Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference MSEC2013 June 10-14, 2013, Madison, Wisconsin

# MSEC2013-1222

# CHARACTERIZING ENERGY CONSUMPTION OF THE INJECTION MOLDING PROCESS

Jatinder Madan Systems Integration Division National Institute of Standards and Technology Maryland, USA &

Sant Longowal Institute of Engineering & Technology, Longowal, Sangrur, India Email: jatinder.madan@nist.gov Mahesh Mani Systems Integration Division, National Institute of Standards and Technology Maryland, USA & University of Maryland College Park, Maryland, USA

Kevin W. Lyons Systems Integration Division National Institute of Standards and Technology Maryland, USA

### ABSTRACT

Presently available systems for sustainability assessment do not fully account for aspects related to a product's manufacturing. In an effort to make more sustainable decisions, today's industry seeks reliable methods to assess and compare sustainability for manufacturing. As part of the Sustainable Manufacturing program at the National Institute of Standards and Technology (NIST), one of our objectives is to help develop the needed measurement science, standards and methodologies to evaluate and improve sustainability of manufacturing processes. As a first step towards developing standard reference sustainability characterization methodologies for unit manufacturing processes, in this paper we focus on injection molding with energy as the sustainability indicator. We present a science-based guideline to characterize energy consumption for a part manufactured using the injection molding process. Based on the study, we discuss the selection of process parameters and manufacturing resources, determination of cycle time, theoretical minimum energy computations, and estimated energy computations for characterizing the injection molding process.

**Keywords**: sustainable manufacturing; injection molding; cycle time; theoretical minimum energy; energy consumption; information models.

### INTRODUCTION

Sustainability assessment systems do not fully account for aspects related to a product's manufacturing, such as manufacturing resources, process parameters and cycle time. In an effort to make more sustainable decisions, today's industry seeks reliable methods to assess and compare sustainability for manufacturing.

The sustainability assessment is made by way of key sustainability performance indicators, such as energy and air emission. The Organization for Economic Co-operation and Development (OECD) [1] defines 18 key performance indicators (KPIs) for sustainable manufacturing, which include water intensity, energy intensity, renewable energy intensity, and others. Energy is an important KPI for sustainable manufacturing and is the focus in this paper.

In this paper, we selected the injection molding process for characterizing energy. Injection molded parts are widely used in consumer products and industrial equipment. For example, the injection molded components constitute 42 % and 33 % in toys and medical equipment components, respectively. The extent of energy use in manufacturing processes in general, and the injection molding process in particular, are well recognized [2, 3]. According to Gutowski et al. [4], injection molding processes use energy in the order of 10 MJ/kg, not counting auxiliary operations such as compounding and drying, which is comparable to other processes like machining [5]. The overall energy consumption in the US injection molding industry on a yearly

basis amounts to  $2.06 \times 10^8$  GJ. This is comparable to the energy consumption for sand casting and to the entire electricity production of some developed countries [6].

The injection molding process consists of melting raw polymer granules, also referred to as plasticating<sup>1</sup> [7], and injecting the molten polymer into a mold (or die). A typical injection mold has a cavity, which is a negative of the part being produced. When the cavity is filled with plastic, it is cooled and the plastic becomes solid material resulting in a positive component. After the injected molten polymer is solidified, the mold, which consists of two halves, is opened, and the solidified part is ejected out by force. Figure 1 shows a schematic diagram of the injection molding machine.



To help US industries, one of the objectives of the Sustainability Manufacturing program of NIST is to develop measurement science standards and methodologies to evaluate and improve sustainability of manufacturing processes [3]. As a precursor, this paper presents a science-based guideline to charac-

terize energy consumption for the injection molding process. The organization of this paper is as follows. The next section presents a summary of the work related to energy consumption in the injection molding process alongside research gaps and objectives of this paper. The following section discusses the stages of the injection molding process, and presents a brief overview of the proposed guideline with the help of its schematic. Subsequent sections deal with different steps of the proposed guideline, namely: (i) select initial process parameters, (ii) define cavity details and determine other process parameters, (iii) select injection molding machine, (iv) determine cycle time and theoretical minimum energy, and (v) estimate energy consumption. Next, a summary of the different parameters influencing energy consumption for the injection molding process is presented. Lastly, we conclude with a brief discussion of future research directions.

#### **RELATED WORK**

In this section, the literature related to the determination of energy consumption in the injection molding processes is discussed at different levels of industry, factory, machine and process. A brief summary of the research gaps and objectives of the present work is also presented at the end of this section.

*Industry sector level*: Thiriez and Gutowski [6] studied the impact of the type of injection molding machine on the specific energy consumption (SEC<sup>2</sup>). The SEC typically varies from 13.2 MJ/kg for electrically powered machines to 19.0 MJ/kg for those using hydraulic systems. The Rigid Plastics Packaging Group [9] quantified total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste for two plastic fabrication processes, namely injection molding and thermoforming. The scope of the study was to generate a life cycle inventory (LCI) database for products made by injection molding and thermoforming in the North America.

Factory level: Lu et al. [10] developed a process modeling parameter optimization algorithm using a genetic algorithm (GA) based on the lexicographic method. The implementation of their framework reduced the energy consumption for a laboratory scale test. Pun et al. [11] proposed a multiple-criteria methodology for evaluating environmental impacts in the plastic injection molding. They identified various indicators of environmental impact assessment and established a multiplecriteria rating matrix. The study provided injection molding manufacturers with a means to assess the environmental performance and perform benchmarking analysis. Muroyama et al. [12] suggested that discrete event simulation (DES) and life cycle assessment (LCA) functionality can be combined to analyze the utilization and processing of manufacturing resources in a factory setting. They demonstrated DES and LCA's ability to facilitate decision-making and, optimize the injection molding process in terms of productivity and energy use.

