CSTEP

Sustainability Analysis and Energy Footprint Based Design in the Product Lifecycle

Technical report 2009010

August 2009

CENTER FOR STUDY OF SCIENCE TECHNOLOGY AND POLICY

Appeared in the Proceedings of the Indo-US Workshop on Sustainable Products, Services and Manufacturing Systems, August 18-20, 2009, Bangalore, organized by Indian Institute of Science, Bangalore and National Institute of Standards and Technology (NIST), USA.

SUSTAINABILITY ANALYSIS AND ENERGY FOOTPRINT BASED DESIGN IN THE PRODUCT LIFECYCLE

S.S.KRISHNAN*, N. BALASUBRAMANIAN**, ESWARAN SUBRAHMANIAN***,
V.ARUN KUMAR, G.RAMAKRISHNA AND A.MURALI RAMAKRISHNAN

Center for Study of Science, Technology and Policy (CSTEP)
CAIR Building, Raj Bhavan Circle,
Bangalore, 560 001, India
*ssk@cstep.in
**nbalu23@cstep.in
***sub@cs.cmu.edu

Abstract

In this paper we study the concept of energy efficiency and specific energy consumption (SEC) of manufacturing processes. We discuss the concepts of sustainable design of products, energy consumption based process planning and optimization which comprise the major challenges within the overall product lifecycle development activity. We show that energy consumption and SEC are important metrics that need to be measured for performing sustainable design and process planning. We present SEC results that we measured on a variety of injection molding and compression molding machines.

Keywords: Energy-efficiency, design, manufacturing, sustainability, PLM, environment.

1. Manufacturing and the Environment

The increasing competition among manufacturers has resulted in greater emphasis on high performance and low cost for products. This implies greater pressure at the design stage of the product lifecycle and a reduced number of design-manufacturing analysis iterations. This has lead to an expansion of the activities and constraints that are considered during the design phase. 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.

An International Technology Research Institute (ITRI) study asked, Is “environmentally benign manufacturing” (EBM) an oxymoron? The study mentions that those involved in manufacturing, may feel that many processes such as injection molding, thermoforming of polymers, and sheet metal forming are already quite environmentally benign (T.Gutowski, C.F. Murphy et al, 2001).

For the purpose of the ITRI study, the panel started with the idea that EBM enables economic progress while minimizing pollution and waste and conserving resources. If one takes the long view of things, the problem is much more complex than just drawing a box around a manufacturing process and responding to what goes in and comes out. Decisions in manufacturing, including design, can have profound implications throughout the entire product life cycle, from *raw materials* production, through the *use phase* of the product and into its *end of life* treatment. Hence a major portion of the environmental impact of a manufactured product could occur hundreds, or even thousands of miles from its original point of manufacture. Furthermore, the consequences of these decisions could occur over a time span affecting generations. One simple way to state this is to say that "environmentally benign manufacturing" does not compromise the environment, or the opportunities for development, for the next generation. In other words, it focuses on integrating manufacturing into a sustainable society.

Manufacturing has a large impact on the environment among industrial activities in the US and similarly worldwide. Manufacturing industries are dominant in their environmental impact in such areas 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 (T.Gutowski, C.F. Murphy et al, 2001). It is fairly clear that manufacturing—and in particular metals processing and polymer processing—deserve our attention for their potential impacts on the environment.

2. Systems View of Manufacturing

Manufacturing is commonly thought of as a simple open system into which flows various resources for conversion, and out of which flows products, wastes and pollution. However, one could take a much more extensive view of this problem (T.Gutowski, C.F. Murphy et al, 2001). 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. These two different views of manufacturing can be seen in Figure 1. The overall view is of the "closed" systems view of manufacturing, showing all of the major activities and the connecting paths for reuse and recycling. In the center of the figure one can see the "open" systems view of manufacturing, which features only the box labeled "Mfg.," along with two input arrows representing design and raw materials, and two output arrows representing wastes and products. It has become clear to us that integrating manufacturing into a sustainable society requires the broader systems view (T.Gutowski, C.F. Murphy et al, 2001).

