How can plastics injection molding help driving down the cost of photovoltaic concentrators?

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Abstract

Plastics injection molding is one of the most used manufacturing technologies for mass produced goods. Since several decades also lenses, prisms, reflectors and other optical functions are molded. CD/DVD molding is one well known example. Characteristics of these products are precision combined with high volume. An attractiveness of the injection molding process is the wide availability of knowledge of design and processing as well as equipment in many variations.

In this paper we will discuss the build up of a cost model for optical products. It will be made clear that time to produce one part (cycletime) is of overriding importance for nearly all cost factors in the model, besides the resin cost itself. In the second part of the presentation the major influencing factors for determination of the cycle time will be discussed, like: shape, accuracy and wall thickness. Also the cost for tooling will be related to design characteristics. In this part it will be made clear how a designer can influence the cost of the part and which factors are most important to consider, when aiming for a design that must meet a predetermined target price. The third part of the article shows a practical example of a parameterised cost model for the injection molding process. Two practical cases will be reviewed: a concentrator optical part and a Fresnel lens. Conclusions are drawn on which design characteristics have most influence on piece part cost.

Introduction

A large portion of the final manufacturing cost of a product is dictated by the design. According to Suh [1] as much as 70 – 80 % of manufacturing productivity can be determined at the design stage. All injection molding companies have their own cost models for estimating and calculating production costs of parts. A price estimation is made when a customer needs a quotation for a specific set of parts and the final process values are not exactly known. Calculations are made when there is enough feedback from the first molding trials and both the part and process are well defined. In general, the cost model input-parameters deal with both process- and product -related issues. Examples of process related parameters are: the hourly wages of workers, machine rate, machine up-time, yield, price of electricity etc. Many of these parameter values are based on knowledge that has been built up inside the company during several years or can be obtained from the company's accounting department. Examples of product related parameters are thickness and weight of the part. Only those parameters that are related to the product features can be directly affected by the design. Design For Manufacturing (DFM) is the term used for this art of designing the parts in such a way that the optimal cost / performance is achieved. The main goal is to find a global optimum design in respect to cost, quality and performance of the whole system. For this purpose a feedback loop in the form of cost models needs to be created for all production technologies used in manufacturing of a multitechnological system.

Injection molding and cycletime

Injection molding is a cyclic process, in which complex 3D geometries are formed from the raw material with a single process step. This simplicity makes it possible to produce large quantities of complex parts fast and cost efficiently. Cycletime is the time that it takes from the injection molding machine to make a single part, or in the usual case of a multicavity mold, a set of parts. Any changes in this time-factor usually measured in seconds, will be multiplied by the number of produced parts. As the size of the production series can be as high as tens of millions, the time spent for making a single piece will have a drastic effect on the time spent for the production of the whole series. A simple example calculation can be made to illustrate this effect. If a product with total production series size of ten million pieces and an eight-cavity mold will have it's cycletime increased by one second, the resulting difference in total production time is: 1s x 10 000 000 / 8 ≈ 22 workdays (16h/day). During this time all of the machines will have to be maintained, workers salaries will have to be paid etc. The increased cost of production will then be reflected in the increased sales price of the products.

The basic structure of an injection molding cycle consists of several parts. Closing of the mold, forward movement of the injection unit, mold filling, mold opening and part ejection build up a time-factor, which is practically constant for each type of injection molding machine. As the parts get thinner the relative importance of this factor will increase and some technological development is needed to shorten it. The varying time-factor, cooling time, consists of parts like holding pressure and recovery time. These factors are dependent on the material used, part geometry, mold design and accuracy requirements. It is possible to eject the piece from the mold before it has been totally cooled, but then it will experience some small uncontrolled shape changes. If the shape accuracy requirement for the part is not high, this can be accepted as it will shorten the cycletime and bring down the cost. Due to demands of high precision, cooling time is usually the dominating factor in cycletime of plastic optics manufacturing and also the main driver for cost.

The simplest theoretical formula for calculating cooling time is meant for the geometry of a flat plate. The formula is written as [2]:

$$t_c = \frac{h^2}{\alpha \pi^2} \ln\left[\frac{4}{\pi}\left(\frac{T_m - T_w}{T_e - T_w}\right)\right] , \qquad (1)$$

$$\alpha = \frac{k}{\rho c} ,$$

where t_c is the time for part centerline to reach ejection temperature T_e, after which the solidified material will not deform anymore at ejection. The other variables in the equation are h the plate thickness, T_m the melt temperature and T_w the mold temperature. Thermal

diffusivity factor α consists of k thermal conductivity, ρ density and c specific heat of the material.
Figure 1 shows how much the cooling time of a flat plate is changed when each parameter in the equation is changed by 1%. One percent increase in thickness causes the cooling time to increase by two percent.

