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Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study

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A B S T R A C T

In an effort to make more sustainable decisions, industry seeks reliable methods to assess and compare sustainability for manufacturing. Sustainability characterization is intended to provide such a reliable method to access and track sustainability information. As a step towards developing a standard reference for sustainability characterization of unit-manufacturing processes, in this paper, we focus on injection molding with energy as a sustainability indicator. This paper proposes a science-based guideline for energy: (i) prediction, (ii) benchmarking and performance evaluation, and (iii) improvement, for unit-manufacturing processes, which unlike the previous methods does not require a physical benchmark. We discuss in detail the steps of the proposed guideline for the injection molding process. The guideline considers different influencing factors such as part geometry, material-related physical and processing properties, and the manufacturing equipment information. The guideline is implemented by developing a user friendly system, and is demonstrated by a case study. We expect this work to contribute to the development of a standard reference methodology to help further sustainability in the manufacturing sector.

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1. Introduction

With the increasing cost and scarcity of energy resources, saving energy is getting more attention of the policy planners. The major energy consuming sectors in the world are: industrial, transportation, residential and commercial, their combined total energy consumption being over 500 EJ[3] (EIA, 2014). Nearly one third of the total global energy demand and resulting CO_2 emissions are attributable to the industrial sector in which manufacturing is a major part. Energy intensity is one of the important indicators for assessing sustainability performance of manufacturing (OECD, 2011).

Manufacturing enterprises need to consider and initiate the implementation of energy assessment and energy quota practices to improve both their economic benefit and environmental performance (Wang et al., 2013). Unfortunately, methods and tools to support such energy performance evaluation and improvement are not available. Today's industry employs life cycle assessment (LCA) tools to assess the sustainability performance (including energy performance) of a product's life cycle. Such a sustainability assessment is predominantly based on the weight of a product's constituting material, ignoring the manufacturing factors, such as part design, manufacturing equipment used, and processing conditions. Despite the application of LCA tools to assess and compare energy footprints of alternative product designs, their usefulness to compare energy performance of alternative manufacturing scenarios is limited.

To help the U.S. industry, it is pertinent to develop the needed measurement science methodologies and related standards to evaluate and improve sustainability of manufacturing processes (Mani et al., 2014). Focusing on energy alone, the U.S. industrial sector consumes about 31 % of the total energy (EIA, 2014; Elliott, 2007). The work presented in this paper is a step towards improving the energy competitiveness.

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[3] EJ = 10^{18} J.

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Nomenclature

Symbol

Symbol	
A_{part}	projected area of the part, cm^2
A_{total}	projected area of all the cavities, cm^2
C_{p}	heat capacity of the polymer, J/kg K
D	diameter of the injection screw, mm
d	depth of the part, cm
$E_{\mathrm{cy\_theo}}$	theoretical energy required for an injection molding cycle, J
E_i	energy required for the ith sub-process, J
E_{part}	per part energy consumption for the injection molding UMP, J
F_{sep}	separating force, kN
f_{i_k}	fraction of the energy of ith sub-process supplied by kth sub-system
H_{f}	polymer heat of fusion (zero for amorphous polymers), J/K kg
h_{max}	maximum wall thickness of the part, mm
L_{s}	maximum clamp stroke of the machine, cm
m	number of sub-processes in a UMP
n	number of cavities in the die
P_{inj}	machine injection power, kW
P_{basic}	power required for basic energy consuming units of the machine, W
P_{idle}	machine idle power, W
l	number of sub-systems of the manufacturing equipment
S	length of injection stroke[2], mm
T_{pol}	polymer temperature at the time of loading in the injection molding machine, K
T_{ej}	part ejection temperature, K
T_{pol}	temperature of the polymer at the time of its loading in the machine, K
T_{m}	mold temperature, K
T_{inj}	polymer injection temperature, K
T_{dry}	polymer drying temperature, K
t_{d}	dry cycle time of the machine, s
t_{cycle}	injection molding cycle time, s
t_{idle}	idle time of the machine for each cycle, s
t_{r}	mold resetting time, s
$V_{\mathrm{inj\_cap}}$	injection capacity, cm^3
V_{att}	practically attainable injection volume, cm^3
V_{part}	volume of the injection molding part, cm^3
V_{shot}	shot volume, cm^3
α	coefficient of thermal expansion of the plastic material, m/m K
λ	thermal conductivity, W/m
ρ	specific density of the polymer, g/cm^3
Δ	fraction of the part volume used in the gating system
ε	change in volume/unit volume of the polymer for a given decrease in temperature, m^3/m^3
γ	thermal diffusivity of the material, mm^2/s
η_k	efficiency of the sub-system k
η_{machine}	overall efficiency of the machine

Manufacturing a product or a component usually requires the integration of a number of unit-processes. *Unit-manufacturing processes* (UMPs) are the individual steps required to produce finished goods by transforming raw material and adding value to the work-piece as it becomes a finished product (National Research Committee, 1995). An effective science-based energy performance evaluation and improvement methodology for manufacturing must therefore consider the energy requirements at the unit-process level.

The scope of this paper is to develop a science-based guideline to estimate the energy consumption of UMPs, with the objectives of benchmarking, evaluation and improvement. Estimating and evaluating energy consumption for manufacturing is useful: at early stages of the product development for decision support, to generate bill-of-energy, and to plan for energy performance improvement. As shown in Fig. 1, both early estimation and bill-of-energy of manufacturing process energy are useful for decision support in the product life cycle management (PLM), and for the supply chain management (SCM), respectively. With industry focus to integrate sustainability information in agile manufacturing systems (Calvo et al., 2008), the energy information at the process level has become more desirable.

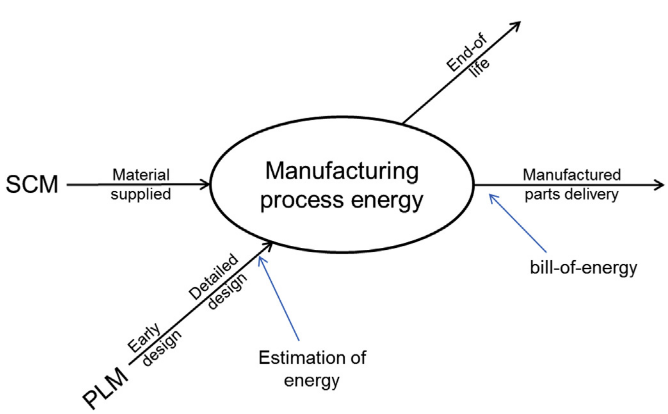


Fig. 1. A schematic showing manufacturing energy information use in design and manufacturing.

We initially focus on the injection molding process to demonstrate the approach for energy performance evaluation and improvement, which will eventually contribute towards developing a standard reference methodology for UMPs. We selected the injection molding process for this study primarily because of its wide application in the consumer, automotive and industrial products. Another major reason is that the proposed guideline, with minor modifications can be used for other near net-shape manufacturing processes, such as casting, plastic fabrication processes and die-casting, which have great similarities with the injection molding process. Further, the extent of energy use in the injection molding process is well recognized (Gutowski et al., 2006), and it consists of a number of identifiable and controllable steps, required for energy performance evaluation and improvement. If we look at the cradle-to-gate energy

[2] The optimum value of the feeding stroke S is generally taken between 1D and 2D to ensure good quality parts. The maximum utilizable shot weight corresponds to feeding stroke of 3D.

consumption of the injection molding parts, production of virgin materials and the injection molding process itself are the two most significant energy consumption sources (Franklin Associates, 2011). But as stated earlier, the scope of this paper is the injection molding process only.

