reduce the volume of energy per unit of industrial production. Failing to optimize energy consumption leads to energy waste. Manufacturers and their facility managers need to understand how energy efficiency supports the companies overall corporate goals. "Current practices see manufacturers selectively implement energy efficiency initiatives for their potential to reduce expenses, build revenue capacity and contain operating risk. By taking a corporate view, one can see that the very activities that provide energy efficiency also provide better control over plant assets and inputs. For example, energy efficient practices ensure that thermal resources are applied at the right temperature, for the right duration and in correct proportion to raw materials. This control reduces a facility's scrap rates as well as energy consumed per unit of production. Control provides reliability. Greater reliability means less down time. Less downtime means orders are filled faster, which allows the facility to complete more orders over the course of a year thus making more revenue." Energy efficiency is not just about reducing utility bills but also about boosting revenue through greater productivity [16].

In terms of environmentally friendly manufacturing practices there are two approaches: pollution prevention and product stewardship. Pollution prevention is manufacturing and operations oriented while product stewardship extends the environmental perspective to the entire value chain, including other internal and external stakeholders such as R&D, product designers and suppliers. Product stewardship is an emerging tool [17] that Ecology Communications, Inc. [18] has begun to use to fulfill its mission of promoting sustainable communities and sustainable natural resource use. Rusinko [19] provides a good overview on the environmental sustainable manufacturing practices and their impact on competitive outcomes, Welford, et al. [20] provides a review for the service sector eco-management and Visser [21] provides a review on the corporate sustainability and the individual.

4. TOWARDS SUSTAINABLE MANUFACTURING

Moving towards energy sustainability in manufacturing will require changes not only in the way energy is supplied, but in the way it is used. Also, reducing the amount of energy required to deliver various goods or services is crucial. One cannot talk about environmental sustainability without considering energy. There have been a number of approaches proposed to determine energy usage, all with large variability and questionable suitability to this problem. This involved efforts from detailed monitoring of specific machine tool cutting operations to measurement of energy use over extended timeframes [22-24].
In the industry as such, monitoring assets may be potential solution to better understand opportunities to reduce waste in energy. Efficient assets minimize energy use and improve productivity.

Asset Management: Since asset management will affect a company's overall environmental efficiency, it may be of importance to integrate energy management into a company's Enterprise Asset Management (EAM) program – both to support corporate social responsibility (CSR) goals and to continue improvements in the company's overall financial performance. The best and most well-rounded EAM programs include [25]:

- Maintenance Program Management: factoring asset operating performance (energy consumption) into maintenance strategy and activities
- Event Management: alerting of an existing asset condition or trend outside of optimum operating parameters for evaluation or remediation
- Planning: assessing existing asset configuration (design basis) and performance (energy consumption) for optimization

This means carefully monitoring assets' energy usage, implementing a comprehensive preventive maintenance program that takes into consideration energy usage, and factoring energy consumption into any plans that include asset acquisition, allocation or replacement. Note the emphasis on monitoring and preventive maintenance. *Energy efficiency cannot be estimated without having accurate data as a basis for that estimation* [25]. Preventive maintenance, as has been proven over decades of operation, is the single greatest contributor to asset useful life and optimum equipment productivity.

Where do we start?

In the pursuit of sustainable manufacturing, our goal is to understand the energy consumption and requirements of different manufacturing equipments used to produce products. To verify this approach it will require a number of pilot studies that are jointly conducted with industry sites. A pilot study would be coordinated with manufacturing companies and would be comprised of multiple production runs of several part numbers in medium to large quantities. The parts would be run on three to five different manufacturing equipments that would include an energy meter to monitor the actual energy consumption for specific process steps on the routed process plan. The start and stop readings from the meter would be entered on to the process plan (Figure 2). In this way, the data would provide the type of machining operation/s performed, the material removed, the number of parts machined and the amount of energy used. This would later be used to precisely calculate the energy used to complete one process step on the part.

