Analysis of Economic and Environmental Performances of Production Alternatives of Light Diffusers

Development of an Integrated Model in a Life Cycle Perspective

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Abstract

In the search for competitiveness and new markets, the development of a product and the comparison of production alternatives cannot focus only on classical methodologies, such as the technical and economic performances. The Integrated decision support Model is a tool that allows an evaluation of the economic and environmental performances of several production alternatives for various parametric combinations or productive scenarios. This Integrated Model includes the methodologies of economic performance (Life Cycle Cost-LCC), environmental performance (Life Cycle Assessment-LCA) and technological performance based on the processes (TPM). The Integrated Model was applied to a case study that incorporates three alternatives for the manufacture of light diffusers, resorting to plastic injection technologies and hot-embossing equipment to obtain micro-components and the final product. The application of the Integrated Model to this case study allowed us to compare the economic and environmental performances of production alternatives by conducting various analyses, such as variation of production volume, hot-embossing’s equipment uptime, number of micromold cavities and fill levels of plates to conform, and lifetime of disposable micro-component. This way, it was possible to compare the alternatives from economic and environmental perspectives for various productive scenarios, demonstrating the versatility of the developed Integrated Model.

Keywords: Life Cycle Cost, Life Cycle Assessment, Technological Performance Model Based on the Processes, Disposable Micro-mold, Hot-embossing, Light Diffuser.

1. Introduction

In the search for competitiveness and new markets, the development of a product and the comparison of production alternatives cannot focus only on classical methodologies, such as the technical and economic performances. Currently there are methodologies for the analysis of economic and environmental impacts throughout the life cycle of a product [1]. But, as comparisons of production alternatives contain several parameters that influence them, this analysis are an extremely useful resource to technological models that allows to compare the performance of various alternatives for several parametric combinations or productive scenarios.

Within this framework, it is proposed the development and implementation of an Integrated Model that incorporates essentially three types of models in accordance with the Life Cycle Engineering: the model of economic performance (Life Cycle Cost - LCC), the model of environmental performance (Life Cycle Assessment - LCA) and technological performance based on the processes model (TPM). The latter is the Integrated Model engine that was built on the basis of process-based Cost Modeling (PBCM). The LCC and LCA models allow the calculation of costs and environmental impact, respectively [2][3].

The proposed model was applied to a case study that incorporates three manufacturing alternatives of light diffusers with very small dimensions, by plastic injection and hot-embossing. The reduced dimensions of the piece force the use of micro-fabrication technologies, usually
used to produce the micro-molds, to be applied in the process of obtaining the light diffuser. The industrial domain of micro-milling technologies to obtain micro-molds or of alternative technologies to produce light diffusers is still scarce.

In this context, the application of the Integrated Model is of the biggest interest and utility because it allows us to compare the economic and environmental performances of the three alternatives for producing light diffusers in a life cycle perspective, through the knowledge of the influence of various parameters, such as variation of the production volume, hot-embossing’s equipment uptime, number of micro-mold cavities and fill levels of plates to conform, and average lifetime of disposable micro-components.

2. Case Study’s Description and Developed Model

Based on the developing technological alternatives for the manufacture of the micro-components, it was defined three alternatives for obtaining the light diffusers:

- Alternative 1.A - Disposable Micro-Mold and Production of Diffuser by Hot-Embossing;
- Alternative 1.B - Disposable Micro-Mold and Production of Diffuser by Injection;
- Alternative 2 - Disposable Micro-Puncture and Production of Diffuser by Hot-Embossing.

**Alternative 1.A e 1.B – Disposable Micro-mold**

The Alternatives 1.A and 1.B – Disposable Micro-Mold have the need to manufacture a micro-component with about 12 mm in diameter in common, which will serve as a mold in order to conform multiple forms of light diffusers on each plate of polymethylmethacrylate (PMMA). In Alternative 1.A it is used in the process of hot-embossing and in Alternative 1.B it is used as a molding cavity in the injection process. To facilitate the understanding of the alternatives’ description, the designation of disposable micro-mold will be used for this micro-component. The sequence of production used in the manufacture of this disposable micro-mold is divided into 3 distinct steps: the Puncture’s Production, the Mold’s Production of Silicon and the Disposables Micro-molds’ Production in series.