The rest of the paper is organized as follows. Section 2 discusses a summary of the previous work related to energy consumption in the injection molding process alongside research gaps and objectives of this paper. Section 3 discusses the injection molding process description. Section 4 discusses an overview of the proposed methodology and the terms and definitions used in this paper. Section 5 discusses energy estimation and benchmarking. Section 6 discusses energy performance evaluation and improvement. Section 7 presents implementation and discussions with reference to a case study to demonstrate the usefulness of the guideline. Lastly, Section 8 discusses conclusions and future scope of work.

2. Related work

Earlier, researchers have investigated performance evaluation and improvement for manufacturing energy consumption. These research efforts can be broadly categorized into industry, plant, machine and process. It is important to individually discuss the energy performance evaluation and improvement efforts at these four levels to specifically understand the importance of the energy performance evaluation and improvement at the process level.

In this section, we present a summary of the literature review for determining energy consumption for the injection molding process along the above mentioned four categories. Those papers, which fall under multiple categories, are discussed separately. Related papers on energy estimation for other manufacturing processes are also discussed. Finally a brief summary of the research gaps and objectives of the present work is presented at the end of this section.

Industry: The studies at the industry level are done with a purpose to find: (i) total energy consumption, and (ii) average energy consumption per unit throughput for an industrial sector in a particular geographical region. Thiriez and Gutowski (2006) performed energy analysis of the injection molding industry. Franklin Associates (2011) quantified total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste for the two plastic fabrication processes, injection molding and thermoforming. The scope of the study was to generate a life cycle inventory (lci) database for products made by these processes in North America.

Plant: Manufacturing energy performance analysis at the plant level is generally carried out to improve the plant energy efficiency per unit of throughput. Lu et al. (2012) developed a process modeling parameter optimization algorithm using a genetic algorithm based on the lexicographic method. The implementation of their framework reduced the energy consumption for a laboratory scale test. Pun et al. (2003) identified various indicators of environmental impact assessment and established a multiple-criteria rating matrix that takes into account energy and provides a means to assess the environmental performance in plastic injection molding. Muroyama et al. (2011) suggested that discrete event simulation can output data indicating the most productive and energy efficient methods in a factory setting. Seow and Rahimifard (2011) developed an approach to model energy flows within a manufacturing system with an aim of representing the amount of energy attributed for manufacturing a product. They applied the concept of direct energy, indirect energy and auxiliary energy. Herrmann et al. (2011) presented an energy-oriented simulation model for planning of manufacturing systems. Their model considers manifold production situations with all relevant energy flows of the factory sub-systems and their dynamics.

Machine: Kanungo and Swan (2008) 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. Li and Kara (2011) proposed an empirical model for predicting energy consumption of manufacturing processes. They suggested that the energy consumption of a machine tool performing turning process not only consists of the energy required by the tool tip but also the auxiliary functions. Li et al. (2011) investigated the fixed energy consumption of machine tools and proposed different ways of improvement in energy efficiency. They segmented the power (or energy) consumption into specific fixed energy, specific operational energy, specific tool tip energy and specific unproductive energy.

Some researchers relate different functional states of a machine with the energy consumption. Zein et al. (2011) presented energy efficiency improvement measures for design and operation of machine tools. They used axiomatic design to relate functional requirements to the machine design parameters. Schmitt et al. (2011) presented an approach to model energy consumption of machine tools, which uses the relationship of power demand and time duration with a particular functional state of the machine tool. Weinert et al. (2011) proposed a method, which divides the operational phases of a machine tool into different energy blocks. The energy blocks are used to determine energy requirements for both the product and the equipment perspective. Avram et al. (2011) presented an energy consumption reduction perspective by considering alternative machining strategies and system component interactions translated into variable and constant power flows with respect to various use phase regimes of a machine tool. Cannata et al. (2009) studied the energy efficiency analysis and optimization in discrete manufacturing. Their method represents different states of a machine tool, and their contribution to the final output. Devoldere et al. (2007) investigated the improvement potential for energy consumption in discrete part production machines. They divide the total energy use into idle, run-time and process energy requirements. Mouzon et al. (2007) developed operational methods for the minimization of energy consumption of a manufacturing equipment. They focus on production sequencing and scheduling to improve energy performance.

Process: Researchers have also studied the effect of process energy on the energy required to manufacture a product. Kalla et al. (2009) presented a methodology to collect unit process life cycle inventory (uplci) for the injection molding process. Kellens et al. (2012) developed an LCA based methodology for systematic inventory analysis of UMPs providing datasets to be used in life cycle inventory databases and libraries. Qureshi et al. (2012) presented an empirical approach to characterize the relationship between energy consumption and process variables for the injection molding process. Giacone and Mancò (2012) propose an approach for energy efficiency measurement in industrial processes. They discussed variation in specific energy consumption as the rate of production in a process industry changes. Ribeiro et al. (2012) presented a thermodynamic model that estimates the energy consumption for any injection molded part based on its geometry and the material. Their model takes into account machine efficiency to estimate energy consumption. Weissman et al. (2010) developed a methodology to compute the energy consumption for manufacturing an injection molded part. It utilizes part information to determine shot size and cycle time. The energy is estimated on the basis of power rating of the machine drives.

Process and plant: Some researchers combined the energy required for the process and the plant level activities to estimate energy for manufacturing. Rahimifard et al. (2010) presented an approach for energy efficient manufacturing through modeling the detailed breakdown of energy inefficiencies throughout a manufacturing system. They divide the product manufacturing energy into the plant and the process level. The process energy is further divided into theoretical energy and auxiliary energy. Götzea et al. (2012) presented an approach for energy evaluation of machine tools, which consists of measurement of energy consumption, modeling of energy flows, simulative analysis of the energy saving potentials, and energy-oriented life cycle costing concepts. Their evaluation approach is based on input–throughput–output model with energy as input and process energy and energy losses as output for a milling process case study.

2.1. Research gaps

The manufacturing industry today seeks information on the manufacturing process energy and its relationship to the energy consumption at higher levels, namely machine, plant and industry. The process level energy information has the potential to be used not only for energy performance evaluation of the manufacturing equipment and embedded energy of products, but also for evaluation at the factory and the enterprise level. Some other methods reported in the literature, such as the use of physical prototype for performance rating of the CNC milling machine energy use (Behrendt et al., 2012) and planning and operating energy efficient production system (Weinert et al., 2011) do not use process energy directly. Furthermore, the relationship between the energy consumption for manufacturing with different sub-systems of the manufacturing equipment has been recognized but less documented (Avram et al., 2011). This aspect has been accounted for in the present paper.

Despite very useful work presented in the literature, there are still gaps that need to be addressed, the prominent ones are mentioned below:

i. Most of the reported research focuses primarily on the development of models for energy and efficiency analysis at the industry, factory, or machine level. A few other research efforts attempt to address energy efficiency at the process level. However, the applications of such research in providing measurement science for consistent comparison of energy performance evaluation of UMPs are limited.
ii. Other research papers focus on the development of methods to collect energy consumption information from the machine tool or the shop floor to build lci data; however, they have limited use for early estimation of manufacturing energy. Early estimation of manufacturing energy is useful for decision support to identify the most energy-efficient manufacturing plan.
iii. A systematic approach for continuous improvement of energy performance of UMPs is lacking in the literature.

2.2. Objectives of the present work

To address the research gaps, there is a need to develop a science-based guideline, which can be used to estimate, evaluate and improve the energy performance of unit-manufacturing processes. In this paper, we make an attempt to develop a guideline specific to the injection molding process. The objectives of the paper to address the research gaps with reference to the injection molding process are threefold, namely:

i. Establish a science-based guideline to estimate energy for early decision making and to generate the bill-of-energy information.
ii. Develop metrics to benchmark and evaluate the energy performance.
iii. Develop and demonstrate a systematic approach to help the end-user select an appropriate energy improvement strategy.