*Machine level*: Kanungo and Swan [13] investigated the energy consumption of all electric and hydraulic injection molding machines. They compared various aspects like energy consumption, cost, throughput, and process parameters affecting energy consumption.

*Process level*: Qureshi et al. [14] presented an empirical approach to characterize the relationship between energy consumption and process variables for the injection molding process. Riberio et al. [15] presented a thermodynamic model that estimates the energy consumption for any injection molded part based on its geometry and the material. They initially consider the efficiency of the system to be 100 % and then take different values of machine efficiency to compare estimated and actual energy consumption. Weissman et al. [16] developed a methodology to compute estimates for the total energy consumption for manufacturing of injection molding parts. It utilizes part

<sup>&</sup>lt;sup>1</sup> Plasticating refers to conversion of plastic granules to flow-able melt. It happens inside the screw barrel assembly of the injection unit in the injection molding machine.

O The plastic granules move inside the screw channel when screw is rotated.

O The screw has three zones: feed, compression and metering.

O In the compression zone the material is gradually compressed.

O Plastic material under shear changes its viscosity (Shear Thinning)

O Melt is then homogenized in metering zone.

<sup>&</sup>lt;sup>2</sup> SEC is the energy consumption per unit of throughput. For example energy consumption per unit mass.

information to determine shot size and cycle time. Based on the actual power consumption of the different drives, the energy usage is determined for a specific injection molded part. Kalla et al. [17] provided a methodology to collect unit process life cycle inventory (uplci) for the injection molding process using the CO2PE! framework [18].

#### Research gaps

Despite very useful work of the researchers, based on our review, we identified some research gaps mentioned below.

- i. Most of the reported research provides industry, factory, or machine level analysis, which cannot accurately estimate the energy performance at the process level.
- Studies at the process level are useful to collect data but have limited application for estimation and benchmarking a wide range of materials and manufacturing resources.
- iii. Pre and post operations, such as drying, which are closely associated with the process, have not been considered.

This paper attempts to fill above mentioned research gaps. To overcome the research gaps, there is a need to develop a science-based guideline, which includes the required pre and post operations to estimate energy consumption for the injection molding process. Various factors related to part design, manufacturing resources, material and process planning need to be considered for energy estimation. The guideline should support multiple methods for comparing injection molding processes based on the theoretical minimum energy requirements.

# **Objectives of the present work**

The objectives the paper are:

- Determine theoretical minimum energy required for the injection molding process.
- Establish guidelines for estimating the energy consumption of the injection molding process, which also includes pre and post operations.

The subsequent sections provide details of our proposed guideline.

# INJECTION MOLDING PROCESS STAGES AND BRIEF METHODOLOGY OF THE PROPOSED GUIDELINE

In this section, we first provide a brief overview of the injection molding process followed by a brief description of our proposed methodology.

#### Stages of the injection molding process

The injection molding process is comprised of three stages: drying, injection molding, and regrinding. In the drying stage, the plastic beads and the reusable scrap are fed into the dryer, where it is either set free of moisture or the moisture is brought down to an acceptable level. In the second stage of injection molding, the solid plastic mixture (plastic beads and reusable scrap) is fed to the injection molding machine, where it is melted and the actual injection molding process is carried out. The injection molding process cycle consists of mold closing, injecting, cooling, mold opening, and ejecting. Other operations of feeding and melting, which take place within the injection molding machine, operate parallel to the injection molding. Lastly, in the third stage of regrinding, runner, gates, and any other solid plastic, which is attached to the part, is removed for regrinding.

#### Sustainability characterization methodology

Sustainability characterization methodology primarily comprises performance metrics, process analytics and supporting information models for sustainability [3]. In lieu of pursuing a comprehensive sustainability characterization methodology, we focus on the injection molding process with energy as a performance metric and discuss corresponding analytics to compute the theoretical minimums for benchmarking and comparison purposes.

Figure 2 presents a schematic of our proposed guideline. The schematic shows the interaction of the information required for characterizing energy consumption for the injection molding process. The steps of the guideline are subsequently explained in later sections of the paper.



Figure 2: Schematic of the guideline for estimating injection molding energy consumption

The five steps of the proposed guideline are mentioned below.

- i. Determine initial process parameters
- ii. Define cavity details and determine other process parameters
- iii. Select injection molding machine
- iv. Determine cycle time and theoretical minimum energy requirements
- v. Estimate energy consumption

An injection mold part design provides the necessary details like part material, volume, weight, and wall thickness. In Step 1, these details are used to find initial process parameters, such as injection pressure and temperature. Step 2 is used to determine other process parameters, such as the injection force, and the required number of cavities. In Step 3, based on the cavity details and process parameters, the selection of the suitable injection molding machine is made. Step 4 helps determine the process cycle time and theoretical minimum energy requirements for the process. Lastly, Step 5 of the guideline helps estimate the energy consumption taking into account the process-specific manufacturing resources. The following sections provide details of these steps.

# SELECTING INITIAL PROCESS PARAMETERS

Injection molding process parameters like injection pressure, injection temperature, and ejection temperature are related to the material and, to some extent, to the geometric details of the part. These parameters affect the energy required for the injection molding process. The determination of these initial process parameters is discussed.