In the Puncture’s Production, after the punch is designed with the reverse geometry of the light diffuser, a tungsten block goes through milling to make the puncture. This sequence of production initially uses laser milling technology to obtain shape and later the projection polishing technology and electron beam machining (EBM) for the subsequent surface polishing.

In the Mold’s Production of Silicon, the tungsten puncture obtained in the previous step is placed in a container. Then, a silicone mixture is poured and the obtainer is placed in a furnace so as to conform the mold with the positive image of the light diffuser. This mixture must be obtained beforehand by mixing silicone with a catalyst, and then putting it in a vacuum chamber to degas it.

In the next step, the Disposable Micro-molds’ Production in series, the silicone mold is then used to get the disposable micro-mold through a process of hot-embossing. Firstly, the feedstock is obtained by mixing a selected powder and binder, in a mixing equipment. Then, the hot-embossing stage begins, conforming the feedstock in the silicone mold, achieving a “green” micro-mold in alloyed steel. After this process, it is performed the debinding and sintering of the “green” micro-mold in a controlled atmosphere of argon with 5% hydrogen.
Alternative 1.A

In Alternative 1.A it must be initially produced several disposable micro-molds that are placed at the base of the hot-embossing machine (with room for 61, 154 and 289 micro-molds). Subsequently, a PMMA plate is preheated at about 70º C. Completed these processes the hot-embossing is made, conforming multiple forms of the light diffuser in PMMA plate through the disposable micro-molds, at a rate of one plate per cycle. Finally, the conformed plate is cut on a cutting press, obtaining this way, multiple light diffusers.

Alternative 1.B

Alternative 1.B consists of two distinct steps: the Conventional Micro-mold’s Production and the Light Diffuser’s Production. In the Conventional Micro-mold’s Production, it is produced a part that, in conjunction with the disposable micro-molds obtained earlier, will form the molding cavity. This molding cavity will be necessary for the next stage that will be explained in its own time. This being a machined alloy steel cavity, a production sequence is used, consisting of Rough Milling/Finishing of steel blocks, Drilling and Grinding. The molding area 1 can have multiple cavities (4, 6 or 8 cavities) and is manufactured by laser milling. The polishing is done using EBM. Molding area 2 consists of the disposables micro-molds obtained previously. In the Assembly process, the moldings areas are assembled in the structure, obtaining a conventional micro-mold.

In the Light Diffuser’s Production the PMMA is injected in the conventional micro-mold produced in the previous step, obtaining the light diffusers.

The conventional micro-mold is consists of two components of different duration. The disposable nature of this micro-mold’s cavity will inevitably lead to its replacement as it evolves in number of units injected.

Alternative 2

Alternative 2 has less productive steps that the previous two. It is composed essentially by 3 steps: Micro-mold’s Production, Disposable Micro-puncture’s Production and Light Diffuser’s Production.

The micro-mold is obtained through a sequence of machining processes of a block of steel: Rough Milling/Finishing, Drilling and Grinding. After these processes, four cavities of moldings areas are produced with use of laser milling technology, and the polishing of these is made by EBM. Then it proceeds to the assembly of the micro-mold.

For the Disposable Micro-puncture’s Production, the Powder Injection Molding technology (PIM) is used. Initially, the feedstock’s is prepared using a mixer. Subsequently, the material obtained in the previous step is injected into the micro-mold, obtaining four micro-punctures per injection cycle. Finally, the Debinding and Sintering of micro-punctures are made.

In the Light Diffuser’s Production step, the disposable micro-punctures obtained in the previous step are mounted in a hot-embossing machine (with room for 92, 231 or 432 micro-punctures). A plate of PMMA is preheated at about 70ºC, and then the hot-embossing is made, conforming multiple forms of light diffuser in PMMA plate, through the disposable micro-punctures. Finally, the conformed plate is cut on a cutting press, obtaining multiple light diffusers.