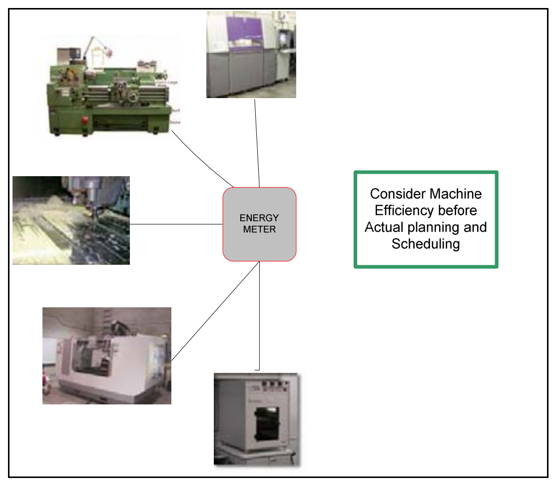

Figure 2 Energy efficiency mapping

If the pilot studies verify the expected outcomes, it will demonstrate that monitoring of all equipment and documenting the energy consumed will provide an accurate calculation of the energy required to manufacture any given part. Thus all process steps would have an associated energy usage value. This will facilitate efforts to minimize energy usage at the manufacturer and help direct efforts for reduction of carbon production. The subsequent section will introduce sustainability in terms of energy usage index to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes.

5. SUSTAINABLE MANUFACTURING INDICES

In order to survive today, manufacturing organizations must satisfy not only the demands of their customers but inevitably satisfy/comply with regulatory standards and environmental protection. In manufacturing terms, today customers demand world-class levels of quality, delivery and cost under the umbrella of a sustainable product. From a business perspective, customers will begin to drop any vendor falling short on any of the three measures against sustainability. Figure 3 presents the new sustainable manufacturing perspective as a balance of quality, cost and time.

Manufacturing process planning: Manufacturing process planning involves steps in converting a design concept into a manufactured product through a complete package of information on how to perform the manufacturing process, and usually includes work instructions for the shop floor, bill of material (BOM), quality control plan, and tool planning. The process planning may additionally include material requirements planning (MRP), product data management (PDM), standards, engineering and manufacturing change control, shop-floor control and other data collection systems. Usually, this initial package of information ultimately contributes to the final cost and quality of the product.

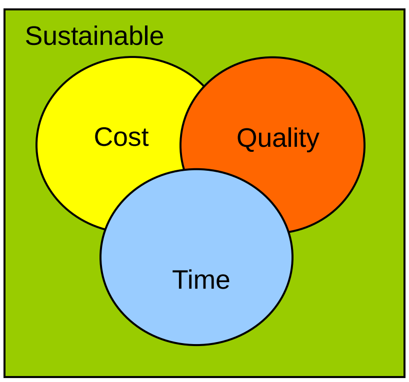

Figure 3 Sustainable manufacturing perspective

Today, energy cost represents a considerable amount of the total production cost and therefore energy savings has become a major concern for manufacturing companies [13-15]. In a factory floor with large production lines many machines may be stationed and operating at the same time, and hence the peak energy consumptions will be generally high, incurring high cost. To minimize setup times and support automation, companies rely heavily on computer-aided process planning (CAPP) [26, 27] along with other manufacturing information systems to meet production queues. While cost, quality and lead time are the typical indices for manufacturability assessment in CAPP, we propose introducing sustainability in terms of an energy efficiency index to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes.

Energy index in CAPP: With CAPP and collaborative manufacturing together with energy sustainability, we envision that it then becomes easier to answer the following questions:

- Which plan best utilizes the facility's capabilities?
- Which plan is most energy efficient?
- Which is an optimal scheduling plan?
- Which plan best reflects the energy efficiency?

The immediate challenge in terms of research is how companies do this implementation and integration with other systems and what other technical and business areas can benefit from understanding energy usage.

Possible uses of Energy Monitoring: Figures 4 and 5 present the tremendous opportunities for energy monitoring as a means for analysis and optimization of machines and manufacturing processes to better implement energy saving strategies. Figure 5 presents an illustration that allows for performance pattern analysis based on the energy meter reading. We believe that the energy meter reading which represents the actual energy consumption for a specific process step on the routed process plan, will pave the way for novel and alternate energy reduction strategies.