3. Polymer Processing

Polymer processing is concerned with the conversion of polymer resins into parts. Resins are generally classified as either thermoplastics or thermosets (T.Gutowski, C.F. Murphy et al, 2001). In general, thermoplastics come as solid pellets or sheets and are softened or melted by heating during the process and solidified by cooling. These materials can be reheated and reformed and can be recycled by this means. Thermosetting materials, on the other hand, usually come in low molecular weight flowable material forms such as

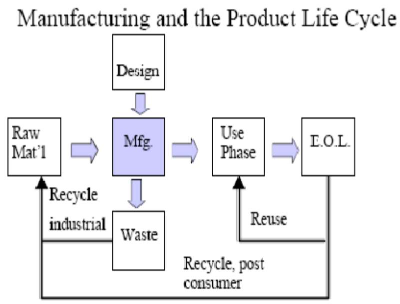

Figure 1. A closed systems view of manufacturing showing all major activities and reuse and recycle paths (T.Gutowski, C.F. Murphy et al, 2001).

liquids or partially cured "pastes" and are solidified by a chemical reaction. Hence they cannot be re-melted. The chemical reaction to form the thermosets is initiated by some external energy source, usually heat, or by mixing the reactants just prior to molding. The major environmental impacts associated with polymer processing fall into four categories: (1) energy usage, (2) waste, especially from thermosets, (3) wastewater, and (4) VOCs and HAPs from the polymers and/or from processing aids or additives such as solvents and blowing agents.

Examples of thermoplastics are PE and PET that are used extensively in automobile interiors, and ABS, PC and HIPS which are used in computer components such as housings. Examples of thermosetting polymers are polyurethanes and polyesters that are used in automobile exterior panels and glass/epoxy composites that are used for printed circuit boards.

a. ***Injection Molding:*** An example of an important process that is used extensively for thermoplastics processing and in a modified form for thermoset processing is injection molding. A schematic of thermoplastic injection molding is shown in Figure 2 (T.Gutowski, C.F. Murphy et al, 2001). Solid pellets are loaded into the hopper and are melted as they move along the extrusion barrel. The melt is then forced into a closed cavity mold under high-pressure. For high-volume production the mold is likely to be water-cooled and to use a hot runner system. The injection-molded part then solidifies by cooling and is automatically ejected from the tool. Typical injection molding cycles are quite short, on the order of tens of seconds. Injection molding can produce precolored, highly complex parts to net-shape. In many cases there are no secondary operations required prior to use of the part. In other cases, cleaning, painting or coating and assembly with other components may be required before the product is ready. The environmental impacts associated with injection molding are related to energy usage, which is primarily associated with melting, pumping and out-gassing of volatiles which for thermoplastics is usually small.

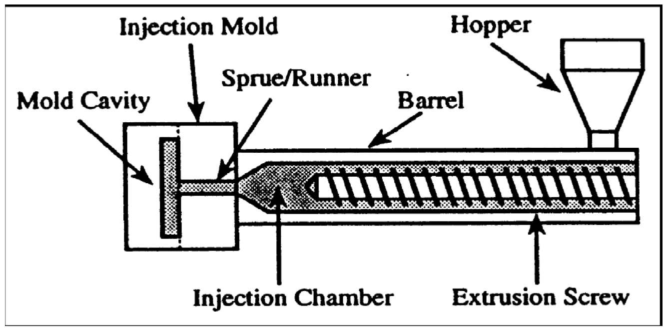

Figure 2. Schematic of injection molding (T.Gutowski, C.F. Murphy et al, 2001).

In-process scrap is usually reground and recycled when a cold runner system is used. Hot runner systems reduce, and in many cases eliminate, the need to recycle the cold runner and save the energy associated with molding and then regrinding and recycling the cold runner.

b. ***Compression molding:*** Compression molding is a high-volume, high-pressure method suitable for molding complex, high-strength fiberglass reinforcements (Wikipaedia, 2009). Advanced composite thermoplastics can also be compression molded with unidirectional tapes, woven fabrics, randomly orientated fiber mat or chopped strand. The advantage of compression molding is its ability to mold large, fairly intricate parts. Also, it is one of the lowest cost molding methods compared with other methods such as transfer molding and injection molding; moreover it wastes relatively little material, giving it an advantage when working with expensive compounds. However, compression molding often provides poor product consistency and difficulty in controlling flashing, and it is not suitable for some types of parts (Wikipaedia, 2009). Products manufactured by compression molding include bottle caps, jar closures, electric plugs and sockets, toilet seats and trays among many others (European Commission, 2006).

4. Energy Requirements for Manufacturing Processes

In their paper(M.Mani et al, 2008), NIST researchers, proposed 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. They also sought 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 account energy usage
- Factor energy consumption into any plans that include asset acquisition, allocation or replacement

As part of the future work, they (M.Mani et al, 2008) suggested identifying potential business use-cases towards implementing and monitoring the individual manufacturing machines 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.

