LEVERAGING ENERGY EFFICIENCY PATHWAYS FOR THE SUSTAINABLE DESIGN OF APPLIANCES, BUILDINGS AND ICT PRODUCTS

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Design is a complex activity and can be viewed as a solution to heterogeneous requirements from different stakeholders including customers, markets, regulators and manufacturers. Traditionally, the environment and society have not been considered as stakeholders. However the impact of the design activity on the environment is extensive and often irreversible. Such impact includes resource depletion and degradation, soil, water, noise and air pollution, and increasing energy consumption and greenhouse gas emissions.

In this paper, we present experimental results on specific energy consumption (SEC) in a number of manufacturing processes. We propose a process model of sustainable design and manufacture, the various components that form this paradigm, and energy efficiency metrics based on our measurement of various discrete manufacturing processes. Lifecycle analysis, energy efficiency and material innovation and recovery provide major pathways to enable the transition from business as usual to an environmental and societal cost inclusive economic system. We survey the potential impact of the design of appliances, buildings and ICT products on the environment.

Keywords: Eco-Design, Sustainable Manufacturing, Design for Sustainability.

1. MOTIVATION

The effect of product design on the environment is immense and the global effort towards sustainable design and manufacture has increased the complexity of the design process. According to the Lowell Centre for Sustainable Production, sustainable production/manufacturing is defined as the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for employees, communities, consumers and socially and creatively rewarding for all working people [1]. Sustainable development consists of three main pillars namely the people (society), environment (planet) and the economy (profit) [2].

A number of process planning, manufacturability and other constraints are now being analyzed during product design. The issues of environmental sustainability and global warming have lead to increased awareness of energy consumption in the product lifecycle. The energy consumed in the entire product lifecycle has become an important design criterion and this paradigm will assume an ever increasing role during product design in the years to come.

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Appliances, buildings, and Information and Communication Technology (ICT) products are a major consumer of energy, fueled by the explosive economic growth. In this paper, we provide a survey of the life-cycle and energy efficiency analysis of various products and also present some results of our studies in discrete manufacturing processes. The results of these and our ongoing studies can be utilized in designing sustainable products which can then form the scientific basis for the design of specific policy initiatives in these sectors.

Manufacturing industries are dominant in their environmental impact in areas such as toxic chemicals, waste, energy, and carbon emissions. Manufacturing is also a heavy user of water, and there have been many cases of air, water and soil contamination which have led to such actions as Superfund cleanups, class actions suits and a variety of other corporate liabilities [3]. Our experimental work has therefore focused on manufacturing-metal and polymer processing.

2. SUSTAINABLE DESIGN AND MANUFACTURE

Manufacturing is always thought of as a simple open system into which various resources flow in for conversion and products and wastes flow out. However, one could take a much more extensive view of this problem [3]. If we take the systems view of manufacturing, and track the consequences of manufacturing and design decisions throughout the entire product development cycle, this would take us through (1) raw materials production, (2) manufacturing, (3) the use phase, and finally to (4) the end-of-life phase. This is a far broader view of manufacturing than the one that simply looks at the consumption, wastes and pollutants occurring at the factory. It has become clear that integrating manufacturing into a sustainable society requires the broader systems view [3].

A Process model on sustainable manufacturing has been developed by researchers at the Center for the Study of Science and Technology (CSTEP) [4]. In this model, shown in Figure 1, the major process activities are represented. Each of these activities has an impact on the environment where an impact can be defined as a material or energy flow in either direction. Some activities such as raw material mining, energy production, manufacturing, use phase, recycling and others have a direct impact on the environment. For example, a car has a direct impact during its use phase. Some activities such as the design process and the maintenance and end-of-life (EoL) analysis have an indirect impact in that these activities have the potential to substantively alter the direct impact of other activities. This study shows that for a completely sustainable manufacturing model, all the processes must interact with the environment through the sustainable infrastructure layer. They define sustainability analysis to be the set