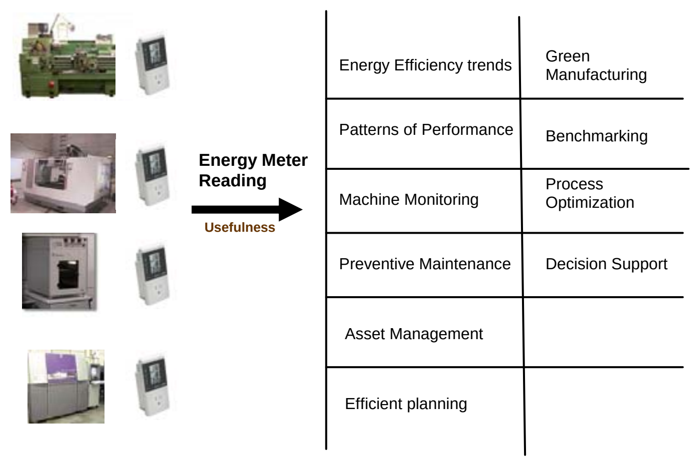

Figure 4 Usefulness of Energy monitoring

The data from the energy meter reading would help companies correlate the type of machining operation/s performed, the material removed, the number of parts machined, and the amount of energy used. This could subsequently be used to precisely calculate the energy used to complete one process step on the part or depending on the requirements it would allow calculation of the following: Energy/machine/cycle, Energy/machine/batch or Energy/machine/part. Further recording the energy readings of a machine in time intervals, for example of a 12- or 24- hour period could allow companies to precisely analyze the corresponding patterns of performance, potentially providing data for preventive maintenance, machine optimization, idle time indications for process planning or scheduling.

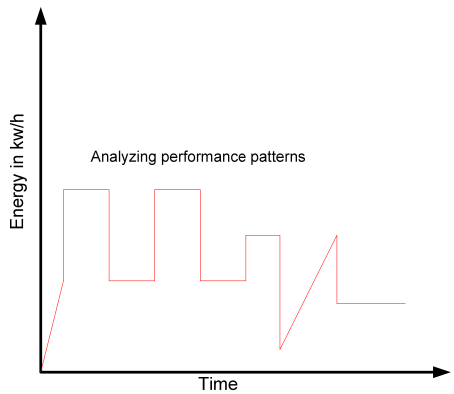

Figure 5 Energy vs. Time

6. ROLE OF STANDARDS IN SUSTAINABLE MANUFACTURING

ISO 14000 is a series of international standards on environmental management [28]. It provides a framework for the development of an environmental management system and the supporting audit program. Of the series, ISO14001 is the most well known and the only ISO 14000 standard that supports certification by an external certification authority. ISO 14001 provides the requirements for environmental management systems, and confirms its global relevance for organizations wishing to operate in an environmentally sustainable manner.

The ISO 14000 series relates to numerous facets of environmental management. ISO 14040 – 14043 were prepared by Technical Committee ISO/TC 207, Environmental Management Subcommittee SC 5, and Life Cycle Assessment (LCA). ISO 14040 provides information on LCA principles and framework, while ISO 14041- 14043 provides additional information regarding the various phases of LCA [29].

At this time the ISO 14000 series standards are designed to guide the practitioner or analyst and are not legally binding or enforceable. They attempt to bring some consistency and credibility to the field as it emerges and takes shape. Table 1 presents a summary of the ISO 14000 series and its purpose of existence.

Table 1 ISO 14000 Series

ISO 14000 Series	**Purpose**
ISO 14001:2004	Requirements with guidance for use
ISO 14004:2004	General guidelines on principles, systems and support techniques
ISO/CD 14005	Guidelines for a staged implementation of an environmental management system, including the use of environmental performance evaluation
ISO 14015:2001	Environmental assessment of sites and organizations (EASO)
ISO 14031:1999	Environmental performance evaluation -- Guidelines
ISO/TR 14032:1999	Examples of environmental performance evaluation (EPE)
ISO 14040:2006	Life cycle assessment -- Principles and framework
ISO 14044:2006	Life cycle assessment -- Requirements and guidelines
ISO/TR 14047:2003	Life cycle impact assessment -- Examples of application of ISO 14042
ISO/TR 14049:2000	Life cycle assessment -- Examples of application of ISO 14041 to goal and scope definition and inventory analysis
ISO/DIS 14050	Vocabulary
ISO 14050:2002	Vocabulary
ISO/TR 14062:2002	Integrating environmental aspects into product design and development
ISO 14063:2006	Environmental communication -- Guidelines and examples