<u>Injection pressure</u>: This is the pressure exerted on the melt in front of the screw tip during the injection stage, when the screw is acting like a plunger. It is a common practice to refer to the corresponding pressure in the hydraulic cylinder as the injection molding pressure. Since a considerable amount of this pressure is lost by the time the melt reaches the cavity, the maximum pressure of the standard barrel is calculated using Eq. 1 [19].

$$p_{\text{max}} \sim 1.25 \times p_{\text{inj}} \tag{1}$$

where  $p_{max}$  (MPa) and  $p_{inj}$  (MPa) are the maximum pressure required from the injection molding machine and the required injection pressure respectively. The required injection pressure depends upon the type of the material and part characteristics. A representative list of pressure requirements for some plastic materials, which varies with part characteristics, is given in Table 1.

<u>Injection and mold temperatures</u>: Injection temperature and the temperature inside the mold are the key process parameters. Recommended processing temperatures for some thermoplastic materials are provided in Table 2.

Table 1: Injection pressure  $(p_{inj})$  for producing plastic parts [19]

Plastic	Required effective injection pressure (MPa)							
material <sup>3</sup>	Easy flow Medium flow High			Thin-wall				
	material,	materials,	cosity	parts, thin				
	heavy	standard sec-	material,	wall injec-				
	sections	tions	thin sec-	tion				
			tions					
ABS	80 to 110	100 to 130	130 to150	150 to 200				
CAB	80 to 110	100 to 130	130 to 160	N/A				
POM	90 to 110	110 to 130	130 to150	N/A				

Table 2: Recommended injection and mold temperatures [19]

Plastic	Injection temperature	Mold temperature
material	(°C)	(°C)
ABS	200 to 260	40 to 60
CAB	180 to 220	40 to 80
POM	180 to 230	80 to120

# CAVITY DETAILS AND SELECTION OF OTHER PRO-CESS PARAMETERS

After the initial parameters are selected, the next step is to decide the number of cavities in the mold (or die). As defined earlier, cavity is a negative of the part being produced. In the injection molding process, the mold may have a single cavity or multiple cavities, which helps attain a higher production rate. The number of cavities effects many parameters of the injection molding process including injection volume (or shot volume), projected area, and injection force. The method to compute these parameters is discussed in the following paragraphs.

<u>Shot volume</u>: Shot volume for a cavity is the amount of molten polymer required to fill the mold cavity, in each cycle. Since most of materials shrink in volume when cooled, a shrinkage allowance is given to the cavity. Therefore, shot volume primarily should take care of shrinkage compensation due to cooling and additional material required for gates and runners. To compensate for shrinkage, the volume of a cavity (m<sup>3</sup>) can be found using Eq. 2.

$$l_{\text{cavity}} = V(1 + \frac{\varepsilon}{100}) \tag{2}$$

where  $\varepsilon$  is the percentage shrinkage rate of the polymer from injection temperature to room temperature and V (m<sup>3</sup>) is the volume of the injection molded part.

Furthermore, using Eq. 3 [20] the volume of the gating system, which is a function of the part volume, can be calculated.

$$V_{\rm shot} = V \left( 1 + \frac{\varepsilon}{100} + \frac{\Delta}{100} \right) n \tag{3}$$

where  $\Delta$  is the percentage of the part volume used for the gating system, and *n* is the number of cavities.

<u>Cavity projected area</u>: The cavity projected area is simply the area of cross-section perpendicular to the withdrawal direction (or opening direction of the mold). According to Boothroyd et al. [20], the increase in projected area of the cavity due to pres-

<sup>&</sup>lt;sup>3</sup> ABS Polystyrene and styrene copolymers

CAB Cellulose acetate butyrate

POM Polyoxymethylene

ence of gates and runners is proportional to the increase in volume. The cavity projected area is therefore found using Eq. 4.

$$A_{\text{total}} = A_{\text{part}} \times \frac{v_{\text{shot}}}{v}$$
(4)

where  $A_{total}$  (m<sup>2</sup>) and  $A_{part}$  (m<sup>2</sup>) are the total projected area of the cavity (along-with gating system) and the part, respectively.

<u>Separating force</u>: When the molten polymer is injected into the cavity at high pressure, core and cavity halves of the die tend to separate by a force, which is known as the separating force. The separating force<sup>4</sup> (MN) is calculated using Eq. 5.

$$F_{\text{separting}} = p_{\text{inj}} \times A_{\text{total}}$$
(5)

# SELECTING THE INJECTION MOLDING MACHINE

After injection molding process parameters are determined, the next step is to identify the production planning requirements for selecting the appropriate machine. For estimating energy consumption, the information about the specific injection molding machine is required. We assume that the number of cavities is decided before the injection molding machine is selected. Basically, an injection molding machine may be divided into two units, namely a clamping unit and an injection unit. The suitability of a die-cavity needs to be checked for both the units. As an example, specifications of an injection molding machine are given in Table 3.

T 1 1 2 C		c	• • .•	1 1'	1 * 1	
Table 31 Sn	ACT TICATIO	n of an	intection	molding	machine l	
1401C J. 5p	concatio	n or an	injection	monume	machine	41

	Item	Unit	Machine ID						
	Clamp	tf <sup>5</sup>	100						
nit	force								
n d	Clamp	m	0.35						
am	stroke								
IJ	Ejector	tf				3			
	force								
Injection			Injection Unit 1			Injection Unit 2			
	unit								
	Injection	cm <sup>3</sup>	38	78	130	78	162	254	
nit	capacity								
n r	Shot	g	35	72	120	72	149	234	
tioı	volume								
ijec	(PS)								
Ir	Max. Inj.	MPa	284	287	174	287	247	158	
	pressure								
	Plasticizing	g/s	6.1	11.1	23	11	23.1	33.3	
	capacity								

The injection molding process parameters used to select a suitable injection molding machine are discussed in the follow-ing paragraphs.