In the next section, we briefly describe the injection molding process. We identify important terms and definitions before describing the stages of the injection molding process.

3. Injection molding process description

Injection molded parts are widely used in consumer products and industrial equipment. An injection molding facility consists of four stages (i) drying, (ii) blending and dosing, (iii) injection molding, and (iv) regrinding, which are briefly discussed in the Appendix.

The injection molding process consists of melting raw polymer granules, also referred to as plasticating[4] (Plasticating, 2014), and injecting the molten polymer into a mold (or a die). A typical injection mold has a cavity, which is a negative of the part being produced. When the cavity is filled with the plastic, it is cooled to form a 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 (Osswald et al., 2008).

A UMP may consist of a number of sub-processes (see *sub-process* definition in Section 4.1). Each of the sub-processes performs a function as the raw material is converted into a form, which brings it closer to the finished part. The information about the sub-processes of the injection molding UMP is a pre-requisite for developing the proposed science-based guideline. The injection molding process consists of six sub-processes, namely mold closing, filling, packing and holding, cooling, mold opening/ejection and plasticating. These sub-processes are briefly discussed in the Appendix.

The average energy use for plastic injection molding in U.S. is 20 MJ/kg, which includes other auxiliary processes (see *auxiliary process* definition in Section 4.1) and all types of injection molding machines, such as hydraulic, hybrid and electric (Franklin Associates, 2011). Such a high energy use in injection molding is comparable to other processes like machining. However, average specific energy consumption (SEC) of electric injection molding machines alone is about 1.47 MJ/kg (Kanungo and Swan, 2008), which does not take into account auxiliary processes. SEC is the energy consumption per unit of throughput, for example, energy consumption per unit mass produced.

[4] 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.

4. Guideline overview

In this section, first we discuss the terms and definitions that have been used in the paper followed by a discussion on the proposed guideline.

4.1. Terms and definitions

- *Sub-process*: A sub-process is a controllable individual step that accomplishes a significant portion or stage of a UMP.
- *Auxiliary process*: An auxiliary process provides a supplemental or additional support in immediate adjacency of the UMP, directly affecting its performance.
- *Manufacturing equipment*: A physical equipment (or machine) capable of performing one (or multiple) UMP/s with the required level of performance.
- *Sub-system*: A group of interconnected and interactive parts that performs an important job or task as a component of a larger system or manufacturing equipment (BusinessDictionary, 2012).
- *Ideal manufacturing process*: In the context of this paper, an ideal manufacturing process consumes only as much energy that directly contributes to manufacture a useful part. For example, for an ideal injection molding process it is assumed that the energy required for gates and runners is excluded since it does not directly contribute to manufacturing of the injection molded part.
- *Ideal manufacturing equipment*: In the context of this paper, an ideal manufacturing equipment makes full or 100 % utilization of the energy it receives from the source to the process without any losses.
- *Ideal manufacturing energy*: It is the energy required for manufacturing a part by considering both ideal manufacturing process and equipment(s).
- *Theoretical process energy*: It is the energy required for the process to be completed with ideal manufacturing equipment(s). The theoretical process energy accounts for all practical requirements of the process, such as energy required for gates and runners, even if it does not directly contribute to the part. However, it is assumed that there are no energy losses due to equipment inefficiencies.
- *Benchmark*: Standard, or a set of standards, used as a point of reference for evaluating the performance or level of quality (BusinessDictionary, 2012).

4.2. Guideline for energy: estimation, evaluation, and improvement

In the following paragraph, we discuss the proposed guideline for energy: estimation, evaluation, and improvement of the injection molding process. The guideline depends on the science-based computational models, and the databases of material, machine, and their performances. The methodology used in the guideline is depicted in Fig. 2. Following are the main constituents of the proposed guideline.

(i) *Energy estimation and benchmarking*: Energy estimation of the injection molding UMP comprises five steps. The guideline also helps to evolve a benchmarking scheme, which includes both science-based and other benchmarks used by the industry. We discuss energy estimation and benchmarking in Section 5.

(ii) *Energy performance evaluation and improvement*: The proposed scheme of benchmarks is further used to evaluate the energy performance of the injection molding UMP, and to evolve an improvement strategy. We discuss the energy performance evaluation and improvement in Section 6.

5. Energy estimation and benchmarking

In this section, we first discuss energy estimation of the injection molding UMP, followed by a discussion on the benchmarking scheme.

5.1. Energy estimation

The energy estimation comprises five steps, which are discussed in the following paragraphs.

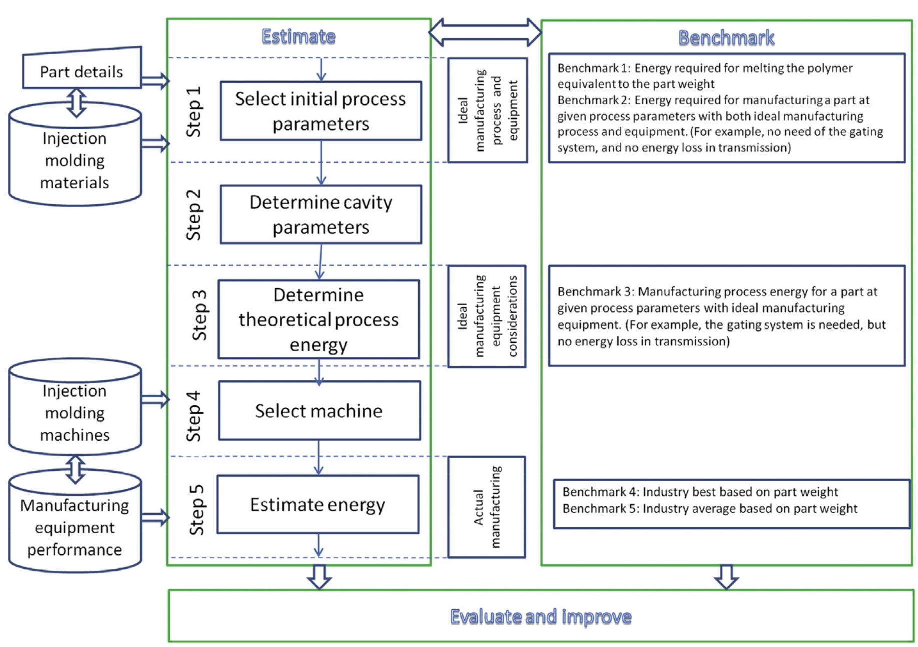


Fig. 2. Schematic of the proposed guideline.

Step 1: Determine initial process parameters and ideal manufacturing energy

As part of step 1, we first discuss the initial process parameters of the injection molding UMP, which are dependent on the part geometrical characteristics and material. Second, based on the initial process parameters and the part design, the energy required for manufacturing under ideal process and manufacturing equipment conditions is determined.

Determine initial process parameters

Injection molding UMP parameters like injection pressure, injection temperature and ejection temperature are related to the material, and the geometric details of the part and the mold. These parameters for some representative injection molding materials are given in Tables 1 and 2. The parameters that affect energy required for the injection molding process are briefly explained in the Appendix.

Ideal manufacturing energy

Here we consider that the part is injection molded under ideal conditions.