In order to calculate the economic and environmental performances of the production alternatives described, an Integrated Model was applied to the case study, incorporating
three types of models: the model of economic performance (LCC), the model of environmental performance (LCIA) and the technological performance based on the processes (TPM).

**LCC Model**

The LCC model used in the Integrated Model is illustrated in Figure 1. For each process the several streams of mass and energy are identified and based on these streams the costs for each process are calculated. The sum of these costs allows the calculation of the costs of the production alternative’s life cycle.

![Figure 1: LCC model.](image)

The total cost of each process is divided into six distinct categories, illustrated in the Table 1.

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>Costs associated with the operator.</td>
</tr>
<tr>
<td>Machine</td>
<td>Costs associated with the machines.</td>
</tr>
<tr>
<td>Tools</td>
<td>Costs associated with tools.</td>
</tr>
<tr>
<td>Materials</td>
<td>Costs associated with the consumption of materials during the process.</td>
</tr>
<tr>
<td>Energy</td>
<td>Costs associated with the amount of energy consumed by the machine.</td>
</tr>
<tr>
<td>Others</td>
<td>Costs associated with the consumption of fluids/gases during the process and costs associated with the maintaining equipment.</td>
</tr>
</tbody>
</table>

**LCA Model**

The LCA model, represented in Figure 2, accounts for the environmental impacts resulting from raw materials, energy and resources consumed in the different processes of each production alternative. In order to calculate the environmental impact of each process it’s necessary to quantify the streams of mass and energy. The total mass (kg) of each material involved in the processes is multiplied by the respective eco-indicator (pts/kg), resulting on the impact of each material used. The energy impact is calculated by multiplying the total sum of the expended energy (kWh) in each process, by the eco-indicator of energy (pts/kWh). The sum of the points recorded in the model indicates the environmental impact of each production alternative.
Technological Performance Model Based on the Processes - TPM

The Technological Performance Model Based on the Processes (TPM) is the engine of the Integrated Model which was built based on Process-based Cost Modeling (PBCM). The use of this model allows for the systematized analysis of each process involved. This way, the impact of each process in terms of the type of resources consumed, energy consumed and utilization time, is quantified through its parameterization, allowing to estimate the economic and environmental impacts of each alternative technology for the several phases of the life cycle.

In order for the TPM (Figure 3) to compute the performance of each production alternative in economic and environmental terms, it is necessary to introduce a set of information (Inputs) that characterize the industrial and productive scenario of the results that will be obtained (Outputs). Through the relationships and technological correlations between inputs and parameters of the technological processes, the TPM calculates the resources consumed in a specific productive scenario. These quantities are crossed with two databases: one is related to the specific costs of materials, equipment, tools and consumables, and the other one is related to the particular environmental impact per unit of mass, energy or volume of each of the resources that generate this impact. The result is, naturally, the total life cycle cost and the related environmental impact, but also the economic and environmental impacts per alternative, per life cycle phase and per type of impact factor: materials, equipment, consumables, tools and energy.

In Alternatives 1.A and 1.B, the model presents some particularities. For a specific production volume and lifetime of each micro-component, the model allows to obtain the number of disposable micro-molds, molds in silicone and punctures to produce. In the Light Diffuser’s Production step of Alternative 1.A, depending on the dimensions of the PMMA plate to conform, the model computes a number of disposable micro-molds to be mounted at the base of the hot-embossing equipment (fill level), in order to obtain a lower material waste. Alternatively, the model contains an option that allows the user to choose the number of disposable micro-molds.
For Alternative 1.B, the model calculates the number of conventional micro-molds and disposable micro-molds to produce for a specific production volume, taking into account the lifetime of micro-molds (conventional and disposable).

In Alternative 2, the number of disposable micro-punctures to be mounted at the base of the hot-embossing equipment is calculated by the model based on the dimensions of the PMMA plate in order to reduce material waste. The model also contains an option that allows the user to choose the number of micro-punctures to assemble in the equipment. For a certain production volume, and taking into account the lifetimes of the disposables micro-punctures and micro-mold, the model calculates the required numbers of micro-punctures and micro-molds to produce.