<sup>5</sup> tf is tonne force

<u>Injection capacity</u>: The injection capacity,  $V_{\text{injection capacity}}$  (m<sup>3</sup>) of the injection machine refers to the maximum possible design displacement of the reciprocating screw and can be found using Eq. 6 [19].

$$V_{\text{injection capacity}} = \left(\frac{D}{2}\right)^2 \times \pi \times S$$
 (6)

where D (m) is the diameter of the injection screw, and S (m) is the injection stroke<sup>6</sup>.

Injection capacity is also used to find the realistically attainable volume,  $V_{attainable}$  (m<sup>3</sup>) of the injection molded cavity using Eq. 7 [19].

$$V_{\text{attainable}} = \mathbf{k} \times V_{\text{injection capacity}} \tag{7}$$

where k is a correction factor with a value between 0.7 and 0.8, which indicates that the maximum possible injection volume does not correspond to the maximum injection capacity. The attainable injection volume is useful to check machine injection capacity against the cavity requirements represented by shot volume.

<u>Clamp force</u>: To keep the die closed during the injection molding process, the machine clamp force should be higher than the separating force.

<u>Plasticizing capacity</u>: Plasticizing capacity is defined as the amount of plastic that can be melted, homogenized and heated to processing temperature in the barrel, per unit of time [22]. The machine plasticizing capacity should be such that the required amount of melt is available, when the machine is ready for the next cycle.

<u>*Clamp stroke:*</u> Clamp stroke of the machine should be higher by 5 cm than the part height (or maximum dimension of the part in the die-opening direction).

# CYCLE TIME AND THEORETICAL MINIMUM ENERGY COMPUTATIONS

In this section, components of the injection molding cycle time are discussed, followed by the theoretical minimum energy requirements.

#### Injection molding cycle time

Components of the injection molding cycle time are: injection time, cooling time and mold resetting time. The procedure to determine each of these components [20] is mentioned in the following paragraphs.

<u>Injection time</u>: To find injection time, shot volume and average flow rate need to be determined. Determination of shot volume has already been discussed in the previous section. The procedure to find the average flow rate is discussed below.

<sup>&</sup>lt;sup>4</sup> The total separating force has to be increased if depth of the part is more than 25 mm. For every additional 25 mm of depth, a 10 % increase in cavity pressure is provided, and this aspect is considered while deciding the separating force. [27]

<sup>&</sup>lt;sup>o</sup> The optimum value of the feeding stroke S is generally taken between 1D to 2D to ensure good quality parts. The maximum utilizable shot weight corresponds to feeding stroke of 3D.

Maximum Flow rate (m<sup>3</sup>/s)  $Q = \frac{P_i}{p_{inj}} \times 10^3$  (8) where  $P_{inj}$  is machine injection power (kW), and  $p_{inj}$  (MPa) is

where  $P_{inj}$  is machine injection power (KW), and  $p_{inj}$  (MPa) is the recommended injection pressure.

However, in practice the average flow rate,  $Q_{avg}$  (m<sup>3</sup>/s) decreases as the mold is filled, which is found using Eq. 9.

$$Q_{avg} = 0.5 \times Q$$
(9)  
Therefore, the injection time (s)  
$$t_i = \frac{v_{shot}}{Q_{avg}}$$
(10)

<u>Cooling time</u>: This is the time taken by the molten plastic to solidify inside the mold. Equation 11 is used to find the cooling time,  $t_c(s)$ :

$$t_{c} = \left( \frac{h_{max}^{2}}{\pi^{2} \times \alpha} \right) \times \log_{e} 4 \left( \frac{T_{inj} - T_{m}}{T_{x} - T_{m}} \right) (11)$$

where  $T_x$  is the recommended part ejection temp (°C),  $T_m$  is recommended mold temperature (°C),  $T_{inj}$  is the polymer injection temperature (°C),  $h_{max}$  is the maximum wall thickness (mm),  $\alpha$  is the thermal diffusivity of the material (cm<sup>2</sup>/s).

However, to make sure that the runners are solidified and the solidified part comes clean from the mold, the minimum cooling time is taken as 3s.

<u>Mold resetting time</u>: Mold resetting time is the time already stated for the mold to open and close. The mold resetting time,  $t_r$ , is estimated using Eq. 12.

$$t_r = 1 + 1.75 t_d \sqrt{\frac{2d+5}{s}}$$
(12)

where  $t_d$  is the dry cycle time of the machine (s), S is the maximum clamp stroke of the machine (cm) and, d is the depth of the part (cm).

The total cycle time,  $t_{total}$  (s) is sum of above three components of the injection molding cycle.

#### Determining theoretical minimum energy

After different components of the cycle time are determined, the next step is to find the theoretical minimum energy required for each stage of the injection molding process. We divide the energy consumption of the injection molding process into the following:

- i. Injection molding process energy
- ii. Auxiliary operations energy

*i. Injection molding process energy* (E<sub>process</sub>): In the injection molding process a number of operations take place. These operations are:

- Melting the polymer
- Injecting the molten polymer
- Cooling
- Clamping, opening, ejecting and closing the mold

The theoretical minimum energy required for these operations is discussed in the following paragraphs. The energy computation is for a single injection molding cycle (or shot).

*Energy for melting the polymer* ( $E_{melt}$ ): Before polymer is injected into the die, it is heated and melted. The energy required for heating and melting is derived from two actions of the injection molding machines: extrusion screw and barrel heating. Equation 13 is used to find power used for heating and melting [23].

