An Environmental Analysis of Injection Molding
Extended Abstract – Green Manufacturing Processes

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Plastic components are integral parts in electrical and electronic (E&E) products. 8.5% of the plastic production is dedicated to this market [Fisher et al. 2005]. Although this number might seem small it is larger than the amount of plastic used for the automotive industry (8%) [Fisher et al. 2005]. In E&E products plastic can represent from 3% of the total weight in medical equipment to 33% in small house appliances and 42% in toys [Fisher et al. 2005]. The majority of this plastic used for E&E products is injection molded in order to attain the specific geometric requirements. Injection molding involves melting polymer resin together with additives and then injecting the melt into a mold. Once the resin is solidified, the mold opens and the part is ejected. At first glance, injection molding may appear to be a relatively benign process with respect to the environment due to its low direct emission levels and apparently low energy consumption. However, when calculating the environmental cost of injection molding one must also take into account the ancillary processes and raw materials used in the process. Aside from the raw material production stage which has substantial emissions, the main metric in the whole injection molding process is energy consumption. The large scale of the injection molding industry makes the environmental impacts of this process especially critical. In other words, a small increase in the efficiency of the process could lead to substantial savings for the environment.

This paper investigates injection molding from an environmental standpoint, yielding a system-level environmental analysis of the process. It provides a transparent process model that includes all major steps involved in the production of injection molded products and shows the dependency of injection molding on the most important process parameters. This paper presents a summary of our findings along with detail on four major issues:

1. Relationship between energy consumption and throughput.
2. Differences in environmental performance between hydraulic and all-electric machines.
3. Role of secondary/subsidiary process in the energy accounting.
4. Environmental scale of injection molding.

Background:

With regards to injection molding life cycle inventories (LCI), much effort has gone into studying the production of raw materials (polymers) as well as the product end-of-life aspects, such as disassembly separation and recycling. Amongst the researchers in this area, it is worth mentioning Ian Boustead, who developed a set of "eco-profiles," or LCI's, of the most consumed polymers in the plastic industry. He also created life cycle inventories for injection molded PVC and injection molded polypropylene. The former LCI studied two injection molding facilities in France that produce PVC fittings for pipe drainage systems [Boustead Conversion PVC]. The latter LCI studied one facility in the U.K. that produces 12 to 76 g polypropylene components [Boustead Conversion PE]. These studies are product specific, narrowing on one application and one set of processing parameters. In an effort to obtain a range of values typical in injection molding, and thus more breadth of data, this study incorporates measurements from machines processing different products and materials. It also provides a transparent outline of all the sub-processes that make up the injection molding process together with their environmental performance.

Other contributors to the field of injection molding include Mattis et al. 1996 and Boothroyd et al. 2002. Mattis et al. used a 3-D solid modeling environment and numerical analysis to explore the influence of mold design, part design, and some process parameters on the process efficiency. Boothroyd et al., whose goals were to develop design-for-manufacturing guidelines, developed a set of empirical equations predicting machine size and processing time of each stage in the injection molding cycle.

Summarized Results:

This environmental analysis of injection molding highlights a few important points. With regards to the injection molding machine, the choice of machine type (hydraulic, hybrid or all-electric) has a substantial impact on the specific energy consumption[1] (SEC), or energy consumption per kilogram of polymer processed. The average SEC values for hydraulic, hybrid and all-electric machines analyzed are 11.3, 5.5 and 4.8 MJ/kg respectively. For hydraulic and hybrid machines SEC seems to exhibit a decreasing behavior with increasing throughput, as portrayed in *figure 1*. 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:

$$\begin{aligned} &P = P_0 + k\dot{m} \\ &where, \\ &P_0 = fn(hydraulic\ pumps, computer, etc..) \\ &k = extra\ SEC\ to\ process\ the\ polymer \end{aligned} \qquad \textbf{Equation 1}$$

where P_o 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:

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

As throughput increases, SEC approaches the constant k as observed in *figure 1*.