Usually the series of production steps involved in manufacturing are automated in the case of high throughput processes. (T.Gutowski, J.Dahmus and A. Thiriez, 2006). For some processes each of these steps can be integrated into a single piece of equipment. For example, a modern milling machine can include a wide variety of functions including work handling, lubrication, chip removal, tool changing, and tool break detection, all in addition to the basic function of the machine tool, which is to cut metal by plastic deformation. The energy required by the additional functions can be a large fraction of the total energy consumption of the machine. At lower production rates the machining contribution is even smaller. This behavior is also found in other processes. In general, there is a significant energy requirement to start-up and maintain the equipment in a "ready" position. Once in the "ready" position, there is then an additional requirement which is proportional to the quantity of material being processed.

Stage	**SEC (MJ/kg)**	**Energy Related Emissions**				
		CO_2	SO_2	NO_x	CH_4	Hg
		g	g	g	g	mg
Compounder	5.51	284.25	1.26	0.51	10.32	0.01
Injection Modler						
Hydraulic	13.08	674.82	2.98	1.22	24.49	0.01
Hybird	7.35	379.33	1.68	0.68	13.77	0.01
All-Eletric	6.68	344.57	1.52	0.62	12.50	0.01

Table 1. Energy-related air emissions for the "compounder" stage and the "injection molder" stage. (A.Thiriez and T.Gutowski, 2006).

5. Energy Requirements in Plastics Molding

Injection molding appears to be on the same order of magnitude in terms of energy consumption when compared to other conventional manufacturing processes (A.Thiriez and T.Gutowski, 2006). For instance, processes such as sand and die casting have similar energy requirements (11-15 MJ/kg). However, the impact of injection molding seems insignificant when compared to processes used in the semi-conductor industry, such as chemical vapor deposition and atomic layer deposition. This is not entirely accurate and in order to understand the real impact of a manufacturing system one has to consider how widespread its use is in the economy. Injection molding is one of the predominant manufacturing processes, and its use is increasing daily in growing economies like China and India. Energy related emissions refer to those emissions originated from the generation of electricity necessary to run the processes. Table 1 presents energy related emissions for the compounder and the injection molder.

Figure 3 portrays the power requirement for a hybrid and an all-electric machine both running the same part with a cycle time of 14 seconds(A.Thiriez and T.Gutowski, 2006). Simple inspection reveals substantial energy savings from using all-electric over hybrid technology. Note that the curve for a hydraulic machine would be even higher than that of the hybrid. For hydraulic and hybrid machines SEC seems to exhibit a decreasing behavior with increasing throughput, as portrayed in Figure 4. This derives from spreading fixed energy costs over more kilograms of polymer as throughput increases. The power in a hydraulic and hybrid can be described as:

$$P = P_0 - k\dot{m} \qquad (1)$$

where,

$$P_0 = fn(hydraulic\ pumps, computer, etc.)$$

k = *extra SEC to process the polymer*

where Po is the fixed power requirement (power required when the machine is on, but not processing any polymer), $\dot{m}$ is the throughput or process rate, and k is a processing constant. In terms of SEC, this formula can be expressed as:

$$\frac{P}{\dot{m}} = \frac{E}{m} = SEC = \frac{P_0}{\dot{m}} + k \qquad (2)$$

As throughput increases, SEC approaches the constant k as observed in Fig. 4.

6. Energy Measurements During Plastics Processing

The energy consumption per kilogram of end product can be calculated for each machine. The literature provides the relevant data in Figure 5 for the examined production process in relation to energy consumption per kilogram (Leonardo Energy, 2009). There is no major difference between injection and extrusion molding. The average consumption per kWh/kg does not differ by much according to a study (Leonardo Energy, 2009). Specific energy consumption (SEC) however can differ quite significantly from machine to machine.

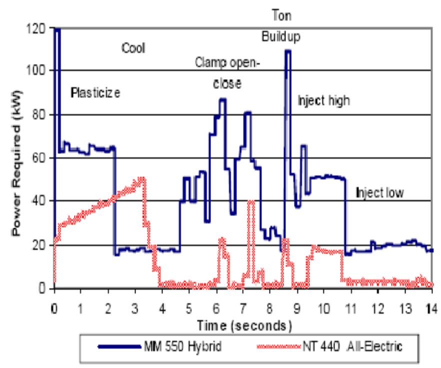

Figure 3. Energy consumed in the injection molding cycle of a hybrid (electric screw drive) and an all-electric machine. Source: (A.Thiriez and T.Gutowski, 2006).