 $P_{o} = \rho Q_{avg} C_{p} (T_{inj} - T_{pol}) + \rho Q_{avg} H_{f}$ (13) where  $P_{o}$  is the power required for melting (kW),  $C_{p}$  is the heat capacity of the polymer (J/kg°C),  $\rho$  is specific density (kg/m<sup>3</sup>),  $T_{pol}$  is the initial temperature of the polymer (°C),  $Q_{avg}$ is the volume rate of flow of the polymer (m<sup>3</sup>/s), and  $H_{f}$  is the polymer heat of fusion (zero for amorphous polymer)

The energy required for melting the volume of plastic required for one shot,  $E_{melt}$  (kJ) is found using Eq. 14.

$$\mathsf{E}_{\mathrm{melt}} = \mathsf{P}_{\mathrm{o}} \times \frac{\mathsf{v}_{\mathrm{shot}}}{\mathsf{Q}} \tag{14}$$

*Energy for injecting the polymer* ( $E_{inj}$ ): According to Johannaber [19], the injection or the plasticating unit of the reciprocating screw injection molding machine has a major influence on the quality of the final molded part. Its basic function is to accept and convey free flowing solid plastic and additives, perform melting, convey the melt along the screw, mix the plastic and additives, possibly devolatilize the melt, inject the melt into a shape providing cavity, and keep it there under pressure. The theoretical energy required for injecting the plasticated polymer into the cavity is the work done for filling the cavity against pressure. The Eq. 15 is used to find the injection energy,  $E_{inj}$  (kJ) [15].

$$E_{inj} = p_{inj} \times V_{shot} \times 10^3$$
(15)

where  $p_{inj}$  is the injection pressure required to fill the cavity (MPa) with the polymer and  $V_{shot}$  (m<sup>3</sup>) is the shot volume.

*Energy for cooling* ( $E_{cool}$ ): The molten polymer, which is injected into the mold is cooled to a temperature, also known as the ejection temperature. This means that a certain amount of heat has to be taken out from the molded part. The amount of heat to be taken out from the molded part,  $H_{cool}$  (J) is represented by Eq. 16.

$$H_{cool} = \rho V_{shot} C_p (T_{inj} - T_x) + \rho V_{shot} H_f$$
(16)

In the previous section, we discussed a method to find the cooling time. The cooling power required to take out the heat from the mold,  $P_{cool}$  (kW) is calculated using Eq. 17.

$$P_{\rm cool} = {}^{\Pi_{\rm cool}} / t_{\rm c} \tag{17}$$

The energy required for cooling,  $E_{cool}$  (kJ) depends upon the COP (coefficient of performance) of the cooling equipment used. In Eq. 18, we assume that the COP of the cooling equipment is the theoretical maximum (based on Carnot's cycle) [24], which leads to theoretical minimum energy requirements.

$$\mathsf{E}_{\mathrm{cool}} = \frac{\mathsf{H}_{\mathrm{cool}}}{\mathsf{cop}} \times 10^{-3} \tag{18}$$

Energy for clamping, ejection and opening/closing ( $E_{reset}$ ): It has been suggested in the literature that the energy required for opening/closing, clamping and ejection is 25 % of the process energy [25]. Equation 19 is used to find  $E_{reset}$  (kJ).

$$\mathsf{E}_{\text{reset}} = 0.25 \left( \mathsf{E}_{\text{inj}} + \mathsf{E}_{\text{cool}} + \mathsf{E}_{\text{melt}} \right) \tag{19}$$

<u>ii. Auxiliary operations energy:</u> As discussed previously, some auxiliary operations are required alongside the injection molding, which need to be included for energy computations. The minimum theoretical energy required for these auxiliary operations is discussed in this section.

*Energy for drying of polymer* ( $E_{drying}$ ): According to Strumitto et al. [26], the measure of energy consumption in a drying process is the unit energy consumption for the evaporation of 1 kg of moisture. Theoretically, the amount of heat required to evaporate 1 kg of moisture under standard conditions is 2200 kJ to 2700 kJ, which is also referred to as the specific moisture evaporation rate (*SMER*), as shown in Eq. 20.

$$SMER = \frac{amount of water evaporated}{energy used}$$
(20)

The upper limit of this value refers to the removal of bound moisture. However, the only drying regime in which such a result could be obtained is the adiabatic equilibrium in which there is no heating of a solid body and accompanying moisture.

However, there are a number of factors which affect the energy efficiency of the drying process. In the majority of the cases, the most efficient approach for drying intensification is likely to be the combination of several methods. By using techniques such as mechanical centrifuging and heat recovery, it is possible to achieve the *SMER*, which is higher than the theoretical maximum. However, here we limit the scope to the theoretical possibilities only.

Moisture content of different types of plastics and their other properties related can be found from material databases or resources such as Johannaber, 2007 [19]. A representative list of material properties relevant for drying is given in Table 4.

Material	Test method (DIN)	Max. water absorption in standard	Max. water absorption in water bath	Max. moisture during injection (%)
ABS	53495	0.3 to 0.5	0.7	0.2
CA	53472	3.5 to 5.0	3.8 to 5.0	0.2
CAB	53472	2.0 to 2.5	2.0 to 2.5	0.2

Table 4: Moisture related properties of plastics [19]

From these properties, the estimated moisture in the plastic can be computed; alternatively, the moisture content can be found by applying the suggested testing method. The theoretical energy required for drying,  $E_{drying}$  (kJ) can be determined using Eq. 21.

$$E_{drving} = (M \times m) / SMER$$
(21)

Where M is the mass of the plastic loaded in the dryer (kg), and m is the percentage of moisture in the plastic.

*Energy required for loading, coloring and blending:* The raw plastic beads and regrind are first loaded in the machine hopper. Blending may be defined as combining two or more types of materials to give a uniform mixture. Blending units are actually metering devices that allow a specified amount of ingredients to be combined with a specific batch of plastic materials, before they are fed into the molding machine hopper. For injection molders, the blending may be required to achieve proper color combinations, combine regrind with virgin pellets, adding ingredients to improve flow, reduce sticking or enhance the base material in a variety of ways [27, 28].