The ideal manufacturing energy in the injection molding process for a part is mentioned in Eq. (1), which is a sum of the energy required for the sub-processes of the injection molding process. The energy required by these sub-processes is found using Eqs. (A3)–(A8), given in the Appendix.

$$E_{\text{ideal\_manufacturing}} = E_{\text{melt}} + E_{\text{inj}} + E_{\text{pack}} + E_{\text{cool}} + E_{\text{reset}} \tag{1}$$

Step 2: Determine cavity parameters

After the initial parameters are selected in step 1, the next step is to decide the number of cavities in the mold (or die). 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 affects many parameters of the injection molding process including injection volume (or shot volume), projected area, and injection force. It is worth mentioning that the geometrical characteristics of the part, such as its volume, affect the quantity of the material required for the runners and gates, which are separated from the solidified part and subsequently scrapped. Generally, the smaller the part size, the higher is the percentage of scrap due to runners and gates used compared to a larger part. This aspect has been accounted for to determine the runner and gate volume. The procedure to determine cavity parameters is discussed in the Appendix.

Step 3: Determine theoretical process energy

The essential process requirements are accounted for to determine the theoretical process energy for the UMP. In the case of injection molding process, gate and runner are a necessity, without which the process may not be possible, which means that molten material is also required for filling the gates and runners besides the cavity. In step 2, we already discussed the parameters of the die cavity, such as shot volume and projected area. The die cavity parameters along with Eq. (1) are used to determine the theoretical process energy.

The theoretical process energy determined in this section represents the amount of energy under ideal manufacturing equipment considerations. For example, it is assumed that there is no loss of energy in transmission. However, other requirements of the process, such as gate and runner are considered.

Step 4: Selecting the injection molding machine

After injection molding process parameters are determined, the next step is to select 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 by the user before the injection molding machine is selected. 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.

The information flow diagram for the injection molding machine selection is presented in Fig. 3.

An injection molding machine with minimum clamp force (or tonnage) is selected from the available database. The database represents injection molding machines available in a manufacturing facility and their specifications. The suitability of the machine is checked against the cavity requirements. Subsequently the stroke length of the machine is checked against the required clamp stroke. If any of the conditions is not fulfilled, the next machine with higher clamp force is selected. Next, the injection unit of the machine is checked to find if it satisfies the conditions of shot volume and plasticating capacity. In case the injection unit does not satisfy these requirements, the next injection unit of the machine is

Table 1
Recommended injection pressure (Johannaber, 2007).

Plastic material[a]	Required effective injection pressure (MPa)			
	Easy flow material, heavy sections	Medium flow materials, standard sections	High viscosity material, thin sections	Thin-wall parts, thin-wall injection
ABS	80–110	100–130	130–150	150–200
CAB	80–110	100–130	130–160	N/A
POM	90–110	110–130	130–150	N/A

[a] ABS – Acrylonitrile butadiene styrene, CAB – Cellulose acetate butyrate, POM – Polyoxymethylene.

Table 2
Recommended processing temperatures.

Plastic material	Injection temperature (°C) (Johannaber, 2007)	Mold temperature (°C) (Johannaber, 2007)	Vicat temperature (°C) (IDES, 2014)	Drying temperature (°C) (Johannaber, 2007)
ABS	200–260	40–60	89–115	80
CAB	180–220	40–80	88–115	75
POM	180–230	80–120	149–162	100

Table 3
Specification of an injection molding machine (Toshiba, 2014).

	Item	Unit	Machine ID				
Clamp unit	Clamp force	tf[a]	100				
	Clamp stroke	m	0.35				
	Ejector force	tf	3				
	Injection unit	Unit	Injection unit 1			Injection unit 2	
Injection unit	Injection capacity	cm^3	78	102	130	201	254
	Screw diameter	mm	28	32	36	40	45
	Shot volume (PS)	g	72	94	120	185	234
	Max. injection pressure	MPa	287	220	174	200	158
	Plasticating capacity	g/s	11.1	16.9	23	30.6	33.3

[a] tf is Tonne force.

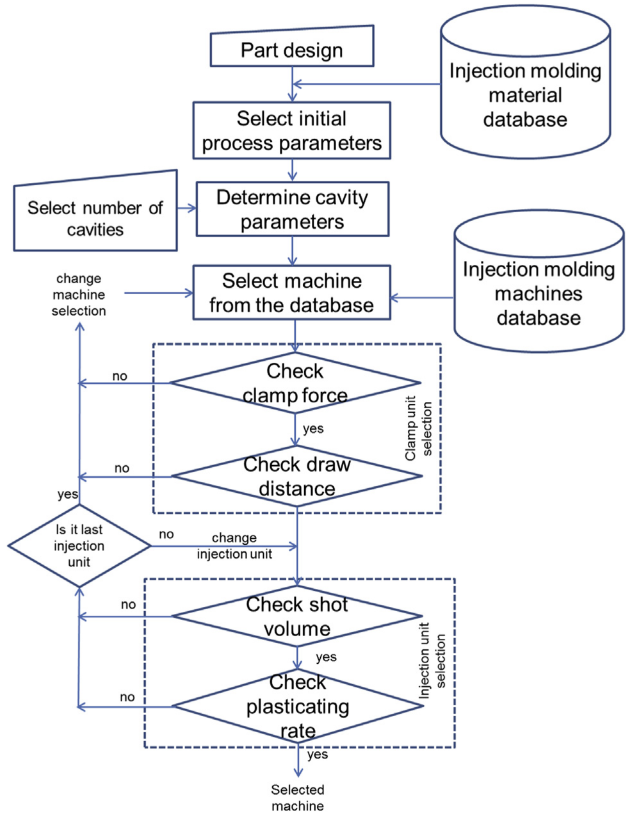


Fig. 3. Information flow diagram for injection molding machine selection.

selected. This step is repeated to find the suitable injection unit of that machine. If none of the injection units satisfy the condition, the next machine from the database is selected. The parameters used for machine selection, clamp force, clamp stroke, injection capacity and plasticating capacity are briefly explained in the Appendix.

Step 5: Determine energy for manufacturing

In this section, we discuss the injection molding cycle time, followed by the estimation of manufacturing energy.

Injection molding cycle time

The time taken for one cycle of the injection molding process cycle is estimated using Eq. (2) (Boothroyd et al., 2011). The injection molding cycle time parameters are injection time, cooling time and mold resetting time, and the procedure to determine them is mentioned in the Appendix.

$$t_{total} = t_i + t_c + t_r \tag{2}$$

Estimate energy for manufacturing

In this section, we attempt to establish a relationship between the required theoretical energy of the UMP and the manufacturing equipment. The concept used here is explained with the help of Fig. 4, which shows that a sub-process of the unit-manufacturing process may derive energy from one or more sub-systems of the manufacturing equipment. For example, in the case of the injection molding UMP, plasticating is one of its sub-processes, and the injection screw is a sub-systems of the injection molding machine. Here, for the sake of simplicity, we assume that each of the sub-system is independent of each other, although in practice a sub-system's functioning may depend on the other sub-system(s).

The total theoretical energy required for one cycle of the UMP is given by Eq. (3).

$$E_{cy\_theo} = \sum_{i=1}^{m} E_i \tag{3}$$

The estimated energy required for one cycle, E_{cycle_est} (J), is given by Eq. (4).

$$E_{cycle\_est} = \sum_{k=1}^{l} \frac{\sum_{i=1}^{m}(E_i)(f_{i\_k})}{\eta_k} \frac{1}{\eta_{machine}} + P_{basic} \times t_{cycle} + P_{idle} \times t_{idle} \tag{4}$$

We applied Eq. (4) to find estimated energy for the *injection molding* UMP. In injection molding, electromechanical or the all-electric injection molding machines, 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 all-electric injection molding machines include: the power supplied in line with the consumption, minimal idling losses and good efficiency.