In short, the TPM described for the three production alternatives of light diffusers are the engines for the performance calculation that will allow a comparison between these alternatives. The particularities presented by the different models allow us to make several analysis of sensitivity. These will focus especially on the variation of the production volume and on the configuration of the light diffusers obtaining systems (number of cavities, number of disposables micro-punctures and micro-molds). Other analysis will focus on the technological aspects where uncertainty is high, particularly the lifetime of disposables micro-components.

![Figure 3: Main steps of calculation of the Technological Performance Model Based on the Processes.](image)

3. Results and Discussion

Cost Analysis

The first cost analysis allows the comparison of the three production alternatives of light diffusers, for an expected productive scenario (Figure 4). For this scenario a production volume of 500,000 diffusers, a fill level of 289 diffusers for Alternative 1.A, a fill level of 432 diffusers for Alternative 2 and a micro-mold with 8 molding cavities were considered.

Taking into account the assumed productive scenario, Alternative 1.B is the most economically viable, while Alternatives 1.A and 2 have the worst economic performance. In both alternatives, the cost related to the equipment is what has had the biggest impact on the final result. In both these last alternatives, the Machine cost is the major cause of poor economic performance, because both use the technology with the largest time-machine cost of all processes (hot-embossing), contributing negatively to the total cost of the alternatives. This cost is lower in the case of Alternative 2, because the fill level is higher. This way, more diffusers per plate are produced, and consequently the production time of the 500,000 diffusers becomes smaller in relation to the same process in Alternative 1.A. In relation to the Material cost, this is considerably lower in Alternative 1.B, because the process of obtaining the diffusers is by injection of PMMA, and as such the amount of waste of material is much smaller than in the hot-embossing process (Table 2). Thus, the amount of material required for this process is much higher, reflected in a higher Material cost than in the injection process.
Figure 4: Distribution costs of 3 production alternatives for a production volume of 500,000 diffusers.

Table 2: Amount of PMMA required in the light diffusers’ production, for a productive scenario expected.

<table>
<thead>
<tr>
<th>Light Diffuser</th>
<th>Total of PMMA [kg]</th>
<th>Waste of PMMA [kg]</th>
<th>Percentage of Waste [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative 1.A</td>
<td>865.2</td>
<td>827.2</td>
<td>95.7</td>
</tr>
<tr>
<td>Alternative 1.B</td>
<td>37.9</td>
<td>0.0004</td>
<td>~0</td>
</tr>
<tr>
<td>Alternative 2</td>
<td>578.8</td>
<td>540.8</td>
<td>93.5</td>
</tr>
</tbody>
</table>

Figure 5 presents the percentage variation between the unit costs of diffusers’ production diffusers for uptimes of 25% and 90%. The costs are presented only for a production volume of 250,000 diffusers, because the percentage values of these cost reductions are similar to other production volumes. There is also a significant reduction in the unit cost of production for an increased uptime at 90%, for both the fill levels. This cost reduction is greater for the fill level of the 61 diffusers, since this productive scenario requires more cycles of hot-embossing, and as such the time of use of the equipment is greater, resulting in a higher cost. Given that this cost has a high contribution to the total costs of production, this increase in the uptime is most noticed on the costs of productive scenario that features an increased use of hot-embossing (NE = 61).

Figure 5: Variation of unit cost of production with the hot-embossing’s equipment uptime, for 3 types of fill level (production volume = 250,000 diffusers).
Figure 6 represents the unit production cost for four lifetimes of the disposable micro-mold. In this analysis it can be seen that the cost of the diffuser’s production for the two lowest lifetimes is slightly higher than for the others. In the lowest lifetime case it is necessary to replace the disposable micro-molds twice, while in the other case is necessary to replace them only once. For the higher lifetimes (25,000 and 50,000 diffusers), it is not required a replacement of micro-molds, therefore they have the same unitary cost. Therefore, the influence of the micro-molds’ lifetime in the cost of the diffuser’s production is not significant, because the cost of production of disposable micro-molds represents a small proportion of the total costs of the production alternative.

![Variation of the Lifetime Disposable Micro-mold](image)

**Figure 6:** Variation of the lifetime disposable micro-mold (production volume = 2 million diffusers; hot-embossing’s equipment uptime=90%).