7. PLAN OF ACTION

The plan of action is to first create awareness in the industry promoting the usefulness of energy monitoring of machines and associated manufacturing processes. The next step is to identify potential manufacturing collaborators. This will be through discussions and dialogues in workshops and manufacturing related conferences such as this international conference on manufacturing. Identifying industrial collaborators is crucial to understand the actual industrial energy needs and usage. Manufacturing related research challenges can then be identified. A typical research challenge may be to initiate machine and process level energy monitoring pilot studies that are jointly conducted within industry sites. The studies must be coordinated with manufacturing companies and may be comprised of multiple production runs of several part numbers in medium to large quantities. Based on the study, experiments can be designed and results analyzed. Results and analysis may potentially lead to performance tuning of associated machine and process for energy efficiency. This will simultaneously contribute to the company's asset management. Over time, the recorded results can be used to generate energy efficient manufacturing process planning and scheduling. The results could also be used in decision support systems suggesting energy efficient machines and processes.

The following steps summarize the proposed plan of action:

1. Create industrial awareness
2. Identify potential manufacturing collaborators
3. Understand industries needs
4. Identify research challenges
5. Design and execute experiments
6. Analyze results
7. Performance fine-tune or decision support on alternative solutions

8. CONCLUSIONS AND RECOMMENDATIONS

In this paper, we propose the idea of introducing sustainability in terms of energy efficiency into computer aided process planning to complement cost, quality and time to arrive at alternate sustainable plans or schedules in identified manufacturing processes. The other aim of this paper was to initiate dialogue regarding the potential usefulness of the energy readings of manufacturing equipments and to identify collaboration opportunities.

Energy readings help companies to carefully monitor their assets in terms of energy usage, and provide means to:

- minimize energy use and improve productivity through improved engineering of product and process
- promote a business both environmentally responsible and economically competitive
- implement a comprehensive monitoring and preventive maintenance program that takes into consideration energy usage
- factor energy consumption into any plans that include asset acquisition, allocation, or replacement

As part of the future work, we are interested in identifying potential business use-cases towards implementing and monitoring the individual manufacturing machines and equipments, to be able to better implement energy reduction strategies through energy efficient process planning, asset management and preventive maintenance to assist industries in pursuit of green and sustainable manufacturing initiatives.

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9. APPENDIX

Following are selected definitions of relevance to this paper:

Sustainability: "a characteristic of a process or state that can be maintained at a certain level indefinitely." The term, in its environmental usage, refers to the potential longevity of vital human ecological support systems such as the planet's climatic system, systems of agriculture, industry, forestry, and fisheries, and human communities in general. It also refers to the various systems on which they depend in balance with the impacts of our unsustainable or sustainable design [30].

Sustainable Manufacturing: "meets the needs of the present without compromising the ability of future generations to meet their own needs" [31]. *Sustainable manufacturing* goes beyond just lean and green. It encompasses manufacturing processes, technologies, inter- and intra-company communications, innovation, and much more [32]. Sustainable manufacturing will build off of the idea of sustainable enterprise and the triple bottom line [33]. The triple bottom line emphasizes financial profitability, environmental integrity, and social equity.

Product Life cycle: "the succession of stages a product goes through." *Product Life Cycle Management* is the succession of strategies used by management as a product goes through its life cycle [34].

Energy Efficiency: "a dimensionless number, with a value between 0 and 1 or, when multiplied by 100, is given as a percentage. The energy efficiency of a process is defined as Efficiency η = Output/ Input, where output is the amount of mechanical work (in watts) or energy released by the process (in joules), and input is the quantity of work or energy used as input to run the process" [35].

Energy conservation: "a practice of decreasing the quantity of energy used." It may be achieved through *efficient energy use*, in which case energy use is decreased while achieving a similar outcome, or by reduced consumption of energy services. Energy conservation may result in increase of financial capital, environmental value, national security, personal security, and human comfort [36].

Sustainable energy: It is the provision of energy such that it meets the needs of the present without compromising the ability of future generations to meet their needs. Energy efficiency and renewable energy are "twin pillars" of a sustainable energy policy. Both strategies must be developed concurrently in order to stabilize and reduce carbon dioxide emissions in our lifetimes [37].

Energy meter: a device that measures the amount of electrical energy supplied to or produced by a residence, business or machine [38].