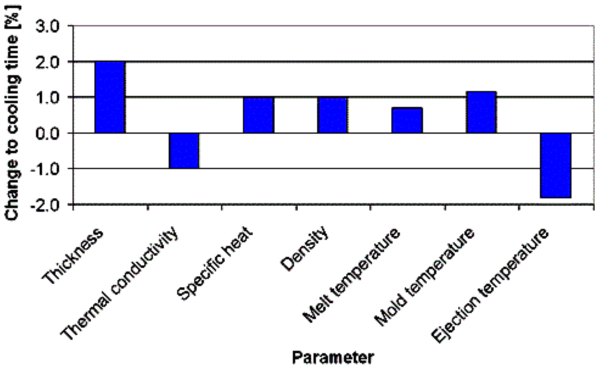

Figure 1. Sensitivity of the cooling time equation to variations in the parameters.

Figure 2 shows the relation between cooling time and part thickness for two commonly used optical plastics, as calculated from the previous equation (1). The difference between polymethyl methacrylate (PMMA) and polycarbonate (PC) is clear, as for example a 4 mm thick piece of PMMA will have a cooling time that is two times longer than with PC material. With both materials the cooling time will increase exponentially when the thickness is increased. Therefore, the most important geometrical factor in plastic parts is wall thickness.

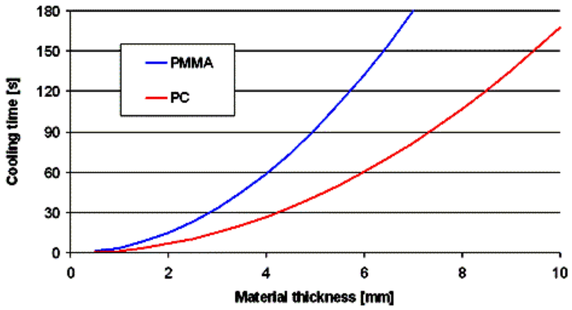

Figure 2. Relation between cooling time and material thickness.

Tooling for injection molded optics

For lenses, high quality injection molds are required. The difference with standard injection tools is found in the finish and accuracy of the optical surfaces [3]. Depending on the optical design of the lens, also opto-mechanical tolerances have a strong influence on the price of the tool. State-of the art values for tool surface roughness are 5 -10 nm R_a RMS. The injection molding process makes a near 100% copy of the tool. Centering tolerance of <10 μm of lens back to front is another characteristic of a quality tool. Good care should be taken that the mold material choice, construction and chosen number of cavities is done with the volume and projected life of the tool in mind. Proper steel choice and durable nickel layers will prolong the life of the tool almost indefinitely (>1Million replications), unless the surface is damaged in cleaning or any other accidental damage. Other product characteristics that have a large influence on the tool cost are requirements for surface shape accuracy, part size, undercuts and other geometrical aspects of the part design.

Injection molding cost model

A cost model was created for this study in order to estimate the cost of injection molded solar concentrator optics. The model was based on an Excel calculation sheet, which is used internally at Philips HTP for estimating and calculating the cost of parts produced in the company's plant in Shuzou, China. For this reason the model is quite realistic and gives a good picture of the cost structure of an injection molding plant situated in a low-labor-cost country. In the model the hourly wages of differently skilled workers were set to be from 3 to 6 US$ per hour. Overhead percentage was set to 30%. The toolcost was not included in the cost model, but it is going to be covered in a different model.

As the sizes of parts considered in this study varied widely, a size related function for calculating the machine rate had to be created into the cost model. As a general rule, when the size of the part increases larger machines are needed and the machine cost will also become higher. Machine rate is a cost factor, which includes the cost of injection molding machines as well as the factory floor space, electricity and all other directly machine related factors. The cost model's calculations were based on a survey made in 2007 by PlasticsTechnology [4]. Figure 3 shows the relation between machine rate and injection molding machine tonnage as found from the survey results. In our model these machine rates were scaled to the production environment in China. This scaling factor as well as the whole cost model were "calibrated" with existing process and cost information from optical parts that are currently in production at the plant. Another real-life solar concentrator example that was used to check the model can be found from reference [5].