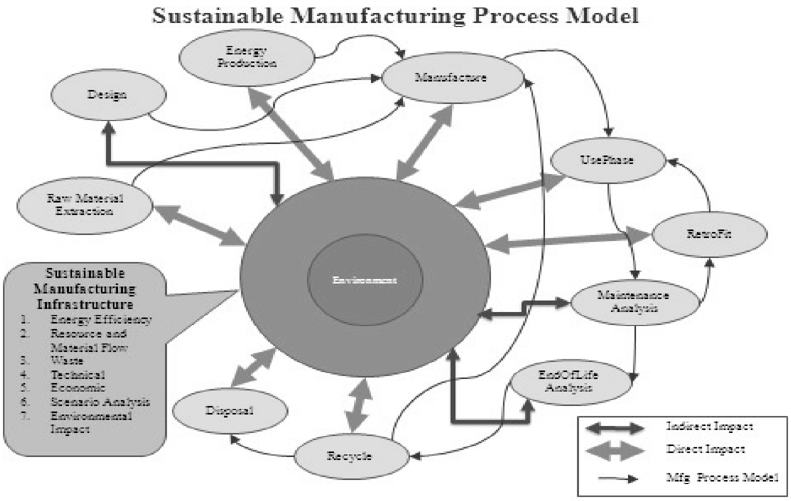


Figure 1. Sustainable Manufacturing Process Model.

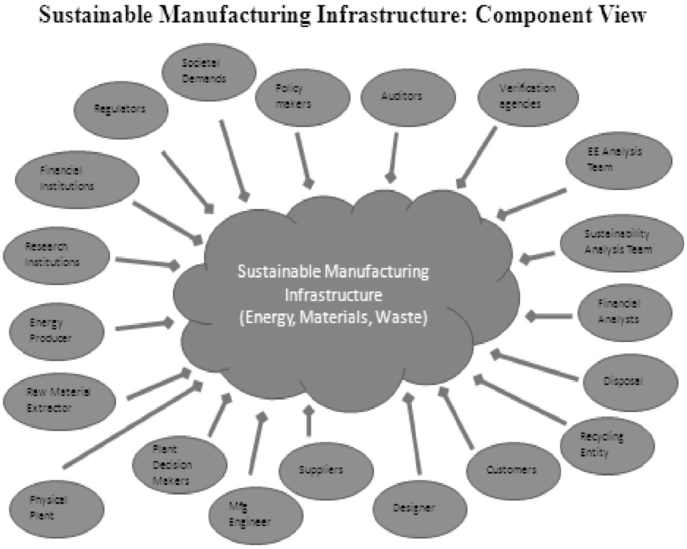


Figure 2. Sustainable Manufacturing Infrastructure: Component View.

of all activities that can reduce the impact of activities on the environment. Some activities listed under sustainable analysis are energy efficiency, material an energy flow, waste flow, total environmental impact and their associated technical, economic and other analyses. The Sustainable Manufacturing (SM) Process Model also details the sequence of processes that occur in the life cycle of manufacturing. The raw material mining and energy production feed the manufacturing plant with required inputs. Inputs also come in from design processes which drive the manufacturing process. The product is also subject to routine and periodic maintenance analysis checks which may feedback with retrofit activities that modify or upgrade the plant. When no further retrofits are deemed to be cost effective, then the end-of-life has been reached and this leads to recycling activities which may partition the material into those that can used up in a next round of manufacturing and those that need to be disposed of in an environmentally benign manner.

The CSTEP researchers [4] also provided a component view of the sustainable manufacturing infrastructure shown in Figure 2. This view represents all of the stakeholders who comprise the SM infrastructure. Each of the institutional stakeholders forms an aggregation relationship, in Unified Modeling Language (UML) terminology, with the SM infrastructure. This report states that sustainability cannot be described as a separate activity that can be taught, trained, learned or practiced independent of the target domain. Sustainability has to be integrated into the various activities that comprise the current economic processes of human endeavor. In SM, sustainability analysis has to be incorporated into the different components shown in the SM infrastructure model. Each activity of the SM process model has to perform its entire repertoire of sub — activities while treating sustainability considerations as an additional factor. This may be treated in various formulations by different components as an optimization function, a hard constraint, a soft constraint, a policy option, a policy mechanism guideline, a compliance target parameter or in other ways such as a modification of societal preferences, value systems and demands. However, the fact remains that in a systems view of the SM process model, sustainability needs to be urgently integrated into the current set of activities.

