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# Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts

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ABSTRACT

This paper studies the environmental impact of the injection molding process by carrying out a life cycle assessment. A review of how EcoInvent's Life Cycle Inventory database characterizes this process has been conducted, and a new methodology based on that analysis has been carried out. Aspects such as the infrastructure of the factory or waste treatment are part of the environmental impact of the injection molding process, but the most significant factor is electricity consumption; therefore, electricity consumption measurements of the process have been performed. This environmental analysis has been applied to the processing of several parts made of high-density polyethylene, which have been characterized by measuring the electricity consumption. As a consequence of this work, it has been proven that electricity consumption can be used as an injection molding machine selection criteria, from an environmental standpoint, as it produces the highest environmental burden of the process.


## 1. Introduction

Today, plastics are one of the most used polyvalent materials and are an important part of the economy. They provide multiple applications in a wide range of sectors, from the packaging market, which represents 39.4% of the demand for plastics, to the building and construction sector, the automotive industry and other examples, such as home appliances or medical products (PlasticsEurope, 2013).

Among the different types of plastics, the three most demanded are the thermoplastic variations, polypropylene (PP), low-density polyethylene (LDPE) and high-density polyethylene (HDPE), according to (PlasticsEurope, 2013). The last one represents 12% of the total European plastic demand (PlasticsEurope, 2013). Injection molding is one of the most used plastic part manufacturing processes due to its precision and cost-effectiveness for large volume productions (Wang et al., 2013; Guevara-Morales and Figueroa-López, 2014). This process is divided into five phases: mold filling, packing, the simultaneously occurring cooling phase and plasticizing phase, and finally the ejection of the injected part. All of these phases make this process quite intensive, energetically speaking. Thus, that high electricity consumption also implies that the injection molding process is also relevant in terms of environmental impact, even more so bearing in mind the large scale of plastic parts manufacturing.

There are different types of injection molding machines depending on how the drives are powered: hydraulic, hybrid and all-electric. In the hydraulic type, the injection molding machine's motions are powered by hydraulic pumps. Today, almost no machinery is purely hydraulic as they typically use hybrid mechanisms, such as the toggle clamping mechanism that helps the hydraulic system and also provides electrical energy savings (Huang et al., 2011; Hsu et al., 2013). All-electric injection molding machines replace the hydraulic circuit with servomotors. One of the main specifications that characterize an injection molding machine is its clamping force, and this is related to the size of the parts that can be injected in it. There is a wide range of clamping forces, from micro-injection molding machines of approximately 50 kN of clamping force up to nearly 100,000 kN of clamping force (Muccio, 1994). In this paper, injection molding machines from 833 to 78,400 kN have been analyzed while manufacturing HDPE parts. This last injection molding machine is one of the largest operating in Spain.

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The plastics industry in Europe started to assess the environmental impact of plastics more than 20 years ago (Boustead, 1992). The societal concern regarding this subject is increasing around the world (Givens and Jorgenson, 2013), with the global warming threat as one of the primary reasons (Czap and Czap, 2010). This environmental concern has promoted the use and development of different methodologies that strive for sustainable development. The life cycle assessment (LCA) is a methodology used to calculate the environmental impact of products, processes or services. The results obtained by an LCA are analyzed so that priority areas in which actions should be applied can be identified (Guinée et al., 2002). Working in those areas allows researchers and designers to improve the environmental performance and, as a consequence, make products and processes more ecofriendly.

In the specific field of injection molding, Thiriez and Gutowski provide a review of the entire process, including the thermoplastic production, the compounding of the additives and the injection molding process (Thiriez and Gutowski, 2006). In that paper, the authors highlight the importance of the choice of the type of the injection molding machine as that could entail a high impact in the specific electricity consumption of the injection molding machine, therefore also influencing, as will be discussed in this paper, the environmental impact of the process. In the thesis of Almeida, a life cycle engineering task was performed, following a cradle-to-grave approach in order to determine the environmental performance of the injection molding of biodegradable plastics (Almeida, 2011). In the article written by Weissman et al., a methodology to estimate the electricity consumption of the injection of a molded part is explained, with the aim of providing an electricity consumption model to help designers make more environmentally conscious decisions (Weissman et al., 2010).