In all-electric injection molding machines, approximately 20 % of the energy is used for control. The power electronics of the servo-motors, consume much of the energy (Johannaber, 2007). The electric drives have efficiencies from 0.87 to 0.95 (Johannaber, 2007). 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 (Vlachopoulos and Strutt, 2003). Furthermore, in addition to the process-related energy consumption, all injection molding machines consume energy for some basic equipment like the display, fan and other equipment, which remain running throughout; this energy is found using basic power, P_{basic} (W), of the machine. We used this information to develop an Eq. 5, which can be used for estimating per part energy consumption for the injection molding UMP.

$$E_{part} = \left(\left(\left(\left(0.75E_{melting} + E_{inj}\right)/\eta_{inj}\right) + (E_{reset}/\eta_{reset}) + \left(E_{cooling}/\eta_{cooling}\right) + \left(0.25E_{melting}/\eta_{heater}\right)\right) \times ((1+\varepsilon+\Delta)n/\eta_{machine}) + P_b \times t_{cycle}\right)/n \tag{5}$$

η_{inj}, η_{reset}, $\eta_{cooling}$, η_{heater} are the efficiencies of different units for injection, resetting, cooling and heating, respectively.

5.2. Benchmarks

When evaluating the energy performance of a UMP, establishing credible benchmarks is important. Industry often uses benchmarks, such as the energy required for melting the material, industry averages, and industry best practices. The actual energy for manufacturing can be compared with the benchmarks for improving the energy performance. The industry-driven benchmarks can be selected based on the information pertaining to the technologies being considered, for example industry average for electrical injection molding machines. In this study, we additionally establish the science-based benchmarks, which are described in Table 4.

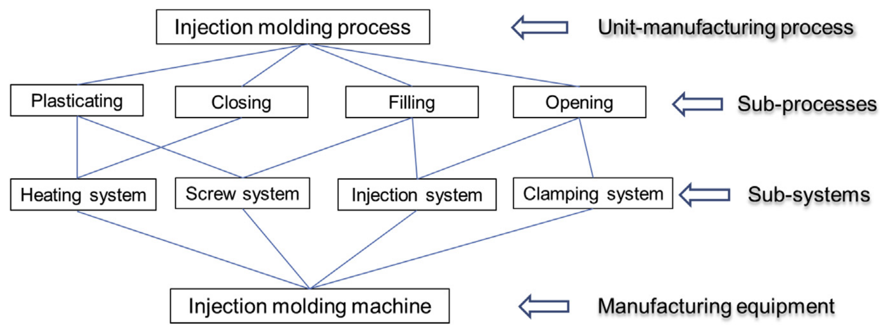


Fig. 4. A schematic of the manufacturing equipment and the UMP relationship.

6. Energy performance evaluation and improvement

The guideline presented in the previous sections, is useful to evaluate the energy performance evaluation and improvement of the injection molding UMP, which is discussed in the following sections.

6.1. Evaluation

After having established the benchmarks for the manufacturing process, we use the ratio of the energy estimate and the benchmark value to get a rating (Eq. (6)). The manufacturing energy performance rating, provides an initial ballpark number of the energy performance with respect to a chosen benchmark. A manufacturing energy performance rating of more than 1 indicates poor energy performance, whereas a lower value indicates better performance. For example, the performance rating number 2, with respect to the benchmark of theoretical process energy (3rd benchmark in Table 4) indicates that the energy consumption is approximately 2 times that of the benchmark, which indicates energy inefficiency due to the process requirements. With reference to the injection molding, process inefficiency could refer to the energy required due to the presence of the gating system, which does not directly contribute to the process but is an essential process requirement. By reducing the size of the gating system or such other inefficiencies, the performance rating may be improved.

$$\text{Manufacturing energy performance rating} = \frac{\text{Manufacturing energy}}{\text{Benchmark energy}} \tag{6}$$

The benefit of having a mix of industry driven benchmarks and the science-based benchmarks is that it provides an overview of the present performance of the manufacturing process.

Table 4
Types of benchmarks.

1	Melting energy	Melting energy (E_{melt}) shown in Eq. (1) is often used in the industry for those manufacturing processes, in which melting is involved.
2	Ideal manufacturing energy	It is the energy required for manufacturing a part at given process parameters by considering both ideal manufacturing process and equipment(s). Please see explanation in Section 4.1.
3.	Theoretical process energy	It is the energy required for manufacturing a part at given process parameters by considering ideal manufacturing equipment(s) only. Please see explanation in Section 4.1.
4	Industry average	This is another important benchmark used by the industry, and represents the average of the industry performance. In this paper, we consider 1.47 MJ/kg, as the average energy use of the injection molding process when using electric machines (Kanungo and Swan, 2008).
5	Industry best practice	The industry uses this benchmark to compare its performance *viz-a-viz* its peers. This provides sufficient insight to the industry to explore the avenues for improvement, but this benchmark is dynamic in nature as the industry best keeps on changing.

6.2. Improvement

Different strategies can be applied for improving the manufacturing energy performance. Some examples of these strategies are: optimizing controllable variables, modification in the manufacturing equipment, manufacturing equipment technological improvements, manufacturing process improvement and development of new manufacturing processes. With reference to the injection molding UMP, in the following paragraphs we discuss the above mentioned energy-performance improvement strategies. Further, Fig. 5 presents an overview of the UMP energy performance evaluation and potential for improvement; the

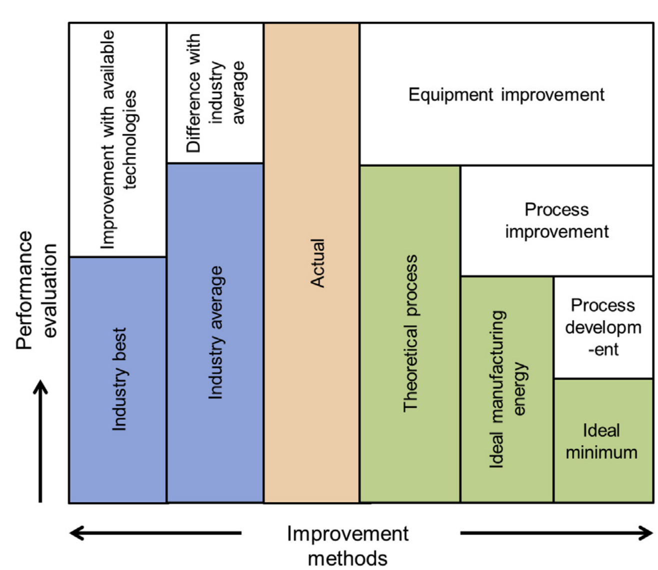


Fig. 5. UMP energy performance evaluation and potential for improvement.

proportion of the vertical axis in the figure is qualitative. The figure provides credible decision support and enough information to set short-term and long-term goals; however, the final decision to select an appropriate strategy remains with the decision maker.

i. *Optimizing controllable variables*: This is one of the most researched areas, wherein the controllable variables are manipulated to optimize an objective function (Qureshi et al., 2012; Lu et al., 2012; Pun et al., 2003). For example, reduction in the injection temperature reduces the energy required for manufacturing, which can be an objective function in this case. Although the controllable variables can be altered with ease for this purpose, the option needs to be carefully weighed by the process experts so that the part quality is not affected.
ii. *Modification in the manufacturing equipment*: The inefficiency of the drive units, transmission units and the fixed energy loads of the manufacturing equipment results in poor manufacturing energy performance. Several studies have been conducted to look into these aspects (Rolls, 1979; Prenatt, 1996; Jiao et al., 2010; Takahashi et al., 2010; Yang et al., 2010; Feng and Zhang, 2012). The benchmark of theoretical manufacturing process energy provides an insight to the energy performance improvement potential of the manufacturing equipment.
iii. *Manufacturing equipment technological improvements*: The manufacturers of machine tools invest valuable resources to improve manufacturing equipment functions and quality. Because of the increased importance of energy, manufacturers are striving to increase the energy performance of their equipment. Energy performance comparison of manufacturing equipment is another issue (Zhang et al., 2012), which is of high interest to the equipment manufacturers and buyers alike. The benchmark of theoretical process energy can be used to assess the energy performance improvement, and comparison of the manufacturing equipment.
iv. *Manufacturing process improvement*: The manufacturing process can be improved by way of process parameters, such as runner volume. For example, replacing cold runner with the hot runner may lead to improvement in the energy performance. The ideal manufacturing energy benchmark is useful to assess the extent of improvement made in the process.
v. *Development of new manufacturing process*: The development of new manufacturing processes, which perform intended functions, is a result of consistent and often long-term research efforts. One such example is a new injection molding process named micro-cellular injection molding (Peng et al., 2012). The melting energy benchmark provides sufficient information to evaluate energy performance of newly developed processes.

