Integrating Low Carbon and Energy Efficiency Constraints in Sustainable Product Design

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Abstract Designing sustainable products are an important element of the low carbon economy that is emerging around the globe. Low carbon materials utilization and energy efficiency in manufacturing and in the consumption phase of a product's life cycle are key components of sustainable product design. However, integrating these factors into the design of consumer products needs further development. The technical, economic and policy aspects of sustainable manufacturing are vital drivers for integrated low carbon and energy efficient products. In this paper, we present some of our work on the technical and policy aspects of sustainable product design. We present a view of the energy efficiency of select appliances in the market and also show an example of integrating low carbon and energy efficiency in various stages of a product life cycle. This work is being extended further to be able to develop an integrated platform for the design of sustainable products.

1.1 Introduction

Life cycle stages of consumer products today directly or indirectly impact the environment in the form of energy and materials usage throughout its lifecycle. Consumer durables such as refrigerators, air conditioners, ceiling fans televisions and other various products are observed to be fast moving energy consuming products utilized in residential and commercial buildings.

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1.2 Sustainable Design and Manufacture

Manufacturing is sometimes 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 [1]. 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 [1].

A Process model on sustainable manufacturing has been developed by researchers at the Center for the Study of Science and Technology (CSTEP) [2]. In this model, shown in Fig 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 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 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.

The CSTEP researchers [2] also provided a component view of the sustainable manufacturing infrastructure shown in Fig 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.

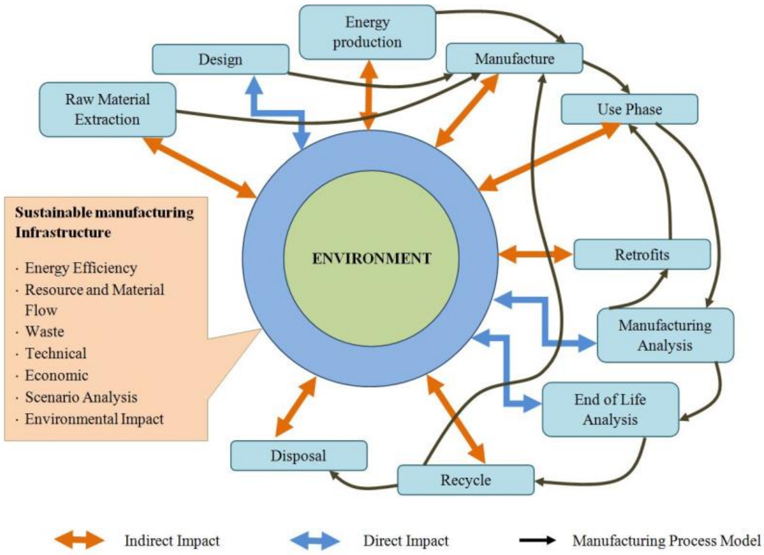

Fig 1 Sustainable Manufacturing Process Model

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.

3.1 Global Initiatives for Sustainable Product Design

India initiated the National Mission for Enhanced Energy Efficiency (NMEEE), one of the 8 missions under the national action plan on climate change enunciating principles of achieving national growth objectives through qualitative directions that enhance ecological sustainability and mitigation of GHG emissions. Bureau of Energy Efficiency (BEE), is the principle organization under the Ministry of Power implementing the star labeling system for appliances. BEE has covered major building appliances and also agricultural pumps in the labeling systems [4]. From 2006, BEE is responsible for the star labeling system for residential and commercial domestic appliances in India. Table 1 shows the numbers of models which have been rated rated till Dec'2010. Energy star program by the U.S. Environmental Protection Agency and the U.S. Department of Energy (DoE) first initiated the energy efficiency among consumer durables helping consumers save money and protect the environment through energy efficient products and practices.

Fig.2 Sustainable Manufacturing Infrastructure: Component View

In 2009, Energy savings from consumers was able to avoid GHG emissions equivalent to those from 30 million cars — all while saving nearly $17 billion on their utility bills according to DoE. Super Efficient Appliances Deployment (SEAD) initiatives are current developments from the US, DoE. , where SEAD partners will work together to “pull” super-efficient appliances and equipment into the market by cooperating on measures like manufacturer incentives and R&D investments. At the same time, partners will “push” the most inefficient equipment out of the market by working together to bolster national or regional policies like minimum efficiency standards. For example, SEAD will identify opportunities for strengthening appliance and equipment efficiency standards through international cooperation.