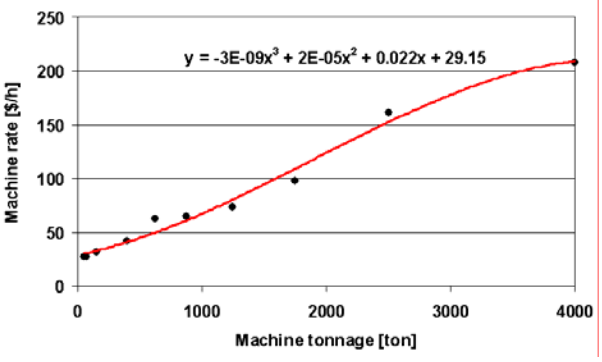

Figure 3. Relation between injection molding machine cost and tonnage.

The cost model created for this study included also factors for calculating the cycletimes of different sized objects. As explained in the next chapter, the optical example system consisted of two types of elements: a Fresnel lens and a CPC part. In the cost model cycletime calculations the Fresnel lens was treated as a flat plate and the equation (1) was used. With the CPC part, a similar equation was used, but as the shape is clearly different from the flat plate approximation some geometrical adjustment factors were added. This equation meant for cylindrical objects is also used at Philips HTP to estimate the cooling times of similarly shaped objects.

Figure 4 shows as an example the relative change in cost when each variable in the cost model is changed by 1%. This sensitivity graph shows that the five most influential factors in the model are: yield, cycle time, machine uptime, number of cavities and machine rate.

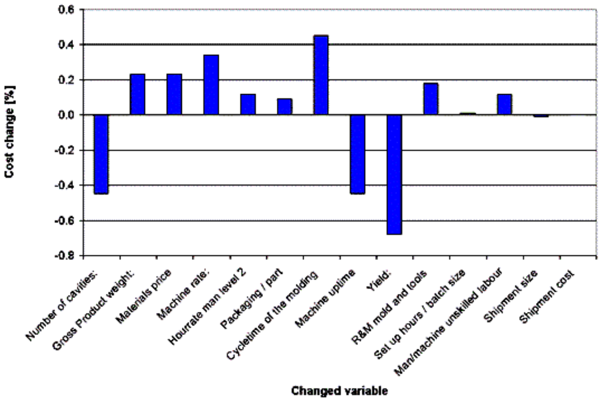

Figure 4. Cost model sensitivity to parameter change.

Example solar concentrator optical system

A two-element solar concentrator optical system was used as an example case for showing the relations between concentrator system cost and optical design choices. The system consists of two optical elements (Figure 5). The Primary Optical Element (POE) is a Fresnel lens, which function is to concentrate the light from the sun into a small spot. The Secondary Optical Element (SOE) has the shape of a Compound Parabolic Concentrator (CPC) and it has two functions. The main function is to provide tolerance for the whole system in respect to pointing accuracy and assembly errors. This is achieved by making the input aperture of the SOE bigger that the spot size produced by the POE. As the system tilts in respect to the sun's direction the spot can move inside this aperture area without large losses to performance of the system. The secondary function of SOE is to homogenize the light distribution falling on the solar cell in both spatial and spectral domains. The solar cell is attached with index matching directly to the output aperture of the SOE

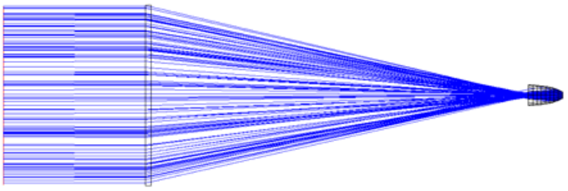

Figure 5. Example solar concentrator optical system

The choice of plastics is very limited for both POE and SOE. From the process and cost point-of-view, a material with short cooling time like polycarbonate would be a good choice. Polycarbonate also has the benefit of fairly large index of refraction, which would have made it possible to use slightly thinner structures for the same optical function. Unfortunately, the high-through-put requirement of a solar concentrator system restricts the choice of material. PMMA is the only affordable thermoplastic, which has good enough transmission characteristics over the lifetime of the system through the whole wavelength spectrum covered by a normal triple-junction solar cell.