3. LIFE-CYCLE ANALYSIS: CASE STUDIES

In this section, we survey some of the life-cycle studies that have been conducted in appliance, buildings and ICT sectors.

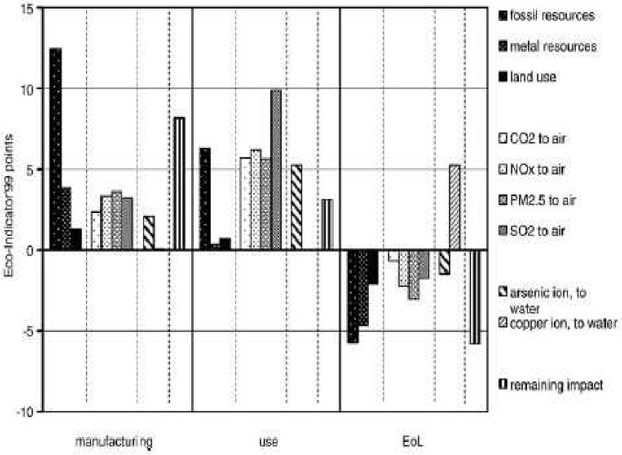


Figure 3. Main contributions to the environmental impacts of a PC system. *Source*: Ref. [5].

3.1. Desktop personal computer

A report examined the complete life-cycle of a desktop personal computer (PC) [5]. The study takes into account the complete life cycle of such a device, ranging from manufacture (including all steps from material extraction up to the final assembly of the system), distribution (from production site to the use site), and functional life span, up to the EoL treatment (including recycling and disposal operations). Figure 3 shows some of the results of an analysis of the main contributions of the environmental impacts of a typical PC system [5].

3.2. Buildings sector

A Lifecycle energy analysis study was conducted on buildings [6]. It is found that worldwide 30–40% of all primary energy is used for buildings and they are held responsible for 40–50% of green house gas emissions. Therefore sustainable development of buildings is necessary to mitigate the energy consumption and the CO_2 emissions in the future.

Life Cycle Energy

The system boundaries of this analysis [6] (Figure 4) include the energy use of the following phases: manufacture, use, and demolition. Manufacture phase includes manufacturing and transportation of building materials and technical installations used in erection and renovation of the buildings. Operation phase encompasses all activities related to the use of the buildings, over its life span. These activities include maintaining comfort condition inside the buildings, water use and powering appliances. Finally, demolition phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants. The energy used is given below:

Lifecycle energy = *Embodied* energy + Operating energy + Demolition energy
LCE = EEi + EEr + OE + DE
Where LCE = lifecycle energy, EEi = intial embodied energy, EEr = recurring embodied energy, OE = operating energy, DE = demolition energy

The analysis of cases found in literature showed that life cycle energy use of buildings depends on the operating (80–90%) and embodied (10–20%) energy of the buildings. Normalized life cycle energy use of conventional residential buildings falls in the range of 150–400 kWh/m^2 per year (primary), as shown in Figure 5, and office buildings in the range of 250–550 kWh/m^2 per year (primary) [6].