7. Implementation and discussions

The guideline proposed in this paper is illustrated by developing a system with a user-friendly GUI (graphical user interface), and is encoded in Visual C#. The GUI allows the user to interact with the system and analyze the results for energy performance evaluation and improvement. Snapshots of the GUI are presented in Fig. A1 in the Appendix. Currently, the GUI functions for the injection molding UMP only, however we intend to develop it to include other UMPs, such as extrusion molding, forming and die-casting. The idea is to allow the user to construct the model of a UMP by selecting constituting sub-processes, material, and machine, etc.

In the following paragraphs, we present the results for an injection molding example part, which was studied by Weissman et al. (2010). The characteristics of the part are: volume (4.5 cm^3), projected area (4.6 cm^2), depth (5.4 mm), maximum wall thickness (2.87 mm) and material (ABS). The injection molding die has four cavities. With reference to the case study part, we discuss the estimation and benchmarking, which is followed by evaluation and improvement. Lastly, we discuss the implementation of the guideline.

7.1. Estimation and benchmarking

In the following paragraphs, five steps of energy estimation and benchmarking with reference to the case study part are discussed.

Step 1 – Select initial process parameters: The system suggests the initial process parameters for injection molding of the example part. As discussed in Section 5.1, these process parameters are injection pressure, injection temperature, mold temperature and ejection temperature. The material of the example part is HIVAL ABS HG6 natural. The initial parameters based on the average values are selected by the system; however, the user may select the processing parameters within a system suggested range. The detailed breakdown of the energy consumption for different sub-processes is also provided.

Step 2 – Determine cavity details: Based on the required number of injection molding parts in a batch, the user selects the number of cavities in the die. The system estimates the cavity parameters, which include shot volume and runner volume, using the procedure discussed in the Appendix (Eq. (A9) onwards). Table 5 provides the system determined part and cavity parameters along with the actual measured values. The actual values represent the cavity parameters taken for the case study.

Step 3 – Determine theoretical process energy: In this step, the theoretical energy required for the sub-processes of the injection molding process is determined, which also takes into account the process requirements of gates and runners. Table 6 gives the ideal manufacturing energy and theoretical process energy required for different sub-processes for the example part. The energy required for gates and runners is not considered to determine ideal manufacturing energy. However, theoretical process energy considers the energy for gates and runners, and therefore is higher than the ideal manufacturing energy. In Table 6, the difference in the ideal manufacturing energy and theoretical process energy is due to the presence of gates and runners.

Step 4 – Selecting the injection molding machine: In this step, an injection molding machine with minimum clamp force, which satisfies the cavity requirements, is selected from the available machines. In this case, the machine with a clamp force of 490 kN is selected. The injection capacity of the selected injection unit is 27 cm^3.

Step 5 – Estimate energy: In this step, first the injection molding process cycle time is determined followed by the manufacturing energy determination. The total cycle time determined by the system is 13.59 s (t_c 11.5, t_r 2.09 s, t_{inj} 0.58 s), while the experimental value of cycle time is 16.13 s (t_c 12.74, t_r 2.64 s, t_{inj} 0.76 s). We discuss

Table 5
Cavity detail determination results.

Parameters	System selected	Actual values
Number of cavities	4	4
Shot volume (cm^3)	22.54	20.87
Runner volume (cm^3)	4.54	2.87
Projected area (cm^2)	92.0	84.10

Table 6
Sub-process level breakup of manufacturing energy.

Name of the sub-process	Ideal manufacturing energy	Theoretical process energy
E_{melt} (J)	1169.4	1464.2
E_{cool} (J)	907.2	1136.0
E_{inj} (J)	427.5	535.2
E_{pack} (J)	9.9	12.5
E_{reset} (J)	628.5	787
Total (J)	3142.5	3934.9

the estimates of energy along with the evaluation and improvement in the next section.

7.2. Evaluation and improvement

Evaluation and improvement of the energy consumption for the example part is discussed. We used the benchmark energy values mentioned in Table 6 to know the manufacturing energy performance rating for the example part. Table 7 presents the energy rating for both the system determined energy estimates as well as the experimental results.

7.3. Discussion

The difference in the system determined and the experimental values of the cycle time is from 10 % to 30 %, which is reasonable given the fact that the average values of process parameters are used by the developed tool. Because of the similar reasons, the estimated energy consumption and the actual values also vary by approximately 10–20 %. Another reason for this variation is that the efficiencies of different drives of the manufacturing equipment are not available. In the absence of that information, we used the information available from the literature, which is applicable to that category of drives.

Table 7
Energy performance rating for manufacturing the example injection molding part.

Sr. No.	Benchmark energy (value in J)	Estimated energy performance rating (6141 J)	Actual energy performance rating (6679 J)	Improvement remarks
1	Melting (1169 J)	5.25	5.71	Indicates the scope of development of new alternative processes that can perform functions similar to the injection molding. The benchmark helps to compare the alternative or newly developed process with the existing process.
2	Ideal manufacturing (3142 J)	1.95	2.12	Indicates the combined scope of improvement in the process and equipment efficiencies.
3	Theoretical process (4331 J)	1.56	1.69	Indicates the scope of improvement in the equipment efficiency.
4	Industry best (5556 J)	1.10	1.20	Energy use is higher than the industry best, and there is scope of improvement by implementing available technologies.
5	Industry average (6945 J)	0.88	0.96	The energy use nearly equals the industry average.

The results provide sufficient information regarding energy performance of the injection molding process. The energy performance evaluation of the process is helpful to choose appropriate improvement strategies. The energy performance evaluation of the unit-manufacturing process will work as a foundation for evolving similar strategies for the shop floor and the factory.

8. Conclusions and future scope of work

A science-based guideline for energy performance evaluation and improvement of manufacturing processes has been developed and presented in this paper. The steps of the guideline were discussed in detail. The main features of the guideline are (i) the five steps, which help the user to obtain an estimate of the energy required for manufacturing a part using an injection molding UMP, (ii) a benchmarking scheme which uses both science-based and industry driven benchmarks, (iii) energy performance evaluation, and (iv) energy performance improvement. The early estimation of energy is helpful at the process planning stage. The UMP energy evaluation and improvement strategy acts as a valuable decision support. A system has been developed, which through its GUI, helps the user to visit the steps of the guideline. The system is demonstrated with the help of an injection molding case study. The guideline can be applied to other processes, such as casting, plastic fabrication processes and die-casting, which require only minor modifications. The methodology, however, can be further extended or modified to include the majority of the manufacturing processes, which remains our future work.