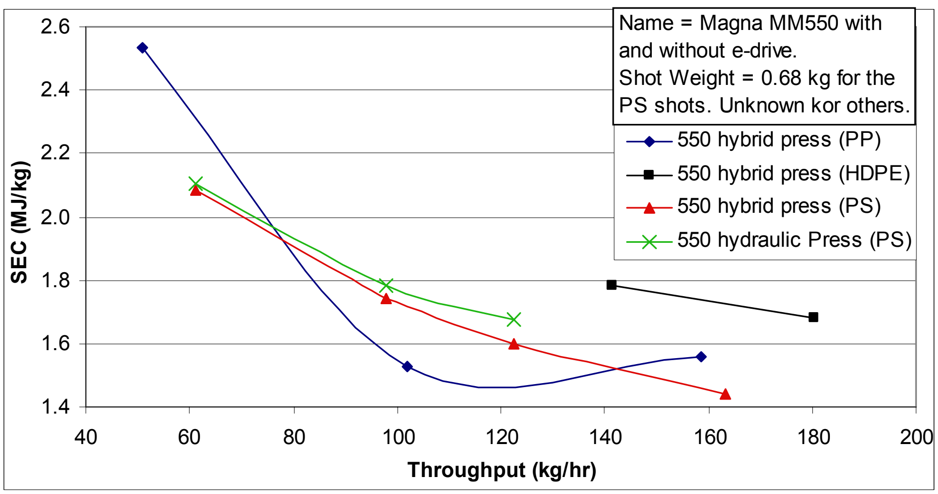

Figure 1 – SEC vs. throughput for a Magna MM550, hydraulic and hybrid. There is no inclusion of the inefficiencies of the grid. Source: [Ferromatik Milacron Excel].

[1] Here we use a common expression, while in fact energy is not consumed but transformed. A more rigorous but less understood definition for SEC would be "specific exergy consumed".

Since all-electrics have very low fixed energy costs (ex: running the computers) SEC stays constant as throughput increases.

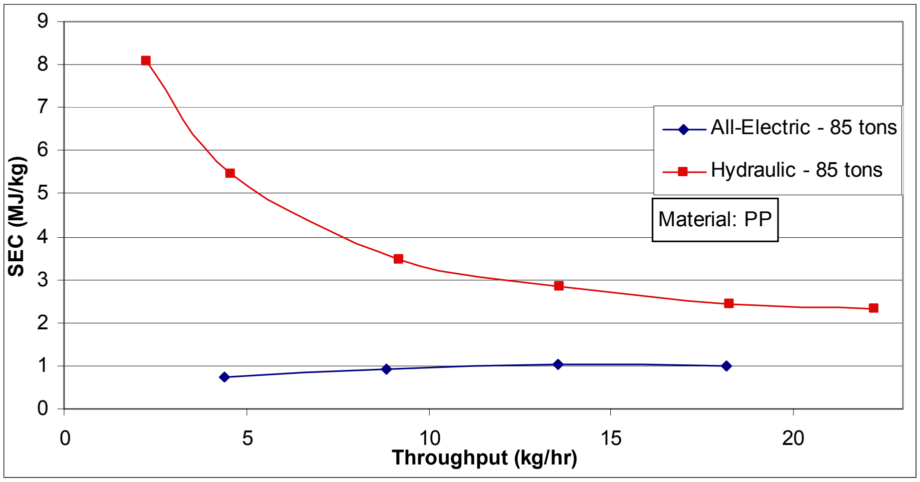

Figure 2 – SEC vs. throughput for an all-electric and a hydraulic machine. No account has been taken for the inefficiencies of the grid. Source: [Ferromatik Milacron 2001].

The type of polymer processed also has an impact on SEC values. As the viscosity and specific heat capacity of the polymer increase so does SEC. Finally, SEC varies greatly with part shape. The thinner and the greater the projected area of the part the greater the SEC.

With regards to the LCI, it is interesting to note how even though the energy consumption for injection molding machinery seems low, when other stages in the process are included the figure becomes substantial. Considering the energy consumption of all stages from the compounder to the injection molder (not including polymer production), hydraulic, hybrid and all-electric machines yield average values for SEC of 19.3, 13.6 and 12.89 MJ/kg respectively. These values take into account the energy burden associated with producing the electricity to power the manufacturing processes. When the polymer production stage is included in the scope of the LCI, the energy consumption values increase up to 100 MJ/kg. In the whole LCI, producing the polymer has the greatest impact on the environment. After the polymer production, injection molding machinery and extrusion have the greatest impact. *Figure 3* provides a diagram of the LCI together with SEC values for each stage. For all stages, except for the polymer production stage, data is presented for a generic polymer, which is a weighted average of the polymers studied according to the amounts injection molded.