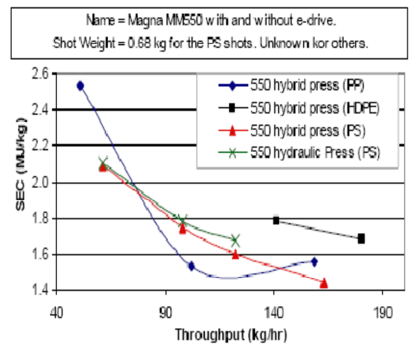

Figure 4.SEC vs. throughput for a Magna MM550, hydraulic and hybrid. There is no inclusion of the efficiency of the electric grid. Source: (A.Thiriez and T.Gutowski, 2006).

Energy consumption depends on a variety of different factors (Leonardo Energy, 2009):

a. Type and characteristics of the plastic (for instance, each material has a different melting temperature)
b. Design, complexity, and size of the end product. The greater the pressure on the mold, the more energy is consumed.
c. Each technique used for the shaping of the product has its own SEC, depending on heating, molding and cooling.
d. The higher the quantity of production, the lower the SEC.
e. The cycle time determines how long the pump or electrical motor is switched on during the molding process.
f. Size of the machine
g. Frequency of use of the mold
h. Outside temperature (there is a 10 per cent higher consumption in the summer)

a. Energy Consumption in Injection Molding:

We have carried out energy measurements for a variety of hydraulic injection molding machines. A summary of the SEC across different machines is shown in Figure 6. 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:
The SEC tends to rise initially and then stabilizes at a lower value as the total material processed increases (Figure 8).

1. The SEC tends to be higher for lower flow rates and lower for higher flow rates (Figure 7).
2. The final summary graphs also show how the machines perform with respect to each other while comparing SEC to flow rate/throughput.

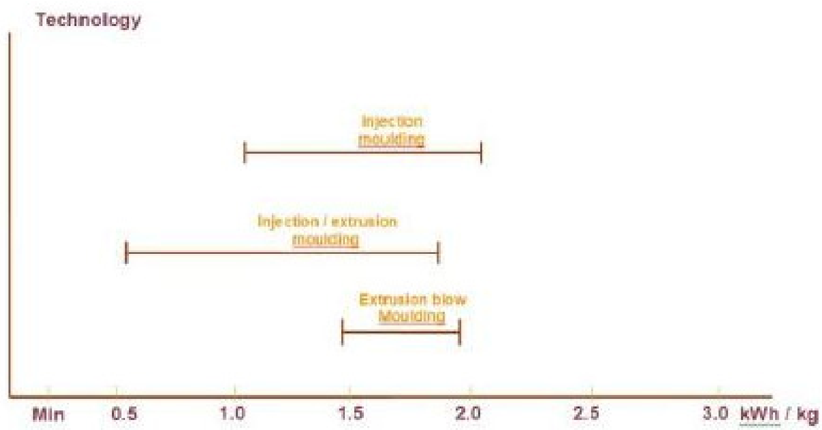

Figure 5. Specific Energy Consumption for some plastic processes from the literature (Leonardo Energy, 2009)