The proposed system will be quite useful as the manufacturing industry seeks energy information for manufacturing processes for early estimates or to generate the bill-of-energy. The issues addressed in the paper, namely energy: benchmarking, evaluation and improvement are also of significant importance to the industry. The manufacturing energy performance rating is a valuable metric, which substantiates the efforts such as external benchmarking of injection molding (Kent, 2009) with an objective to improve energy performance of manufacturing.

With increased focus on sustainable manufacturing and energy consumption in the manufacturing sector, we intend to extend this work to develop a standard reference methodology for energy evaluation and improvement for manufacturing. The standard reference methodology will support different technological and practice-based efforts (Avram et al., 2011; Balogun and Mativenga, 2013; Jovanovic et al., 2014; Li et al., 2013; He et al., 2012; Zhu et al., 2014) to reduce energy consumption in the manufacturing sector. Development of manufacturing-energy-related information models is another important area of research, on which we are focusing. Our objective is to help achieve sustainability in manufacturing by developing the needed science-based standards for the industry. One such initiative is the ASTM E60.13 sub-committee (ASTM, 2014). The work presented in this paper may be extended to develop a performance rating scheme of manufacturing processes and equipment.

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. The work presented in this paper was funded in part by the cooperative agreement between the University of Maryland and NIST.

Appendix

Stages of the injection molding process

The injection molding facility consists of four stages (i) drying, (ii) blending and dosing, (iii) injection molding, and (iv) regrinding. In the drying stage, the material (plastic beads and the re-usable scrap) is fed into the dryer, to remove or reduce moisture to an acceptable level. In the second stage of blending and dosing, material is further mixed with the additives, like colors and other property enhancers. In the third stage, the injection molding process takes place, wherein the plastic mixture is melted and converted into a solid part. In the fourth stage of regrinding, runner, gates, and any other unwanted plastic, which is attached to the part, is removed and ground into granules appropriate for adding to virgin mix. In Fig. A1, we present a schematic view of the stages of the injection molding manufacturing facility and identify major energy consuming UMPs. The system boundary of the injection molding UMP is shown in the figure, which is the scope of this paper.

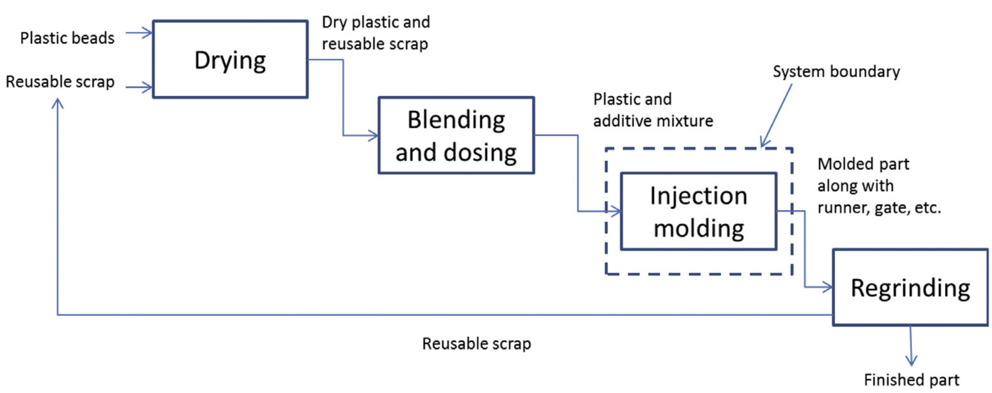


Fig. A1. Stages of an injection molding manufacturing facility.

Sub-processes of the injection molding process

Six sub-processes of the injection molding process are briefly discussed below, whereas a schematic of the sequence of the sub-processes is presented in Fig. A2.

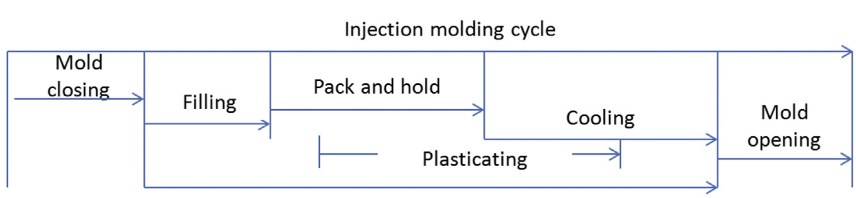


Fig. A2. A schematic of the sequence of the sub-processes in the injection molding process.

i. *Mold closing*: The die halves are closed to allow filling of the mold cavity.
ii. *Filling*: The plasticated material is injected into the cavity under high pressure.
iii. *Pack and hold*: The injected material is kept at high pressure for some time, until it starts solidifying and loses pressure. During this time, an external force is required to oppose the internal pressure of the material and hold the two halves of the die together.
iv. *Cooling*: The plastic inside the mold is cooled by a coolant that circulates through cooling channels in the die. This cycle is completed when the material in the die becomes completely solid due to the temperature of the part being lowered.
v. *Mold opening/ejection*: The die halves are opened to eject the solid part(s).
vi. *Plasticating*: The plastic granules, which are mixed with re-usable scrap and other additives, are heated and melted.

Injection molding process parameters

Injection pressure: It is the pressure exerted on the melt in front of the screw tip during the injection stage.

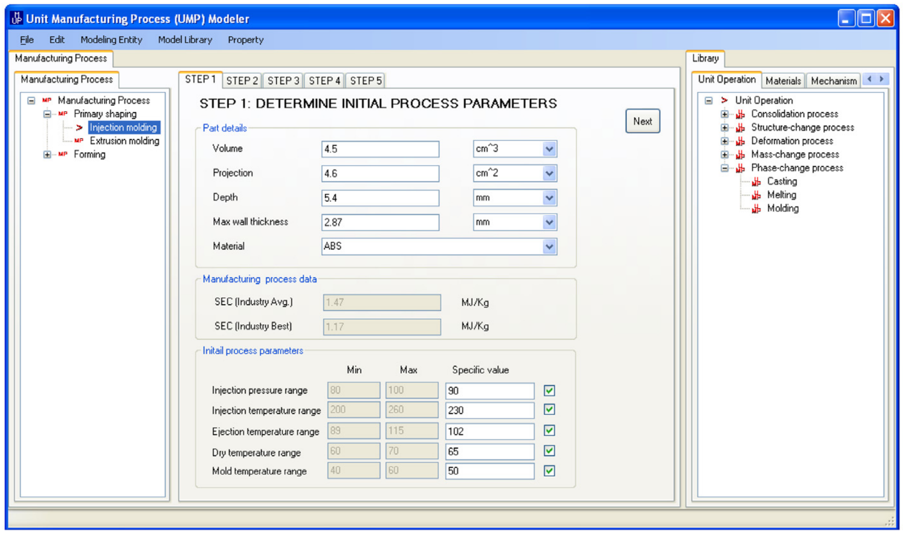
Injection temperature: It is the temperature at which the plasticated material is injected into the mold cavity.

Mold temperatures: It is the temperature at which the mold is maintained during the injection molding process. The injection temperature of representative injection molding materials is presented in Table 3.

