The Effect of Selective Assembly on Tolerance Desensitization

Max C. Funck[1], Peter Loosen[1, 2]
[1]Chair for Technology of Optical Systems, RWTH Aachen University, Steinbachstr.15, 52074 Aachen, Germany
[2]Fraunhofer Institute for Laser Technology, Steinbachstr.15, 52074 Aachen, Germany

ABSTRACT

Tolerancing has long been identified as a crucial part in the development of optical systems. It aims at finding the best balance between quality and cost as tolerances closely tie together manufacturing expenses and performance. Tolerance effects have been included into the optimization function (merit function) by some lens designers to find insensitive designs[1-5] and frequently compensators are employed to further improve the performance of assembled lenses. Compensators are limited to a small number of system parameters, but selective assembly of components can extend the number of parameters available for compensation. It can be employed to reduce tolerance effects of disturbed parameters by finding the best matches out of a set of components.
In this work we discuss how desensitization and selective assembly can be combined to loosen tolerances and increase as-built performance. The investigations concentrate on tolerance insensitive design forms under the presence of selective assembly compensators. In contrast to desensitizing a given lens or introducing new design means we focus on introducing new assembly strategies into the design procedure and investigate how using selective assembly as a compensator while desensitizing the remaining design parameters can lead to even less sensitive designs.

Keywords: Lens design, tolerance, desensitization, selective assembly

1. INTRODUCTION

The ultimate task of a lens designer is to create a design that will deliver the desired performance once the lens is build while reducing the cost of production to a minimum. This task is frequently constrained by a number of boundary conditions. Available glass materials, possible alignment strategies, manufacturing technology and many more make this a complex endeavor. In addition, the cost minimum is subject to many influences, tolerances being one of the major ones. It is thus logical that finding a cost-optimal lens design has typically been addressed by finding a tolerance-optimal design taking individual tolerance costs into account.
A number of different strategies that allow the lens designer to find tolerance insensitive designs will be reviewed subsequently. They all aim at the reduction of tolerance effects and can therefore be employed not only to reduce tolerance requirements but also the cost of a lens. Strategies to find a real cost optimum are based on similar techniques and include cost models for the various manufacturing errors[6]. However, the cost-optimal lens design is as hard – or even harder – to find than the global optimum of the lens design problem itself. Even more parameters need to be considered and uncertain data such as tolerance distributions and manufacturing cost impact the solution.
One effect is frequently observed during desensitization. A design solution that is less sensitive to tolerances will often have a worse nominal performance or a higher value of the merit function. A common description of this phenomenon is that desensitization favors flat valleys in the merit function landscape over deep and narrow valleys. It appears that nominal design performance and tolerance effect are in a trade-off relation and that the reduction of one leads to an increase of the other.
Another observation can be made for sensitivities of individual parameters. While sensitivities can generally be very different, desensitization will help to reduce the effect of worst offenders, while relatively insensitive parameters can actually become more sensitive. Conversely, if specific sensitivities are drastically reduced, sensitivities will increase elsewhere in the system.
If the most sensitive tolerances could be treated otherwise – through compensation for example – would it be possible to reduce the sensitivities of remaining tolerances even further? We investigate if this is indeed true and make use of selective assembly as a strategy to use parameters such as element thickness or curvature as compensators that cannot be used as compensators otherwise. In order to avoid much of the tolerance cost related complications we consider fixed tolerances for which the designs will be desensitized.

2. DESENSITIZATION STRATEGIES

2.1 The goal of desensitization

If a system is said to be insensitive it is expected that the overall performance of the system does not change significantly when parameters change (e.g. due to tolerances). Desensitization is thus the finding or generation of design forms that exhibit only small performance degradation under the presence of parameter perturbations and deliver the best as-built performance. Typically, desensitization focuses on imaging properties. However, paraxial specifications such as focal length, magnification or image shift can sometimes be very important. Most of the research has been focussed on reducing tolerance effects of decentrations, tilts and other mechanically induced errors to facilitate assembly and reduce manufacturing costs. Desensitization can principally be achieved by changing available design parameters, by adding new design elements (additional lenses, aspheric surfaces) or by applying different assembly strategies such as compensation.

Suppose a design optimum has been found what can be expected from desensitization? Desensitization will find a local optimum in the merit function that has a higher value than the former solution, but with lower tolerance effects such that the as-built performance is better than before. The task is thus to find the best compromise between nominal performance and tolerance effects. This compromise between sensitivity and nominal merit function can be observed in other works as well[7]. If nominal performance and tolerance effect are investigated separately as a function of lens designs their respective minima will not necessarily coincide. Similarly, this is true for the degree of desensitization (for example the root sum square average incident angle). Figure 1 illustrates the balancing of nominal system performance and tolerance effect. The optimal as-built solution is neither the one with the lowest tolerance effects nor the one with the best nominal performance. Designs with different average angles of incidence are plotted. Tolerance contributions are 98 percentile values obtained from monte carlo simulations.