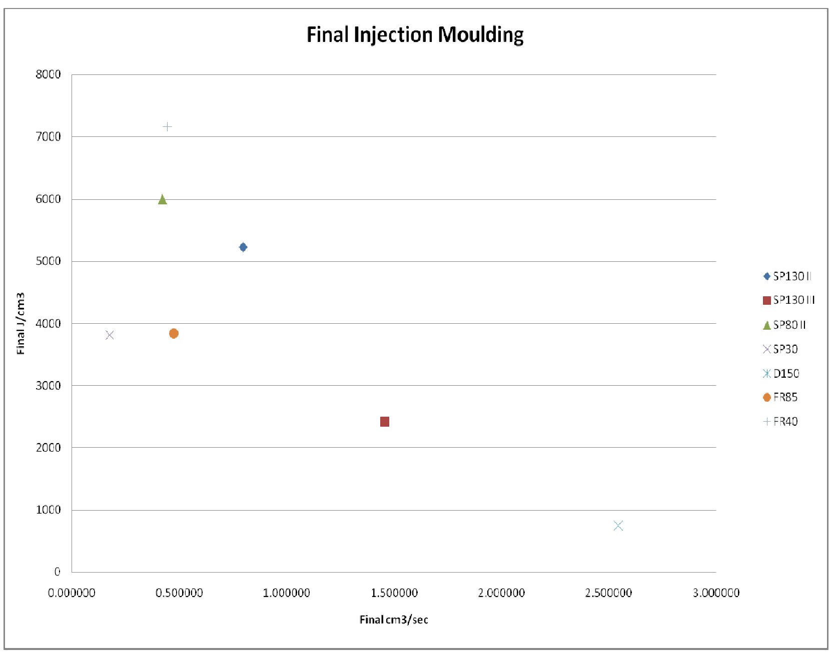

Figure 6. SEC for multiple Injection Molding machines as a function of throughput

3. The general SEC values for IM are between: 1 - 7 MJ/kg, assuming a grid efficiency of 33%.
4. Across machines, it is observed that some machines have lower SEC values for a given throughput.

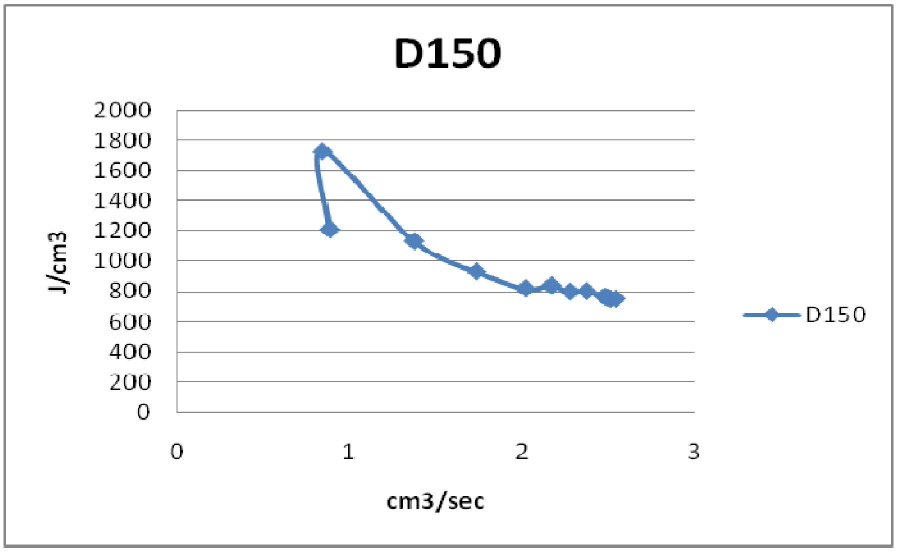

Figure 7. SEC for a specific Injection Molding machine as a function of throughput.

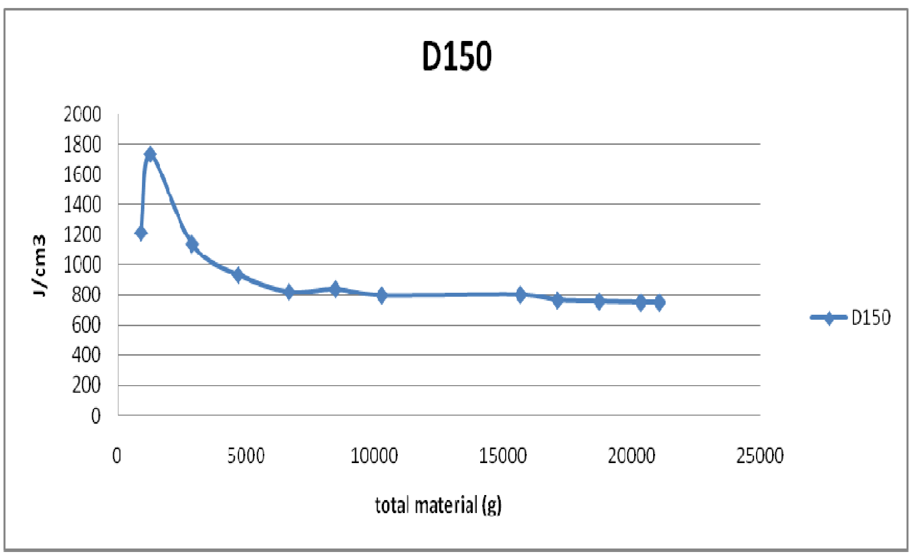

Figure 8. SEC for a specific Injection Molding machine as a function of total material flow

b. Energy Consumption in Compression Molding

We have also carried out energy measurements for a variety of compression molding machines. A summary of the SEC across different machines is shown in Figure 9. It is observed that there is a wide band of SEC across different machines and across different material flow rates.