ENERGY CONSUMPTION BY STAGE in MJ/kg of shot

Thermoplastic Production

	HDPE	LLDPE	LDPE	PP	PVC	PS	Generic by Amount: Consumed	Generic by Amount: Inj. Molded	Extras: PC	Extras: PET
avg	89.8	79.7	73.1	83.0	59.2	87.2	81.2	74.6	95.7	78.8
low	77.9	79.7	64.6	64.0	52.4	70.8	69.7	62.8	78.2	59.4
high	111.5	79.7	92.0	111.5	79.5	118.0	102.7	97.6	117.4	96.0

Polymer Delivery		
	avg	0.19
	low	0.12
	high	0.24

Compounder

	Internal Transport	Drying	Extrusion	Pelletizing	Building (lights, heating, ect..)
avg	0.09	0.70	3.89	0.16	0.99
low	-----	0.30	2.40	0.06	-----
high	-----	1.62	5.00	0.31	-----

Subtotal

avg	5.84
low	3.83
high	8.01

Polymer Delivery		
	avg	0.19
	low	0.12
	high	0.24

Injection Molder

	Internal Transport	Drying	Injection Molding (look below)	Scrap (Granulating)	Building (lights, heating, ect..)
avg	0.04	0.70		0.05	0.99
low	-----	0.30		0.03	-----
high	-----	1.62		0.12	-----

	Injection Molding - Choose One: Hydraulic	Hybrid	All-Electric
avg	11.29	5.56	4.89
low	3.99	3.11	1.80
high	69.79	8.45	15.29

Subtotal

	Hydraulic	Hybrid	All-Electric
avg	13.08	7.35	6.68
low	5.35	4.47	3.17
high	72.57	11.22	18.06

TOTAL w/ Generic Inj. Molded Polymer

	Hydraulic	Hybrid	All-Electric
avg	93.92	88.20	87.52
low	72.23	71.35	70.05
high	178.68	117.34	124.18

TOTAL w/o Polymer Prod

	Hydraulic	Hybrid	All-Electric
avg	19.29	13.57	12.89
low	9.42	8.54	7.24
high	81.04	19.70	26.54

Notes

Drying - the values presented assume no knowledge of the materials' hygroscopia. In order words, they are averages between hygroscopic and non-hygroscopic values. For hygroscopic materials such as PC and PET additional drying energy is needed (0.65 MJ/kg in the case of PC and 0.52 MJ/kg in the case of PET)

Pelletizing - in the case of pelletizing an extra 0.3 MJ/kg is needed for PP

Granulating - a scarp rate of 10 % is assumed

Figure 3 - Overall System Diagram. The values above account for the efficiency of the electric grid. Multiple sources. Contact authors for extended bibliography.

The overall injection molding energy consumption in the U.S. in a yearly basis amounts to 2.10 x 10^8 GJ. This value includes all steps in the LCI, except polymer production. Including polymer production would increase this number by an order of magnitude. This value (2.10 x 10^8 GJ) is of similar magnitude to the overall U.S. energy consumption for sand casting, and greater than the whole electric production for some developed countries, as seen in *table 2*. It seems imperative for industry to keep improving the efficiency of the process, since small savings anywhere in the LCI can lead to tremendous energy savings on a national scale. This seems an intelligent move in a time of raising energy prices.

Annual Electric Production			
Smaller than U.S. Injection Molding Values		**Same Order of Magnitude than U.S. Injection Molding Values**	
Country	**GJ/year**	**Country**	**GJ/year**
Bolivia	1.38E+07	Mexico	7.15E+08
Chile	1.50E+08	Argentina	3.11E+08
Colombia	1.53E+08	Venezuela	3.15E+08
Costa Rica	2.39E+07	Austria	2.19E+08
Cuba	5.18E+07	Belgium	2.68E+08
Dominican Republic	3.50E+07	Finland	2.56E+08
Ecuador	3.87E+07	Italy	9.29E+08
Guatemala	2.22E+07	Netherlands	3.18E+08
Jamaica	2.26E+07	Norway	4.32E+08
Nicaragua	8.41E+06	Spain	8.04E+08
Paraguay	1.62E+08	Sweden	5.54E+08
Denmark	1.27E+08	Switzerland	2.47E+08
Greece	1.80E+08	Turkey	4.20E+08
Iceland	2.84E+07	Czech Republic	2.52E+08
Ireland	8.35E+07	Poland	4.87E+08
Portugal	1.59E+08	Ukraine	5.88E+08
Hungary	1.24E+08	Iran	4.47E+08
Romania	1.85E+08	Saudi Arabia	4.65E+08
Iraq	1.18E+08	Malaysia	2.44E+08
Israel	1.48E+08	Pakistan	2.48E+08
Kuwait	1.13E+08	Taiwan	5.44E+08
United Arab Emirates	1.36E+08	Thailand	3.48E+08
Korea, North	1.14E+08		
New Zealand	1.39E+08		
Philippines	1.58E+08		

Table 1 – Selected countries with smaller or same order of magnitude electric production to the amount of energy spent injection molding (compounder + injection molder) in the U.S. Source: [EIA 2002].