Design choices vs. cost of the POE

Design choices for the primary element include size of the square aperture, number of Fresnel rings and F#, which is the ratio of aperture size to focal length. Size of the square aperture is determined by the desired collector system concentration ratio and solar cell size. After the aperture size is set, the choice of F# will determine the distance between the POE and SOE as the SOE is positioned close to the focus point of POE. F# together with the number of Fresnel rings and aperture size will determine the thickness of the primary element. With lower F#, a surface with higher curvature is needed, because the light needs to be bent faster in order to achieve the shorter focal length. The higher curvature leads to higher thickness of the piece and, therefore, to a higher cost.

Aperture size of the primary element affects also the thickness of the piece. Very long and thin pieces are difficult to make with standard injection molding as the material will not flow through infinitely small gaps. A minimal thickness can be found that is material dependent. The part will also start to solidify immediately when the material is injected to the cavity and it is possible that a too small injection gate will be blocked before the part is completely filled. Another factor, which makes the thickness increase with the size of the element is the mechanical rigidity condition of the part. A part that is too thin will start to bend and the optical functioning will be affected. All of these issues will drive the thickness and cost of the part higher when the aperture size is increased. However, a smaller number of elements is needed to cover a particular area if the elements themselves are bigger. This creates a situation where the two opposite cost drivers will need to be balanced. An optimum cost per square meter can be found if the costs of different sized elements are calculated.

With the mentioned design issues in mind, a table of different sized POE elements was created. The nominal system was set to have a concentration factor of 1000 and the primary element F# was set to 2. For each design case the number of elements that is needed to cover an area of 100 000 m^2 was calculated. With these numbers in mind, the number of cavities was set as well as the expected yield and machine uptime. With larger parts the yield, machine uptime and maintenance costs can be expected to be lower due to the fact that the probability of having defects on the part surfaces will increase with part surface area. For each POE case, the expected cycletime was calculated from the flat plate equation and the machine rate was calculated from the previously mentioned model. In the calculated group of POE's, the element thicknesses varied from 0.8mm (15.8mm wide Fresnel) to 3.5mm (47cm wide Fresnel). When these input parameters were fed in to the cost model, the cost per piece was obtained. When the cost per piece was multiplied by the number of elements needed for the area, a cost per square meter was calculated for each POE case. As the concentration ratio was fixed, it was possible to relate this number to the size of the solar cell. Figure 6 shows this relation between solar cell size and cost of the primary elements. Minimum cost of POE's (~22 $/$m^2$) is reached with a solar cell size of 5mm. In this case the primary element is 158mm wide and 1.6mm thick, which is very close to the size of a CD.

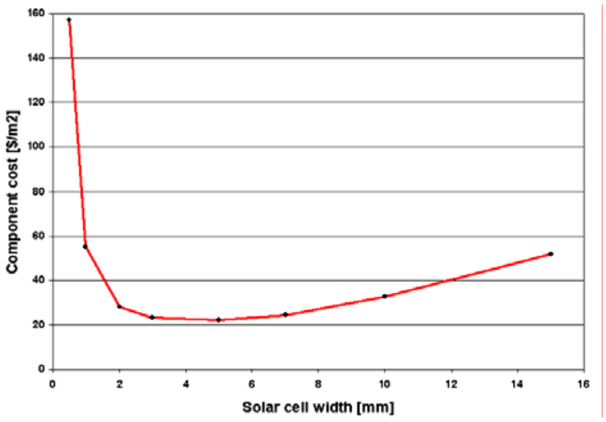

Figure 6. Solar cell size relation to POE cost with a concentration ratio of 1000 and primary element F# 2.

The number of Fresnel rings is definitely a factor, which affects the cost of an injection molded part as the piece can be made thinner simply by breaking the base curved surface into a number of rings. Figure 7 shows three different versions of the same optical element with the same optical function. All of the lenses have an aperture size of 50mm x 50mm and their F# is 2. The first one has only three rings and it needs to be 4.9 mm thick in order to be manufacturable. The second lens is 2 mm thick and it has 10 rings as the last one is only 1.15 mm thick and has 20 rings. The created cost model was used to estimate the injection molding cost of such pieces in respect to the number of rings. Figure 8 shows this relation. It is clear from the graph that as the number of rings is increased the cost approaches a value of approximately 30 $/m^2.

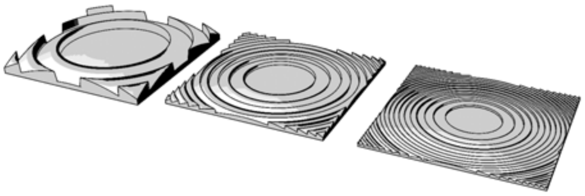

Figure 7. Three versions of a 50 mm wide Fresnel lens with different number of rings (3, 10 and 20).