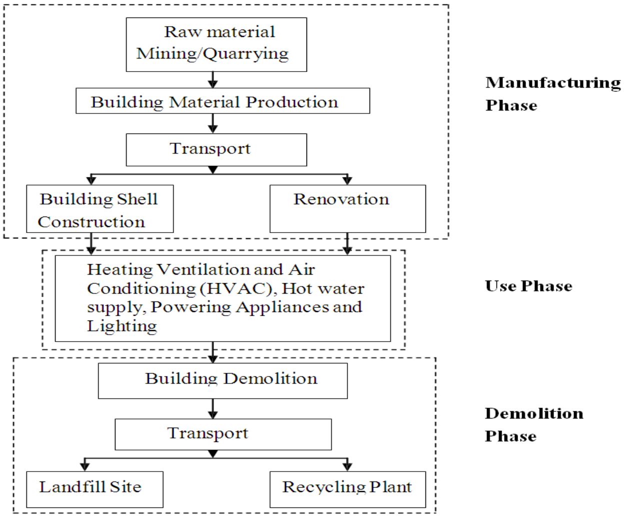


Figure 4. System boundaries for life cycle energy analysis. *Source*: Ref. [6].

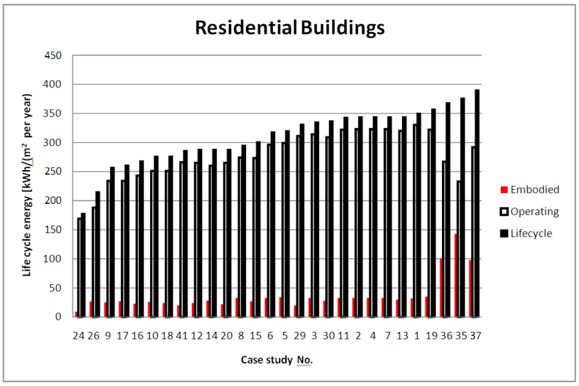


Figure 5. Normalized lifecycle energy for conventional residential buildings (primary). *Source*: Ref. [6].

Boundary of the study

Building’s life cycle energy demand can be reduced by reducing its operating energy significantly through use of passive and active technologies even if it leads to a slight increase in embodied energy. However, an excessive use of passive and active features in a building may be counterproductive. It is further observed that low energy buildings perform better than self sufficient building in life cycle context. Most of the literature studies were done in the foreign countries where oil/gas is used for larger part of the operation phase i.e., for space heating. However, in non-cold and developing countries like India, Thailand etc. electricity derived mostly from fossil fuels (coal) is being used in operation phase for space cooling, lighting, and other purposes. In addition, construction of buildings may involve usage of indigenous building materials and architectural techniques. Hence, a difference in the total life cycle energy of the buildings in non-cold developing countries is expected. For example, life cycle energy indicative figure for office building for Thailand is coming around 850 kWh/m^2 per year (primary). This is quite high compared to office buildings in cold countries. Hence, energy indicative figures for non cold countries need to be evaluated separately [6].

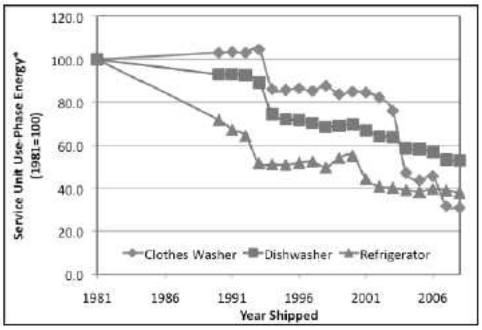


Figure 6. Change in energy consumption for major appliances. *Source*: Ref. [7].

3.3. Appliances

Policy interventions and technological improvements have led to substantial reductions in energy consumption of appliances since 1981, as shown in Figure 6 below. LCI Boundary for this study entails raw material extraction, manufacturing, and use phase for a functional appliance unit. Other phases such as the transportation phase and the end-of-life phase are ignored in the analysis [7].

The paper has also discussed the importance of remanufacturing which does not include the total appliance recycling but rather to a part that is integral to the operation and that can be prone to failure such as compressors, valves, pumps, or control units. Once these units are repaired and reinstalled, the appliance has a new life and can last until another component fails. For new appliances the life cycle inventory (LCI) includes raw material processing ($E_{rm,new}$), manufacturing ($E_{m,new}$), and use ($E_{u,new}$). Similarly, for remanufactured appliances the life cycle energy impacts encompass remanufacturing [7].