The blending can be done manually, which of-course does not consume any energy. We therefore assume theoretical minimum energy for this process to be zero. However, due to inconsistencies of the manual method, automated, integral blending systems are often used.

*Energy for trimming:* In the trimming operation, extra material attached to the solid part, like runner, gate, and fins, are removed from the part by shearing operation. The energy used in the trimming operation,  $E_{trim}$  (kJ) depends on the shear strength of the material and the surface area of the trimming portion.

 $E_{trim} = \tau \times A_{trim} \times d_{trim} \times 10^3$  (22) Where,  $\tau$  is the shear strength of the polymer (MPa),  $A_{trim}$  is the surface area of the trimming portion (m<sup>2</sup>), and  $d_{trim}$  is the depth of trim portion (m).

#### COMPUTING ESTIMATED ENERGY CONSUMPTION

The estimated energy consumption in the injection molding process is higher than the theoretical minimum energy requirements. Some of the energy is lost during transmission from the energy-supplying unit to the energy-consuming unit (or operation). Furthermore, there is some energy loss, when the energy-supplying unit converts one form of energy to another. For example, an electric motor converts electrical energy to the rotational energy. We classify these energy losses into two categories:

i. Energy loss during transmission

ii. Energy loss at drive unit

#### Energy loss in transmission

In the previous section, we discussed different operations, which take place in the injection molding process. These operations need energy and some of the energy is needed during transmission. For example, it is estimated that approximately 25 % of the injection pressure [19] is lost when switching injection pressure to the holding pressure. The maximum pressure therefore should be more than the required pressure by 25 %, which contributes to the energy loss for injection. Similarly, there is a loss of heat energy when heating and melting of the polymer and cooling of the mold. These energy losses are added to the theoretical minimum energy requirements of the various operations of the injection molding process.

#### Energy loss at the drive unit

Injection molding machines impose a very high demand on the drive and control systems, because of the fact that the plastic injection molding process is complex and the machine cycle times are mostly short [19]. Though the modern electromechanical drives have clear advantages, single electrohydraulic drives, consisting of an electric motor and a hydraulic pump, are still in use in many places [29]. Energy loss for both of these drives is discussed in this section.

<u>Electro-mechanical drives</u>: Electro-mechanical or the allelectric injection molding machines, as they are commonly called, do have the advantage of precision programmed operations. In the new injection molding machines, all axes are driven by the electric servo-motors. These axes control different operations of the injection molding machines.

The advantages of having the all-electric injection molding machines are that power is supplied in line with the consumption, has minimal idling losses and good efficiency.

Approximately 20 % of the energy is used for control. The reason for this is the power electronics of the servo-motors, which consume much of the energy [19]. The electric drives have the efficiencies from 0.87 to 0.95 [19]. It is also found that 75 % of the energy required for plastication comes from the rotation of the screw, and the remaining 25 % by the heating elements [23]. Furthermore, in addition to the process related energy for some basic equipment like the display, fan, and other equipment, which remain running throughout. The energy consumption for an injection molding part manufacturing can therefore be computed using equations 23-26.

If we take into account the injection molding process only, the energy used for a single shot is sum of the energy required for all the drives, as given in Eq. 23.

$$E_{\text{shot}} = \left(\frac{0.75 \, E_{\text{melting}} + E_{\text{inj}}}{\eta_{\text{inj}}} + \frac{E_{\text{reset}}}{\eta_{\text{reset}}} + \frac{E_{\text{cooling}}}{\eta_{\text{cooling}}} + \frac{0.25 \, E_{\text{melting}}}{\eta_{\text{heater}}}\right) \times 1.2 + P_{\text{b}} \times t_{\text{cycle}}$$
(23)

where  $E_{shot}$  is the energy required for injection molding a single shot,  $P_b$  is the power required for the basic energy consuming units (kW), when machine is in stand-by mode, and  $\eta_{inj}$ ,  $\eta_{reset}$ ,  $\eta_{cooling}$ ,  $\eta_{heater}$  are the efficiencies of the different units for injection, resetting, cooling and heating, respectively.

The auxiliary equipment like dryer, loader/blender, and trimmer, are operational for a fraction of the time compared to the injection molding machine. The energy required for auxiliary operations can be found using Eq. 24.

$$E_{auxiliary} = \left( \left( \frac{E_{drying}}{\eta_{dryer}} \right) + \frac{P_{loader}}{W_{loader}} \times t_{cycle} \times f_{loader} + \frac{P_{blender}}{W_{blender}} \times t_{cycle} \times f_{blender} \right) \times W_{shot} + \frac{E_{trim}}{\eta_{trimmer}}$$
(24)

where  $P_{loader}$  and  $P_{blender}$  are the power rating of the loader and the blender (kW),  $W_{loader}$  and  $W_{blender}$  are the weight of charge in loader and blender (kg),  $\eta_{dryer}$  is the efficiency of the drying unit,  $E_{drying}$  is the energy required for the drying operation (kJ), and  $f_{loader}$  and  $f_{blender}$  are the fraction of time the loader and blender are on. Similarly,  $\eta_{trimmer}$  is the efficiency of the trimmer.

Lastly, the energy consumption per part (kJ/part) is determined by aggregating all the above components of energy consumption and dividing by number of parts in a single shot as shown in Eq. 25.

$$\mathbf{E}_{\text{part}} = \frac{\left(\mathbf{E}_{\text{shot}} + \mathbf{E}_{\text{auxiliary}}\right)}{\mathbf{n}}$$
(25)

where n is the number of cavities in the die.