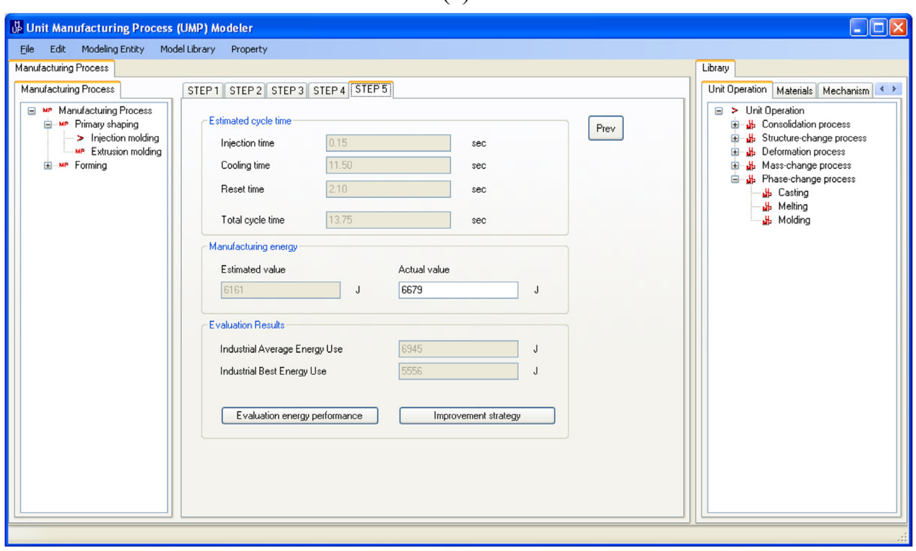
Ejection temperature: It is the temperature at which a part is ejected out of the die. The ejection temperature nearly equals Vicat temperature of the polymer (Malloy, 1994), which represents its softening point.

Machine selection parameters

Clamp force: It is the maximum force which a machine can exert to keep the die closed during the injection molding process. The machine clamp force should be higher than the separating force.



(a)



(b)

Fig. A3. Snapshots of the GUI of the system for energy performance evaluation and improvement for UMPs.

Clamp stroke: It is the maximum possible distance between fixed and movable die platens of the machine in the die-opening direction. To allow sufficient space for part ejection, the clamp stroke of the machine should be 5 cm more than the part height (or maximum dimension of the part in the die-opening direction).

Injection capacity: It is the maximum possible design displacement of the reciprocating screw. The injection capacity is generally given as a specification of the injection unit of the machine or can be found using Eq. (A1) (Johannaber, 2007).

$$V_{\text{inj\_cap}} = \left(\frac{D}{2}\right)^2 \times \pi \times S \times 10^{-3} \tag{A1}$$

Further, the injection capacity is used to find the realistically attainable volume, V_{att} (cm^3) of the injection molded cavity using Eq. (A2) (Johannaber, 2007).

$$V_{\text{att}} = C_{\text{f}} \times V_{\text{inj\_cap}} \tag{A2}$$

The value of correction factor (C_{f}) is between 0.7 and 0.8, which indicates that the maximum possible injection volume does not correspond to the maximum injection capacity.

Plasticating capacity: It is the amount of plastic that can be melted, homogenized and heated to the processing temperature in the barrel, per unit of time (Rosato et al., 2000). The machine plasticating capacity should be such that the required amount of melt is available, when the machine is ready for the next cycle.

Theoretical energy for sub-processes of the injection molding process

Plasticating (E_{melt}): The theoretical energy required for heating and melting, the polymer, E_{melt} (J), is found using Eq. (A3) (Vlachopoulos and Strutt, 2003).

$$E_{\text{melt}} = \rho V_{\text{part}} \times 10^{-3} \times \left[C_{\text{p}}\left(T_{\text{inj}} - T_{\text{pol}}\right) + H_{\text{f}}\right] \tag{A3}$$

Injecting (E_{inj}): The theoretical energy required for injecting the plasticated polymer into the cavity, E_{inj} (J), is the work done for filling the cavity against pressure, which is found using Eq. (A4) (Ribeiro et al., 2012).

$$E_{inj} = p_{inj} \times V_{part} \tag{A4}$$

Packing (E_{pack}): The theoretical energy required for packing the molten polymer inside the cavity and to compensate for the shrinkage volume of the plasticated polymer, E_{pack} (J), is found using Eq. (A5). As a rule of thumb, the packing pressure is 75 % of the injection pressure (Yang et al., 2010).

$$E_{pack} = 0.75 \times p_{inj} \times V_{part} \times \varepsilon \tag{A5}$$

Cooling (E_{cool}): The theoretical energy required for cooling the injected plasticated material inside the mold to the ejection temperature, E_{cool} (J), is found using Eq. (A6). The coefficient of performance (COP) of the cooling equipment used is assumed to be the theoretical maximum (based on Carnot cycle) (PowerKnot, 2014).

$$E_{cool} = \frac{H_{cool}}{COP_{Carnot}} \tag{A6}$$

In the above equation, the amount of heat to be taken out from the molded part, H_{cool} (J), is found using Eq. (A7).

$$H_{cool} = \rho V_{part} \times 10^{-3} \times \left[C_p\left(T_{inj} - T_{ej}\right) + H_f\right] \tag{A7}$$

Clamping, ejection and opening/closing (E_{reset}): It is suggested that the energy required for opening/closing, clamping and ejection is 25 % of the process energy (Mattis et al., 1996). Equation (A8) is used to find E_{reset} (J).

$$E_{reset} = 0.25\left(E_{inj} + E_{cool} + E_{melt}\right) \tag{A8}$$

Determining cavity parameters

Shot volume: It is the amount of molten polymer required to fill the mold cavity, in each cycle. The shot volume takes care of the shrinkage compensation due to cooling, and the volume of runner and gates, and is found using Eq. (A9). The volumetric shrinkage in plastics is three times the linear shrinkage (Malloy, 1994) and is found using Eq. (A10). The volume of runner and gate is estimated using the information available from Boothroyd et al. (2011).

$$V_{shot} = V(1 + \varepsilon + \Delta)n \tag{A9}$$

$$\varepsilon = 3 \times \alpha \times \left(T_{inj} - T_{ej}\right) \tag{A10}$$

Cavity projected area: It is the area of cross-section of the cavity perpendicular to the withdrawal direction (or opening direction) of the mold. The cavity projected area also accounts for the presence of gates and runners, and is found using Eq. (A11) (Boothroyd et al., 2011).

$$A_{total} = A_{part} \times \frac{V_{shot}}{V_{part}} \tag{A11}$$

Separating force: 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 is calculated using Eq. (A12). The pressure inside the cavity is assumed to be 50 % of the injection pressure (Boothroyd et al., 2011).

$$F_{sep} = 0.5 \times p_{inj} \times A_{total} \times 10^{-1} \tag{A12}$$

Injection molding cycle time parameters

Injection time (t_i): It is the time required to inject the plasticated material into the cavity. 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. To determine average flow rate, the maximum flow rate is required, which is found from the machine specifications or using Eq. (A13) (Boothroyd et al., 2011).

$$\text{Maximum flow rate } \left(m^3/s\right)\ Q = \frac{P_{inj}}{p_{inj}} \times 10^3 \tag{A13}$$

However, in practice the average flow rate, Q_{avg} (m^3/s) decreases as the mold is filled, and is found using Eq. (A14).

$$Q_{avg} = 0.5 \times Q \tag{A14}$$

Therefore, the injection time is given by Eq. (A15).

$$t_i = \frac{V_{shot}}{Q_{avg}} \tag{A15}$$

Cooling time (t_c): It is the time taken by the molten plastic to solidify inside the mold, and is found using Eq. (A16) (Boothroyd et al., 2011). However, to make sure that the runners are solidified and the part comes clean from the mold, the minimum cooling time is taken as 3 s.

$$t_c = \left(\frac{h_{max}^2}{\pi^2 \times \gamma}\right) \times \log_e \frac{4}{\pi}\left(\frac{T_{inj} - T_m}{T_{ej} - T_m}\right) \tag{A16}$$

Mold resetting time (t_r): It is the time taken for the mold to open and close, and is estimated using Eq. (A 17) (Boothroyd et al., 2011).

$$t_r = 1 + 1.75 t_d \sqrt{\frac{2d + 5}{L_s}} \tag{A17}$$

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