The use phase dominates by consuming between 88 to 95 percent of the life cycle energy of the appliances; as such, it is critical to consider the use-phase impacts while evaluating the energy savings potential of appliance remanufacturing [7].

Figure 7 illustrates the retrospective assessment of the total life cycle economic comparison in dollars (normalized by unit volume) of a newly produced refrigerator against 1 generation (one lifetime) older remanufactured refrigerator from 1994 to 2000. The labels on the plot represent the year for which the comparison analysis is conducted (e.g. 2000 refers to the economic comparison analysis in year 2000 between purchasing a new 2000 model refrigerator versus remanufacturing a 1986 refrigerator). ‘REMANUFACTURE’ and ‘BUY NEW’ indicate the optimal decision for economic saving for data points positioned above diving-line and below dividing-line, respectively [7].

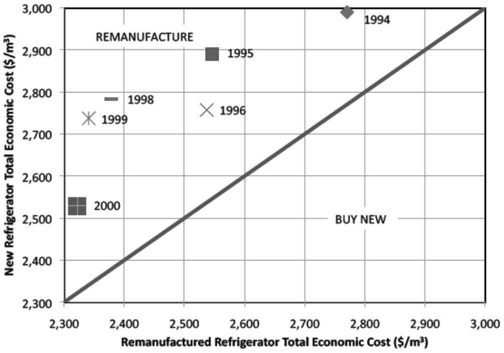
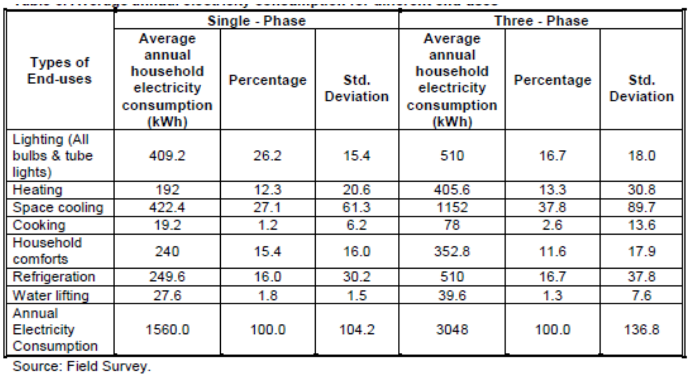


Figure 7. Comparison of total life cycle economic cost for new and remanufactured refrigerators. *Source*: Ref. [7].



Types of End-uses	Single - Phase			Three - Phase		
	Average annual household electricity consumption (kWh)	Percentage	Std. Deviation	Average annual household electricity consumption (kWh)	Percentage	Std. Deviation
Lighting (All bulbs & tube lights)	409.2	26.2	15.4	510	16.7	18.0
Heating	192	12.3	20.6	405.6	13.3	30.8
Space cooling	422.4	27.1	61.3	1152	37.8	89.7
Cooking	19.2	1.2	6.2	78	2.6	13.6
Household comforts	240	15.4	16.0	352.8	11.6	17.9
Refrigeration	249.6	16.0	30.2	510	16.7	37.8
Water lifting	27.6	1.8	1.5	39.6	1.3	7.6
Annual Electricity Consumption	1560.0	100.0	104.2	3048	100.0	136.8

Source: Field Survey.

Figure 8. Average annual electricity consumption for different end–uses. *Source*: Ref. [8].

Another study shows the average annual electricity consumption for different end users based on appliance usage in an Indian city and is shown in Figure 8 [8]. In our view, more studies are needed to evaluate the energy efficiency in the manufacture and service life of appliances and also to provide inputs to formulate public policy in this important sector.