<u>Electro-hydraulic drives</u>: Unlike the electromechanical drives, which use a different drive unit for each axis, the electro-hydraulic drives use a single drive unit and power is then distributed to the different energy-consuming units or operations. The basic operations of the injection molding process remain the same. The flow of energy from the electric motor, up to the energy-consuming operation goes through various systems of the machine, like the hydraulic pump, control valve, pipes and manifolds, and hydraulic motors. The hydraulic motors are responsible for actually delivering the power to the desired operation of the injection molding process. Inefficiency at each stage of the power flow contributes to the power loss. The efficiency of a hydro-mechanical system is found by using Eq. 26 [19].

$$\eta_{\text{tot}} = \eta_{\text{mech}} \times \eta_{\text{hydr}} \times \eta_{\text{vol}}$$
(26)

where  $\eta_{tot}$ ,  $\eta_{mech}$ ,  $\eta_{hydr}$ ,  $\eta_{vol}$  are the total, mechanical, hydraulic and, volumetric efficiency, respectively, of the hydraulic system.

To achieve higher efficiency, it is therefore necessary to use the individual components with smaller losses, especially for the hydraulic pumps and motors. The efficiency of a hydraulic system is further reduced by modifying valves, length, cross-section and flexibility of the pipeline, sharp elbows, compressibility of the hydraulic fluid, and external leaks.

The major difference between the electric injection molding machine and the hydraulic one is that in hydraulic machines the electric motor, which powers the hydraulic unit, is always on. Because of this reason there are some idling losses. The energy consumption of the hydraulic injection molding machine therefore can be summarized as shown in Eq. 27.

 $E_{shot} = (P_{idle} + P_b) \times t_{cycle} + E_{process}$  (27) where  $P_{idle}$  is the power consumption (kW), when the injection molding machine is idle,  $P_b$  is the basic power consumption, and  $E_{process}$  is the energy required for completing the injection molding cycle (kJ).

The equations derived in the previous section are also applicable in the case of electro-hydraulic injection molding machines, except for the values of the total efficiency available for each of the operations.

### FACTORS INFLUENCING ENERGY CONSUMPTION

In this section, we identify the relationship of various influencing parameters with different components of the energy

consumption. The components of the energy use are divided into two: injection molding and auxiliary operations. In Table 5, these parameters are organized according to their dependence on different sources, i.e., part geometry, part material, material/process, others and manufacturing resources. For example, the influence of part material information on energy use can be easily identified from the table, which shows the relationship of different material properties like heat capacity, thermal diffusivity, and shear strength with different components of energy. The motivation behind the schematic of the guideline presented in Figure 2 and the classification of various influencing parameters presented in Table 5 is to facilitate development of supporting information models for computing energy consumption as a scope of future work.

,	Table 5: En	ergy cons	suming o	operatio	ns an	d affecti	ng parar	neters
	,						0+0+0+0+0+0+0+0+0+	1-1-1-1-1-1-1-1-

Parameters		Part geometry	Part Material	Material/P rocess	Others	Manufactu ring resource
con	nponent 🗸		Estimated energy			
	Melting	V olume	Heat of fusion, Degree of crystalliza tion, Densty	Injection temp.	Polymer initial temp.	Efficiency of heating unit, injection unit, electric drive
ımolding	Injection	Max.wall thickness Volume		Injection pressure		Efficiency of the injection, electric drive
Injectior	Cooling	V olume, Max imum Wall thickness,	Specific heat capacity, Heat of fusion, Density, Thermal diffusivity	Ejection temp.		Efficiency of cooling channels, electric drive and, cooling unit COP
	Resetting		Efficiency of the resetting systems			
suo	Drying	V olume	Density		Moisture	Efficiency of the drying umit
xiliary operati	Loading/ blending					Efficiency of the loading and blending umit
Au	Trimming		Shear strength		Trim Cross- sectional area	Efficiency of the trimming unit

#### **CONCLUDING REMARKS**

This study is a step towards developing a generic sustainability characterization methodology for unit manufacturing processes. In this paper, the guideline to characterize energy consumption of the injection molding process was discussed. We discussed five steps of the proposed guideline for computing estimated energy consumption. We also presented a schematic which shows the various steps of the guideline and the parametric information requirements for characterizing energy for the injection molding process. Classification of the parameters which influence energy computations was also presented. The proposed guideline overcomes the shortcomings of the available methods by: (i) extending the system boundary of the injection molding process to cover other stages like drying, blending, dosing, and trimming, (ii) considering factors related to part design, material, and process planning to compute theoretical minimum energy and, (iii) making estimates of energy consumption using manufacturing resource information. The proposed guideline will be useful for estimating and benchmarking diverse manufacturing processes and products made using the injection molding process.

Another motivation behind the schematic presented, and the classification of various influencing parameters, is to facilitate the development of structured information models for computing energy consumption. Development of structured information models will help seamless information flow between design and manufacturing domains, which would greatly help develop *design-for-energy* tools.

The following are the potential future research directions that need to be explored.

- Showcase effectiveness of the proposed guideline with actual case studies.
- Define system boundaries of the injection molding process and auxiliary operations.
- Include other inputs and outputs (material, water usage and waste) of the process, along with energy consumption.
- Develop guidelines to determine the efficiency of the manufacturing resources, which vary according to the technology use and process conditions.
- Define structured information models for seamless flow of information across design and manufacturing domains.
- Address the issue of uncertainty in the analytical models.
- Develop a standard reference methodology for sustainability characterization of unit manufacturing processes.

#### DISCLAIMER

Mention of commercial products or services in this paper does not imply approval or endorsement by NIST, nor does it imply that such products or services are necessarily the best available for the purpose.

# REFERENCES

[1] Sustainable Manufacturing Toolkit, Organization for Economic Co-operation and Development, France [Web page]: http://www.oecd.org/innovation/green/toolkit/. [accessed 8/12/12].