1.3.1 Product Classification and Energy Rating

Table 1 Total number of models from each appliances categories rated till Dec' 2010 by BEE [4]

Appliances Category	Model rated (2010)	% Growth rate (2010)[5]
Frost Free Refrigerator	633	5
Air Conditioner	1508	5
Tubular Lighting	64	10
Direct Cool Refrigerators	599	5
Water heaters	325	9
Television	60	30

Each durable has a factor called load or power needed to function, which is expressed in wattage (w) or Kilo watts (kW). A typical tubular lighting needs 30-40 watts, and water heater needs 1.5kW or simply 1500W. From the yearly models rating information data, Heating Ventilation and Air Conditioner (HVAC) are the major energy consuming durables with load of 1200-1800W on average. Other appliances are observed to be less than 200W on average as shown in Figure 3.

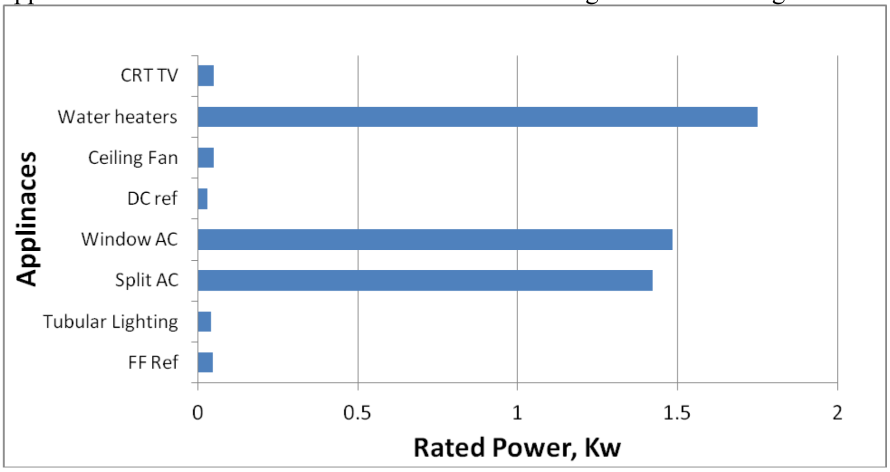

Fig 3 Average rated power of appliances

1.3.2 Product Usage Patterns

Duration of utilization varies from product to product. Each appliance is used only to serve the purpose of our needs. Some are used as mandatory such as refrigerators. A refrigerator a most widely used appliance is continuously in operation round the clock in order to preserve the food. Typical refrigerators either frost free or direct cool are assumed to be in use for 24 hours per day which is

[5] IndiaStats

8760 hours per year. [4,5]Some are seasonal like ceiling fan which are mostly used in summer or during hot conditions. Table 2 summarizes the assumed operating time in hours.

Table 2 Average hours of use of appliances

Appliance	Hours in use
FF refrigerator	8760
Tubular Lighting	2920
Split AC	3360
Widow AC	3360
Direct Cool Refrigerator	8760
Ceiling Fan	2400
Water heaters	1095
Television	2920

1.3.3 Annual Energy Consumption and CO2 Emissions

Table 3 shows the comparative energy consumption scenarios of selected appliances between best and the average rated appliances today. The estimations is based on the current average energy rating and assumed consumption hours as explained in the earlier section.

Table 3 Average Energy Consumption and CO_2 from Average and best technology appliances in 2010

Appliance	Technology	Per Unit, kWh	Total volume Energy GWh	Primary Energy (PJ)	CO2 Emission (Kg, per unit)
Frost Free Refrigerator	Average	663.0	5,151.9	58.5	543.7
	Best	397.4	3,088.5	35.1	325.9
Direct cool Refrigerator	Average	390.0	12,123.1	137.8	319.8
	Best	256.6	7,975.7	90.7	210.4

4 Life cycle Assessment

A Life cycle assessment (LCA) tool can be used to evaluate the environmental aspects and potential impact associated with a product and services throughout its life span. The generic approach to evaluate the LCA of a product is by cradle to grave. The basic aim of LCA is to:

1. Identify the energy and materials used and waste released to the environment.

2. Assess the impact of energy and materials used and wastes released
3. Identify the opportunities for reducing environmental impacts.