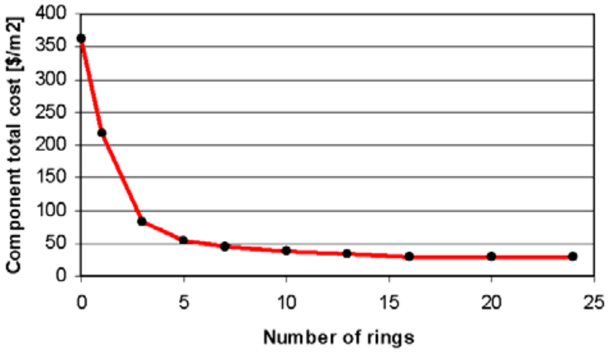

Figure 8. Number of Fresnel rings vs. the cost of a 50mm x 50mm F# 2 lens component.

Unfortunately, the adding of rings will also increase the area on the element that is wasted due to the rounding of ring tips and the draft angles needed for part ejection. The wasted area will lower the transmission of the Fresnel and some throughput is lost. Figure 9 shows a calculated relation between the number of rings and wasted area in two cases. In the first case the tip and valley radius was 25µm and the draft angle was 2 degrees. In the second case the tip radius was 5µm, valley radius 14µm and draft angle 2 degrees. This loss of throughput will need to be compensated in the system level by adding more concentrator systems, and again a cost optimum can be found for the number of Fresnel rings.

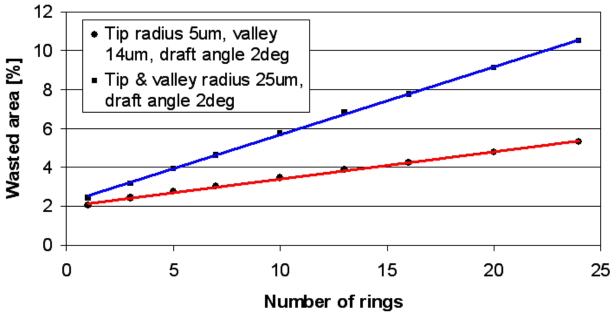

Figure 9. Calculated relation between number of Fresnel rings and wasted area due to tip radius and draft angles in two cases.

Design choices vs. cost of the SOE

Design choices for the secondary element are very limited. The close-to-ideal CPC concentrator shape is totally defined when three out of four main design parameters are set. Solar cell size and acceptance angle define totally the smaller output side of the concentrator. On the input-side, the POE F# together with the limited angular tolerance will determine the ideal shape of the part. Size of the input aperture is practically fixed when these three parameters are fixed. If the F# of the POE is kept the same, the secondary element geometry will simply scale up and down with the size of the solar cell. This will of course mean that with larger solar cells the SOE's will be bigger and more expensive. Figure 10 shows this relation calculated with the same cost model and with the same procedures as was used in the case of the POE. Secondary element maximum thicknesses varied from 1.8mm to 53mm. Naturally, with the biggest concentrators some other manufacturing methods than injection molding or some other engineering solutions like coated hollow concentrators would be preferable. The lowest cost (~14 $/m^2) was achieved with the same solar cell width of 5mm as with the POE's. In this case the SOE's had a maximum thickness of 17.7mm and they were 30mm long.

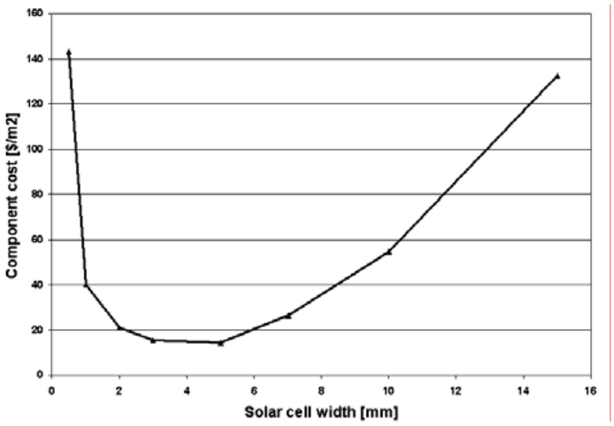

Figure 10. Solar cell size relation to SOE cost.