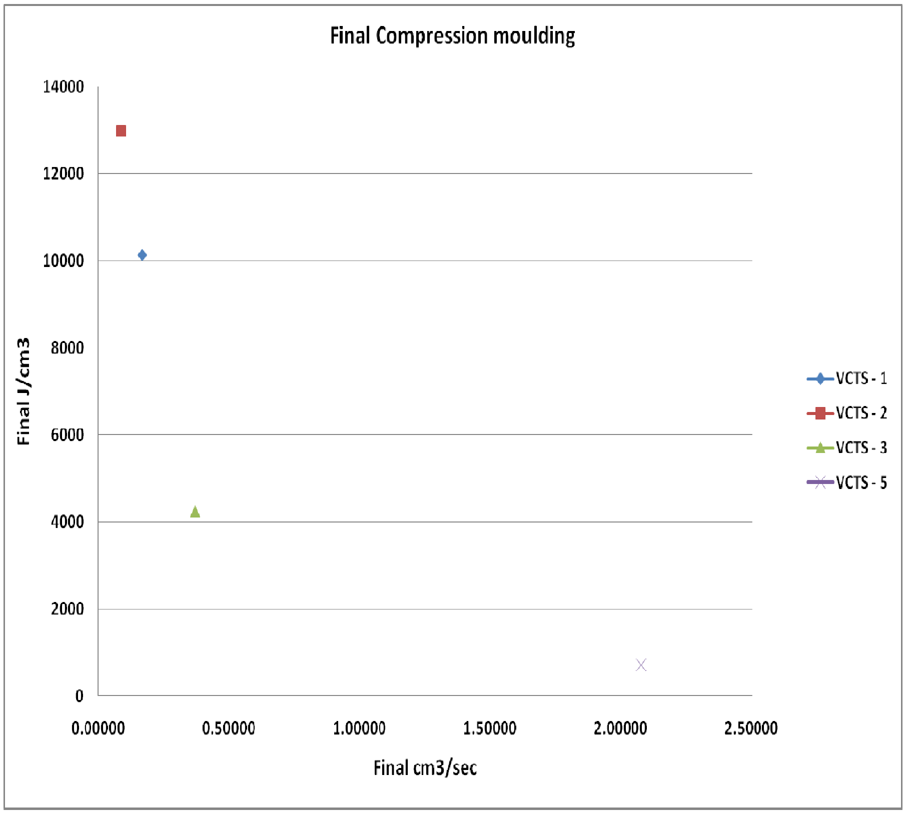

Figure 9. SEC for multiple Compression Molding machines as a function of throughput

We have also made the following observations:
The SEC tends to rise initially and then stabilizes at a lower value as the total material processed increases (Figure 11).

1. The SEC tends to be higher for lower flow rates and lower for higher flow rates (Figure 10).
2. The final summary graphs also show how the machines perform with respect to each other while comparing SEC to flow rate/throughput.
3. The general SEC values for CM are between: 1 - 13 MJ/kg. , assuming a grid efficiency of 33%.