When performing an LCA of a product, the materials and manufacturing processes have to be identified. Among these processes, the injection molding process is usually included. Databases, such as EcoInvent, have defined the injection molding process based on measurements of several facilities at a European level (Hischier, 2007). In another report (TNO for Plastics Europe, 2010), PP and HDPE along with polyvinyl chloride (PVC), which are among the most demanded plastics, are used as a reference to characterize the environmental impact of the injection molding process.

These values could be used to incorporate them into the calculation of the environmental impact of that product as a first approach. However, if the level of detail required is higher or the injected parts are an important component of the study, this approach is not precise enough. As Gutowski et al. note in their research, the manufacturing process's electrical energy requirements are not independent of the characteristics of the manufactured parts, as the LCA databases traditionally assume (Gutowski and Thiriez, 2006).

The main aim of this essay is to analyze the different factors in the environmental impact of the injection molding process. From this analysis, a methodology is developed to calculate the environmental impact of a specific injection molding process, and it has been applied to several parts that use the same raw material (HDPE). The units of the obtained results will be per injected kilogram.

## 2. Materials and methods

In the following section, a review and analysis of the state of the art is going to be presented, as well as the equipment that has been used during this research, such as the raw material, molds and injection molding machines analyzed and the required measurement equipment.

### 2.1. State of the art review and analysis

Various authors have investigated the electrical energy requirements of plastics manufacturing processes. Muller et al. analyzed the injection molding by using dual electrical energy signatures to determine value- and non-value-adding elements to improve the process's efficiency by studying the influence of the process time and power levels on the injection molding machine (Müller et al., 2014).

Madan et al. also studied this process by considering its electricity consumption as an indicator of sustainability. They suggest that the LCAs performed today give much more importance to the material than to the manufacturing factors, and they propose a guideline to estimate the electricity consumption of UMPs (unit manufacturing processes), based on the analysis of the stages of the injection molding process, with the goal of benchmarking, evaluation and improvement (Madan et al., 2014).

Lucchetta and Bariani also conducted research based on this idea, suggesting that most LCE (Life Cycle Engineering) tasks, where the environmental and economic impact of the product are assessed simultaneously, are focused on minimizing the use of materials and increasing the recycled materials but do not take into account the cost and environmental impact of the manufacture of the design alternatives. They also remark on the importance that the injection molding industry has, in terms of environmental impact, due to its large scale (Lucchetta and Bariani, 2010). Yam and Mak studied the gas-assisted injection molding process. This process allows for the reduction of the use of petrochemical polymers and, at the same time, achieves electrical energy savings of 20% thanks to the reduction of processing parameters, such as the injection pressure and the clamping force of the injection molding machine (Yam and Mak, 2014).

The electrical energy demand has also been studied in other plastics manufacturing processes, such as polymer extrusion. For instance, Abeykoon et al. studied the electrical energy demand with different process conditions in order to optimize the process's efficiency (Abeykoon et al., 2014a). Alternately, Deng et al. presented a real-time electricity consumption monitoring method and used it to study the effect of process settings on melt quality and electrical energy efficiency, which are highly related with the electricity consumption (Deng et al., 2014). Moreover, results in other papers showed that the specific electrical energy demand was reduced as the throughput was increased (Abeykoon et al., 2014b). These experimental studies help to select operational conditions and equipment to optimize the process.

In this research, in order to analyze the environmental impact of the injection molding process, we have studied the injection molding dataset of EcoInvent v3.01 as a starting point (named in this paper as EcoI). To create the dataset for the generic injection molding process, EcoInvent calculates the arithmetic mean of data gathered from three average injection molding processes, PVC, PP and PET (Hischier, 2007), and correlates the inventory data to its own datasets. There are notable differences between input data of the different plastics.

To manufacture one kilogram of injected plastic parts, this inventory includes water used during this process, lubricating oil, and different types of additives, such as chemicals, solvents, pigments or fillers. It also considers packaging materials: pallets, polypropylene, LDPE and cardboard. The electricity, natural gas and other fuels are classified as energy inputs. The generated waste is separated into waste to landfill, hazardous waste and plastic waste from which energy is recovered by incineration.

Given that our raw material is going to be high-density polyethylene, we can use the report from which this database has been constructed (Hischier, 2007) and particularize it in order to obtain a