The whole framework follows ISO principles and requirements for conducting and reporting life cycle assessment studies. [3] For all appliances evaluated, it is significant the use phase dominated the life-cycle impact, with a proportion of more than 90 percent. Production represented less than 8 percent of the overall environmental burden [7].

Policy interventions and technological improvements have led to substantial reductions in energy consumption of appliances since 1981. The boundary for this study entails raw material extraction, manufacturing, and use phase for a functional appliance unit.

1.4.1 Integrating Low Carbon Materials and Energy Efficiency

We have developed a method to assess the life cycle impact of a product during the design stage by factoring in the low carbon material substitution options and energy efficiency constraints during manufacturing and the service life of common products. In this work, we have assessed the emissions and energy impact for a refrigerator which is one of most commonly used appliances. For a top door or front door refrigerator a typical materials used in the manufacturing is estimated. Figure 6 shows an integrated LCA model of a refrigerator. The proportion and kinds of materials used in this model is an approximate estimate and referring to the analysis of AHAM [1].

1.4.2 Results

The model was demonstrated using the GaBI 4 software. However, the integration of low carbon material substitution and energy efficiency in manufacturing and service life energy consumption are concepts which can be integrated independent of the software analysis tool. We have shown the various materials used as baseline Case 1 and in Case 2 we have substituted a certain amount of steel with a low carbon material. We have also replaced the existing manufacturing process with a more efficient process and have improved the design of the product by reducing its energy consumption during usage as well. All three factors need to be incorporated at the design stage in order to efficiently produce competitive products for a low carbon economy.

The results show that the carbon emissions from the metals such as Steel and aluminum emit high quantity of CO_2, 56.68 and 22.71 Kg CO_2 respectively per unit manufacturing and plastics materials like ABS and EPS together estimated to emit 34 kg CO_2 as shown in Figures 4 and 5 below. Case 1 pertains to the base case and Case 2 is the result of low carbon material substitution and energy efficient manufacturing and service life consumption standards.

Additionally, the particles in the air from typical refrigerator units were contributed by aluminum, glass and other metals. Collectively from metals, about 100-110g of particle is displaced and on an overall from all the selected materials approximately 170g of particles is displaced in the air from a single unit manufactured.

The figures below illustrate the reduced emissions that result from substituting low carbon materials at the design stage and also the energy savings during manufacture and during the service life due to design decisions taken early on. These savings have been demonstrated for the case of one refrigerator unit and are multiplied at the national and global levels by the large volumes of such appliance products that are manufactured annually.

Such an integrated approach can help in improving environmental sustainability of large volumes of appliances and the transition to a sustainable low carbon economy while retaining the competitiveness of manufacturing businesses.

Refrigerator	**Case 1**	**Case 2**	**Case 1**	**Case 2**
Materials	Mass (kg)		Emissions (Kg- CO2)	
Aluminum	2.321	2.321	22.715	22.715
Polystyrene expandable granulate (EPS)	6.875	6.875	17.711	17.711
Acrylonitrile-butadiene-styrene granulate (ABS)	5.577	5.577	17.020	17.020
Copper	2.97	2.97	11.555	11.555
Glass	3.256	3.256	7.254	7.254
Cast Iron	5.016	5.016	6.144	6.144
Brass	0.781	0.781	3.539	3.539
PVC	1.111	1.111	2.481	2.481
Styrene-butadiene rubber mix (SBR)	0.187	0.187	0.580	0.580
Steel	52.305	39.22875	56.680	42.510
Low carbon Materials		13.07625		10.627