Total cost of the example optical system

In the two previous chapters, graphs were presented that showed the costs of the separate optical components. Figure 11 shows now the combined cost of the two elements. In addition to the previous case of concentration ratio of 1000, two other systems with ratios of 500 and 100 are presented. As the F# was kept constant in these new calculations, the same SOE's were applicable. Only new POE cases were needed in order to calculate the costs of different concentration ratio systems. From the graph it can be seen that for all of the optical systems, a solar cell size of 5mm is the optimal choice. The lowest achievable combined cost is estimated to be around 36 $/m^2. Naturally, if the lower concentration ratio systems can be built without the secondary elements, an even lower cost target can be reached.

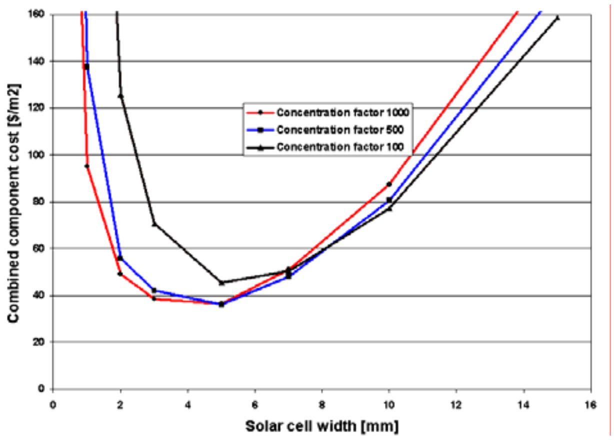

Figure 11. Combined costs of three different optical systems with concentration ratios of 1000, 500 and 100.

Discussion – the case of CD

CD and DVD molding is most likely the best example of what the injection molding can do for a low cost optical product. The injection molding of disks started in the 80's, in parallel to other manufacturing processes like compression molding. After an initial optimization phase it became clear that the injection molding process had the best conditions to achieve the required cost targets. Starting with the use of standard equipment the processes were developed and gradually more and more specialized machines were engineered and put to use. This has led to a world-wide disk making industry with highly standardized manufacturing equipment and standardized processes. One of the biggest achievements has been a reduction of the manufacturing cycle time from an initial 20 seconds to 3.5 seconds nowadays.

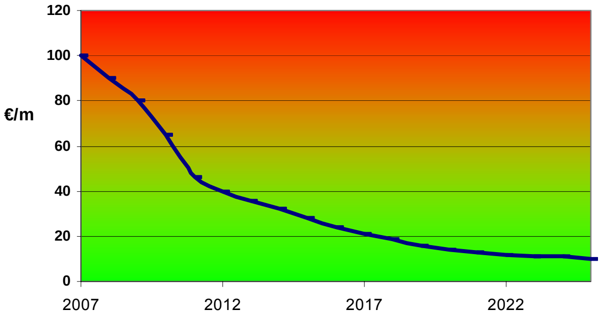

Figure 12. Projected cost development of Fresnel optics modeled after the existing CD/DVD example.

When we transfer the process conditions of CD molding to the case of Fresnel molding, the price for Fresnel lenses would be less than 10€/m^2. Applying the CD cost/time curve to this case leads to the graph shown in Figure 12. After an initial period, where the volumes are relatively low, price decrease starts under influence of R&D on product, processes and equipment, driven primarily by large volume demand. What is large? Looking to the CD/DVD example again: >>10 km^2/year of optical surface.

Summary and conclusions

The most important product-feature-based factor driving the cost of injection molded optics is part thickness. By minimizing this feature it is possible to bring down the price of molded pieces considerably right from the first stages of design. However, an optimum can usually be found between performance and cost as every production process has it's own specific region of superiority in respect to production volume, part complexity and quality. As shown in the case of Fresnel lens, the cost can be reduced by adding more rings to the element, but some performance is simultaneously lost and design will turn into a balancing act between engineering and economics.

We have shown in the article, that it is possible to build a feedback-loop around the design phase of a solar concentrator optics system and manufacturing cost estimation. This loop can be used to find an optimum design in respect to both performance and cost in the case of injection molded plastic optics. Similar models should be developed for all of the technologies used in production of photovoltaic systems in order to be able to find the construction with global optimum design. The case of CD/DVD is a very good example of extremely low cost, but high precision injection molded optical product. By following the path of CD production through the phases of standardization and technology development the price of photovoltaic system optics can be brought down to a considerably lower level in the future.

Acknowledgements

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