4. ENERGY EFFICIENCY ANALYSIS IN DISCRETE MANUFACTURING

An appliance, ICT product or building consists of various parts which are manufactured using a variety of discrete manufacturing processes. We have carried out energy measurements by installing meters in each unit and tracking the readings for a variety of hydraulic injection molding (Figure 9), compression molding, sheet metal processing (Figure 10), and electro-discharge machining (EDM) machines (Figure 11). We carried out the process for all the machines in each department. Due to space constraints, a summary of the specific energy consumption (SEC) across different machines is shown. It is observed that there is a wide band of SEC across different machines and across different material flow rates. We have made the following observations:

1. The SEC tends to rise initially and then stabilizes at a lower value as the total material processed increases.
2. The SEC tends to be higher for lower flow rates and lower for higher flow rates (Figure 11).
3. The SEC values can be used to perform energy estimation for various batch sizes.
4. Across machines, it is observed that some machines have lower SEC values for a given throughput.

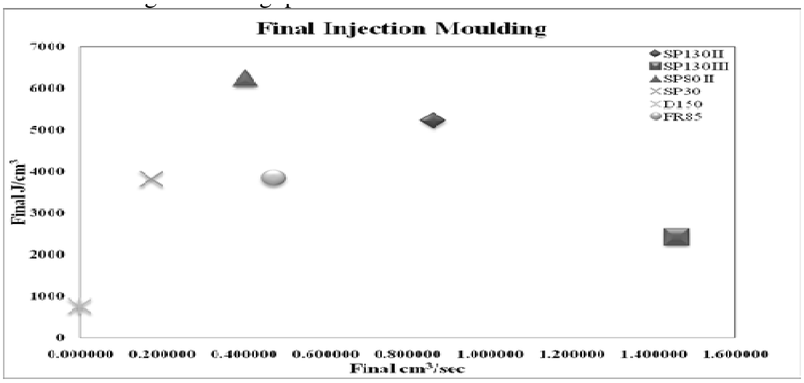


Figure 9. Injection Molding: SEC of various machines as a function of throughput.

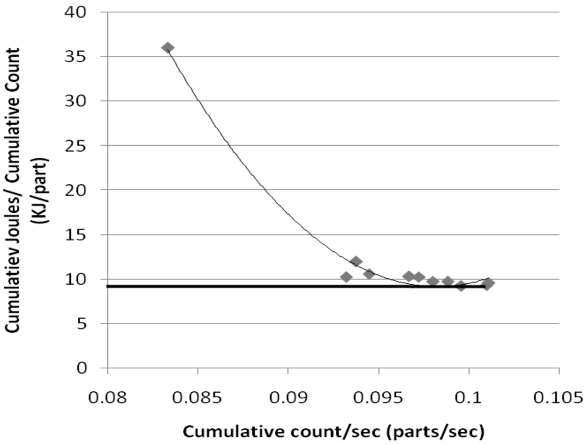


Figure 10. Sheet Metal processing: SEC Vs Flow Rate.

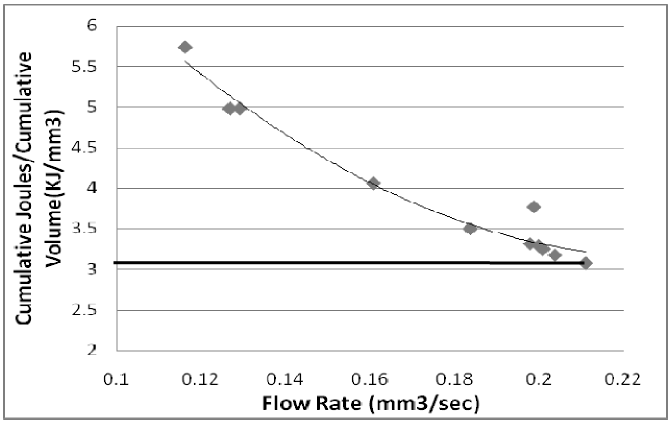


Figure 11. Electro-Discharge Machining: SEC Vs Flow Rate.

5. CONCLUSIONS

In this work, we have performed energy consumption and energy efficiency studies on different discrete manufacturing processes. These studies will be followed up with more detailed studies on the life-cycle energy profile of various products during the manufacturing, service life and recycling phases. These studies will be utilized to form indicators for sustainable design and manufacture of products and to provide inputs for policy design in these sectors.

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