Figure 4 Impact on Emissions through Low Carbon and Energy Efficient Design

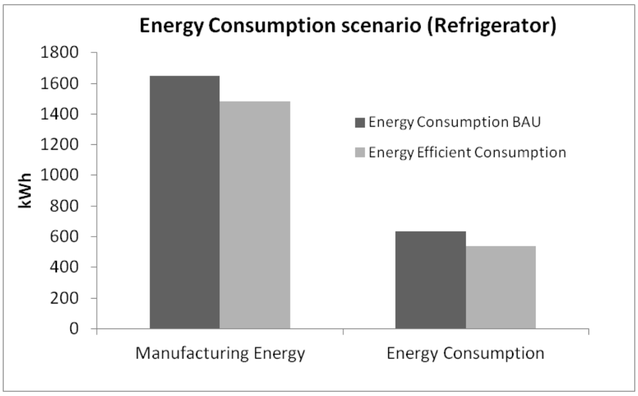

Figure 5 Energy Consumption during Manufacture and Annual Service Life

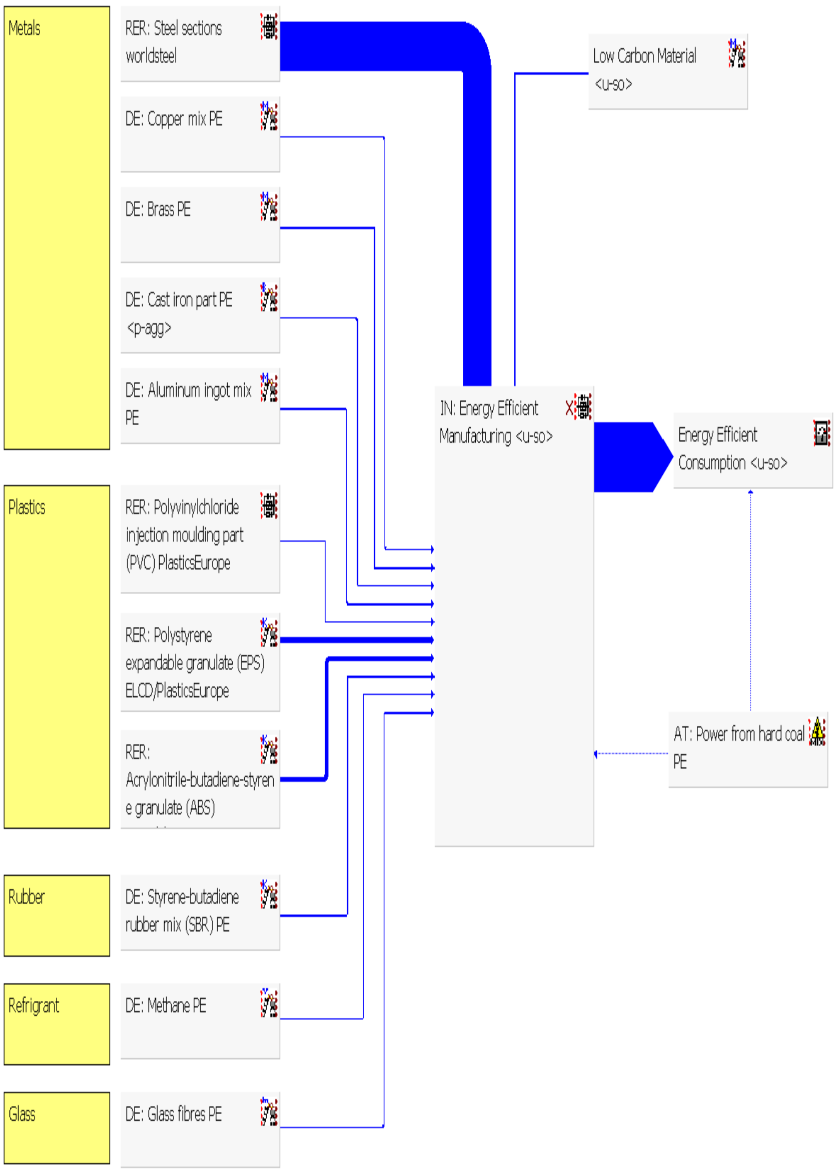

Figure 6 Integrated LCA model of Refrigerator using GaBi 4

1.5 Conclusion

In this work we have presented some of our work on integrating low carbon material substitution and energy efficiency in manufacturing and service life of common appliances. It is seen that both these factors can be integrated into products at the design stage itself and this can results in large energy and emissions savings over the life cycle given the large volumes of the common appliances.

These factors need to be integrated into a framework for sustainable product design for a low carbon economy. These design methods need to become standard practices for increasing the competitiveness of products given the societal and policy moves for sustainable practices and stricter environmental norms. We are continuing the above work with the development of specific design options in the Indian manufacturing context.

1.6 References

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