Figure 7 illustrates the variation of the unit cost with the production volume of all production alternatives. The coordinates "y" evidenced in the figure correspond to the curves of the alternatives with a better economic performance. In are represented three “main” curves associated with each alternative (1.A, 1.B and 2). Each “main” curve has “secondary” curves associated. For example, the curve of Alternative 1.A, is associated with three “secondary” curves corresponding to production scenarios (fill level = 61, fill level = 154 and fill level = 289) that exhibit the best costs, depending on the production volume. The dashed lines correspond to the continuation of the “secondary” curves. After an extensive analysis to each production alternative, ranging several production scenarios, it is noticeable that the Alternative 1.A with fill level of 61 diffusers presents the best economic solution for production volumes up to about 40,000 diffusers. While for volumes larger than this number, the Alternative 1.B with 8 molding cavities comes up with the best economic performance. All other productive scenarios have worse costs.
Environmental Impact analysis

After an economic analysis of the various production alternatives, a comparison of the environmental impact between the three production alternatives of the light diffuser will be performed, taking into account the expected productive scenario.

Figure 8 shows the structure of the environmental impact of each production alternative and the respective total impact, distributed by each phase of the life cycle (Material, Production, Use and End of Life). Alternative 1.B presents a lower environmental impact, followed by Alternative 2 and Alternative 1.A presents the highest environmental impact value. Analyzing the weight of the life cycle phases in the three alternatives, it can be observed that the impact of material’s phase in Alternative 1.B is smaller than in the others production alternatives. This is due to the fact that the amount of material wasted per diffuser is much greater in the hot-embossing process than in the injection process. Between the hot-embossing processes of the Alternatives 1.A and 2, the amount of waste material (PMMA) is greater in the first alternative, because the occupation area of a disposable micro-mold (Alternative 1.A) to conform on the plate of PMMA, is larger than the occupation area of a disposable micro-puncture (Alternative 2). Therefore, the hot-embossing process of the Alternative 1.A displays a greater environmental impact value in the Material phase. Regarding the End of Life phase, it presents a greater contribution on the impact of Alternative 1.A, because it is the production alternative that presents the greater amount of wasted material.

In short, the alternate 1.B presents itself as the production sequence of the light diffuser with the best economic and environmental performance in this productive scenario.

Figure 7: Variation of unit cost with the production volume for the several producives scenarios of each production alternatives (lifetime of the disposable micro-mold and the disposable micro-puncture = 50.000 diffusers; hot-embossing’s equipment uptime = 90%).

[Graph showing variation of unit cost with production volume]
Figure 8: Influence of the 4 phases of the life cycle in the structure of the environmental impact of each production alternative for an expected production scenario (production volume = 500,000 diffusers).

4. Conclusions

In the performed analysis for an expected productive scenario, it was concluded that the alternative production of light diffuser by injection of PMMA in an 8 cavity micro-mold has the best economic performance. For the two production alternatives that use the hot-embossing’s technology (Alternatives 1.A and 2) we varied the production volume with the unit cost of production for three fill levels and concluded that for low production volumes, the setting with the lowest fill level has the lowest costs. With the increase of the production volume, the highest fill level is the most economically viable option. Another analysis made concerned the influence of uptime in hot-embossing equipment and it was concluded that with an increase in the uptime the unit cost of diffuser decreases and this reduction is greater for the lowest fill level. In Alternative 1.A we also concluded that the influence of the lifetime of the disposable micro-mold is almost negligible in the unit cost of the light diffuser. Finally, we concluded that for production volumes up to about 40,000 diffusers, the production alternative that uses disposable micro-molds in the hot-embossing process, with the lowest fill level (61 diffusers), presents the best economic performance. From this production volume on, the alternative that produces the diffusers by injecting PMMA in a micro-mold with 8 molding cavities presents the lowest and, therefore, most accessible production costs.

Regarding to environmental impact, it was concluded that for an expected productive scenario, the Alternative 1.B presents the best environmental performance, in resemblance with its economic performance for the same productive scenario.

References