The work presented in this paper hopes to provide an easy way of estimating the energy cost and emissions in all the life cycle stages surrounding injection molding. Further work in this topic should refine the analysis and provide more theoretical models to predict energy consumption trends.

References:

1. Boothroyd, Geoffrey, Peter Dewhurst, and Winston Knight [Boothroyd et al. 2002]. Product Design for Manufacture and Assembly. New York: Marcel Dekker, 2002.

Boustead LCI's:

2. Boustead, Ian [Boustead Conversion PE]. Eco-profiles of the European Plastics Industry: Conversion Processes for Polyolefins. Brussels: APME, 2003. Visited: Visited: 25 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20040610_153828/PolyolefinsConversionReport_Nov2003.pdf>

3. Boustead, Ian [Boustead PC]. Eco-profiles of the European Plastics Industry: Polycarbonate. APME. Visited: 20 Mar. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20010821_112344/41.pdf>

4. Boustead, Ian [Boustead PET]. Eco-profiles of the European Plastics Industry: Polyethylene Terephthalate. Brussels: European Centre for Plastics in the Environment, 2002. Visited: 18 Mar. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20020218_124341/EcoProfile_PET_Resins.pdf>

5. Boustead, Ian [Boustead PE]. Eco-profiles of the European Plastics Industry: Polyolefins. Brussels: APME, 2003. Visited: 10 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20030820_140541/PolyolefinsReport_July2003.pdf>

6. Boustead, Ian [Boustead GPPS]. Eco-profiles of the European Plastics Industry: Polystyrene (General Purpose)(GPPS). Brussels: APME. Visited: 13 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20010820_083836/19.pdf>

7. Boustead, Ian [Boustead PVC]. Eco-profiles of the European Plastics Industry: Polyvinyl Chloride. Brussels: APME & ECVM, 2002. Visited: 10 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20021009_123742/EcoProfile_PVC_resins_Sept2002.pdf>

8. Boustead, Ian [Boustead Conversion PVC]. Eco-profiles of the European Plastics Industry: PVC Conversion Processes. Brussels: APME, 2002. Visited: 25 Feb. 2005 <http://www.apme.org/dashboard/business_layer/template.asp?url=http://www.apme.org/media/public_documents/20021009_123742/EcoProfile_PVC_conversion_Oct2002.pdf>

NOTE: All the Boustead LCIs are available at <http://www.apme.org/lca/>

9. Energy Information Administration [EIA 2002]. International Energy Annual 2002. Washington: Department of Energy, 2002. Visited: 23 Feb. 2005 <http://www.eia.doe.gov/iea/contents.html>

10. Ferromatik Milacron [Ferromatik Milacron 2001]. A Communications Update for Ferromatik Milacron Sales Professionals. North America: 2001. Sent by Mark Elsass (Cincinnati Milacron Supervisor for Technical Service). Received on: Apr. 2005. via email: <Mark_Elsass@Milacron.com>.

11. The previous reference was received as a word document. In it was imbedded an EXCEL file that will be referred to as: [Ferromatik Milacron Excel].

12. Fisher, Michael M., Frank E. Mark, Tony Kingsbury, Jurgen Vehlow, and Takashi Yamawaki [Fisher et al 2005]. Energy Recovery in the Sustainable Recycling of Plastics from End-of-Life Electrical and Electronic Products. 2005 IEEE International Symposium on Electronics and the Environment, 16 May 2005, IEEE Computer Society.

13. Mattis, James, Paul Sheng, William DiScipio, and Ken Leong [Mattis et al. 1996]. A Framework for Analyzing Energy Efficient Injection-Molding Die Design. Technical Report (CSM Report-96-09). University of California, Berkeley, 1996.

NOTE: for the LCI results not all references that were used in the calculations were listed. If the reader desires to obtain the references please send an email to athiriez@mit.edu requesting them.