[2] J. Jeswiet and S. Kara, Carbon emissions and CESTM in manufacturing, CIRP Annals Manufacturing Technology. vol. 57 (51), p. 17–20 (2008).

[3] M. Mani, J. Madan, J. H. Lee, K. Lyons and S. K. Gupta, Characterizing sustainability for manufacturing performance assessment, in Proceedings of the ASME 2012 IDETC/CIE, Chicago, IL, USA (2012).

[4] T. Gutowski, J. Dahmus and A. Thiriez, Electrical energy requirements for manufacturing processes, in 13th CIRP International Conference on Life Cycle Engineering, (2006).
[5] T. Gutowski, J. Dahmus, A. Thiriez, M. Branham and A. Jones, A thermodynamic characterization of manufacturing processes, in 2007 IEEE International Symposium on Electronics and the Environment, ISEE, May 7, 2007 - May 10, 2007, Orlando, FL, United states (2007).

[6] A. Thiriez and T. Gutowski, An Environmental Analysis of Injection Molding, in IEEE International Symposium on Electronics and the Environment, San Francisco, CA (2006). May 8-11.

[7] Plasticating, [Web page]:

http://www.pitfallsinmolding.com/plasticatingpage.html. [accessed 8/17/12].

[8] Material Project Laboratory, Massachusetts Institute of Technology, [Web page]: http://ocw.mit.edu/courses/materialsscience-and-engineering/3-042-materials-project-laboratoryspring-2008/. [accessed Nov. 7, 2012].

[9] Life cycle inventory of plastic fabrication processes: Injection molding and thermoforming,

CLIENTS\RPPG\KC112362, Rigid Plastic Packaging Group, (2011).

[10] N. Lu, G. Gong, Y. Yang and J. Lu, Multi-objective process parameter optimization for energy saving in injection molding process, Journal of Zhejiang University - SCIENCE A. 382-394 (2012).

[11] K. F. Pun, I. K. Hui, W. G. Lewis and H. C. W. Lau, A multi-criteria environmental impact assessment for the plastic injection molding process: a methodology, Journal of Cleaner Production. vol. 11, pp 41-49 (2003).

[12] A. P. Muroyama, M. Mani, K. Lyons and B. Johansson, Simulation and Analysis for Sustainability in Manufacturing Processes, NISTIR 7790, National Institute of Standards and Technology, Gaithersburg, (2011).

[13] A. Kanungo and E. Swan, All electric injection molding machines: How much energy can you save?, in Proceedings of the 13th Industrial Energy technology Conference, New Orleans, LA (2008).

[14] F. Qureshi, W. Li, S. Kara and C. Herrmann, Unit Process Energy Consumption Models for Material Addition Processes: A case of the Injection Molding Process, in 19th CIRP International Conference on Life Cycle Engineering, Berkeley (2012).

[15] I. Ribeiro, P. Pecas and E. Henriques, Assessment of Energy Consumption in Injection Moulding Process, in 19th CIRP International Conference on Life Cycle Engineering, Berkeley (2012).

[16] A. Weissman, A. Ananthanarayanan, S. K. Gupta and R. D.

Sriram, A systematic methodology for accurate design-stage estimation of energy consumption for injection molded parts, in Proceedings of the ASME 2010 International Design Engineering Technical Conference & Computers and Information Science in Engineering Conference, IDETC/CIE 2010, Montreal, Quebec, Canada (2010).

[17] D. Kalla, J. Twomey and M. Overcash, Injection Molding Process: Unit Process Life Cycle Inventory, MC 2, Wichita State University, (2009).

[18] K. Kellens, W. Dewulf, M. Overcash, M. Z. Hauschild and J. R. Duflou, Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)-CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology Description, International Journal of Life Cycle Assessment. vol. 17 (11), 69-78 (2011).

[19] F. Johannaber, Injection Moulding Machines, Hanser Publications, Munich, Germany (2007).

[20] G. Boothroyd, P. Dewhurst and W. A. Knight, Product design for manufacture and assembly, 3rd ed., CRC Press, Boca Raton (2011).

[21] Toshiba Machine, Toshiba Inc., USA [Web page]: http://www.toshiba-

machine.com/IMProductDetails.aspx?dept=1&machine\_id=182 [accessed 8/12/12].

[22] D. V. R. Dominick V. Rosato, Marlene G. Rosato, Injection molding handbook, Kluver Academic Publishers, Norwell, Massachusetts, USA (2000).

[23] J. Vlachopoulos and D. Strutt, Polymer processing: Materials Science and Technology. 1161-1169 (2003).[24] COPs, EERs, and SEERs: How Efficient is Your Air Conditioning System?, [Web page]:

http://www.powerknot.com/how-efficient-is-your-airconditioning-system.html. [accessed Nov. 7, 2012].

[25] J. Mattis, P. Sheng, W. DiScipio and K. Leong, A

framework for analyzing energy efficient injection-molding die design, Berkeley (1996).

[26] C. Strumitto, P. L. Jones and R. Zytta, Energy aspects in drying, in: Handbook of industrial drying, A. S. Majumdar, CRC Press, Boca Raton, FL, USA (2007).

[27] D. M. Brycee, Plastic Injection Molding, Society of Manufacturing Engineers, Dearborn, MI (1996).

[28] Blending and Dosing, Plastics Technology [Web page]: http://www.ptonline.com/knowledgecenter/blending/blending-basics/how-blenders-work. [accessed 11/15/12].

[29] J. Wortberg and T. Kamps, Hydraulics and all-electric injection molding machines in practice, Plast Europe. 7, p. 12-15 (2002).