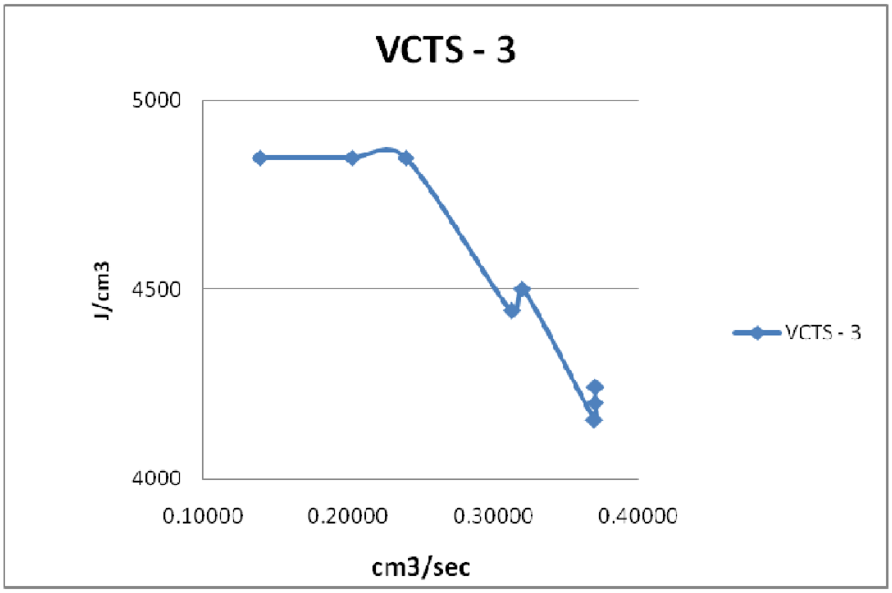

Figure 10. SEC for a specific Compression Molding machine as a function of throughput

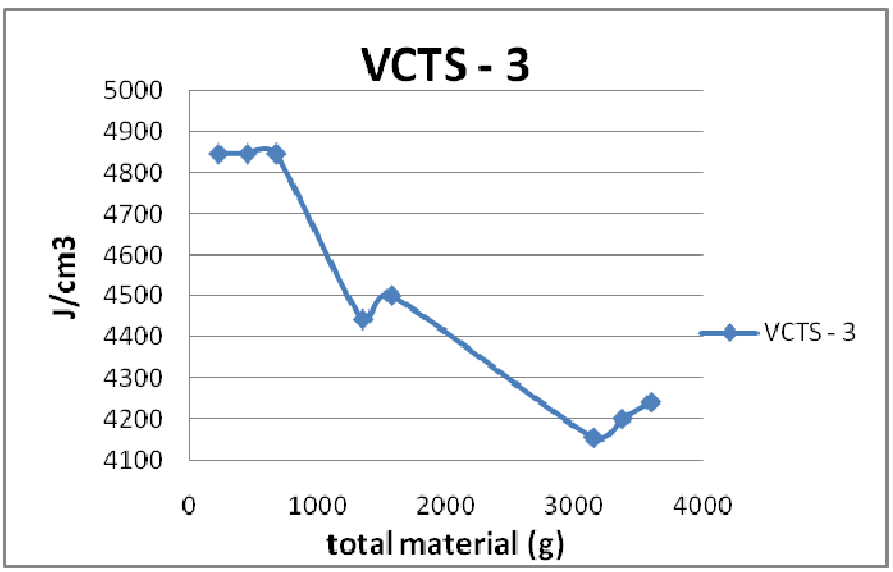

Figure 11. SEC for a specific Compression Molding machine as a function of total material flow

8. Conclusions

In this work, we have performed energy consumption and energy efficiency studies on different plastic molding machines. These studies are important steps towards several goals such as sustainable and low energy consuming design of products, energy consumption based process planning and optimization, design of machines with lower SEC values for a given throughput, among others. We propose to continue our studies in areas such as sheet metal stamping, NC and other manufacturing operations.

Acknowledgements: We gratefully acknowledge the cooperation extended to us by NTTF where we carried out the energy measurements described in this paper. We also gratefully acknowledge the SSN Educational and Charitable Trust and the Jamshetji Tata Trust for their support of the above work.

References

1. European Commission, Low Energy Plastics Processing, *Reduced Energy Consumption in Plastics Engineering European Best Practice Guide*, October 2006.
2. Leonardo Energy, Power Capacity and Utilization Guide, *Plastics Industry Report*, www.leonardo-energy.org, January, 2009, accessed June 16, 2009.
3. M.Mani, S.Rachuri, E.Subrahmanian, K.W.Lyons, R.D.Sriram, Introducing Sustainability Analysis Early into Manufacturing Process Planning, In *Proceedings of the 14th International Conference on Manufacturing Science and Engineering*, Evanston, IL, USA., October 2008.
4. T.Gutowski (Panel Chair), C.F. Murphy (Panel Co-chair) et al, Wtec Panel Report On Environmentally Benign Manufacturing, *International Technology Research Institute*, April 2001.
5. T.Gutowski, J.Dahmus, and A.Thiriez, Electrical Energy Requirements for Manufacturing Processes, in *Proc. 13th CIRP International Conference on Life Cycle Engineering,* Leuven, 2006.
6. A.Thiriez and T.Gutowski, An Environmental Analysis of Injection Molding, In *ISEE*, 2006.
7. http://en.wikipedia.org/wiki/Compression_molding, accessed in June 2009.