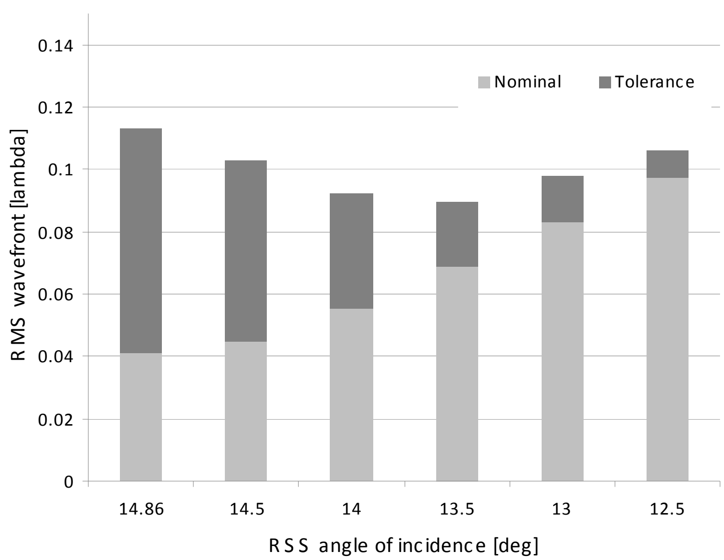

Figure 1: Trade-off between tolerance effect and nominal design performance

2.2 State of the art

A very straightforward way to find insensitive design forms is to simultaneously optimize multiple configurations of a design. If the configurations slightly deviate from each other an optimum is sought that delivers balanced performance for all configurations. Subsequently, parameter changes will not lead to dramatic performance changes. This method is frequently used to correct a system for multiple wavelengths, zoom positions, etc. but can be extended to any parameter or system variable.

The multi-configuration approach has been adopted and modified by a number of researchers. Rodgers[1] uses only a small number of configurations with perturbations of every parameter. Because the parameter deviations are randomly distributed a statistically representative set of configurations is established.

Global optimization techniques have been adopted to reduce tolerance sensitivities. Using a merit function based on the as-built performance, McGuire[2] uses global optimization to find desensitized design forms.
The most general approach would probably be the inclusion of a complete tolerance analysis (e.g. a monte carlo analysis) into the merit function, accurately determining the as-built performance of the lens at every optimization step. Today's computational capabilities limit this endeavour. Statistical prediction of the performance is the only practical way to incorporate as-built performance and some commercially available optical design programs allow the inclusion of root sum square (RSS) estimates into the merit function.
Due to computational intensity indirect ways to predict as-built performance have been employed. Isshiki[3] incorporates the change of ray angles due to refraction at optical surfaces into the merit function, assuming that small angles of refraction correspond to small aberration contributions and small aberration contributions exhibit small changes due to tolerances. However, it should be expected that surfaces obeying the aplanatic condition are less prone to parameter deviations despite a considerable refraction. Dilworth[4] considers third order aberrations whereas predicted wave aberrations due to manufacturing errors have been included in the merit function by Dobson and Cox[5].
Epple and Wang[8] take an entirely different path and introduce new design means into the system to further reduce tolerance sensitivity. The use of aspheric surfaces proves to be a powerful means of reducing tolerance sensitivities. The advantage of this strategy lies in additional degrees of freedom during the design process allowing for better control of sensitivities.
Ideally, desensitization is able to locate a design form in parameter space that results in the best as-built performance. Unfortunately, this optimum depends on the tolerance distributions. The global tolerance optimum seems to be as hard to find as the global design optimum.

3. COMPENSATION THROUGH SELECTIVE ASSEMBLY

3.1 Selective assembly vs. compensation

Compensation is the ability of a set of system parameters to reduce errors induced by a different set of parameters. Frequently compensation is realized with a single parameter, typically an airspace, decenter or tilt of a component with the intention to reduce spherical aberration or coma, respectively.
Selective assembly allows formerly unfeasible parameters to be used as compensators. This includes surface form, component thickness or material properties. The procedure of selective assembly is as follows: after determining characteristic parameters of a component through measurements, a selection of matching components can be made such that the effects of individual deviations compensate each other. The additional effort is justified by coarser tolerances and reduced cost or by increased yield.
For many applications, selective assembly seems inappropriate due to the increase in assembly and measurement effort and a limitation to mass production. However, much of the required data is frequently available after quality assessment and simply remains unused during assembly. Furthermore, a considerable effect of tolerance reduction can be achieved for comparably small production runs. Selective assembly is usually executed by sorting components into different tolerance classes. This approach works well for a variety of applications, but is naturally limited to large scale production. For small production runs it is not unlikely that two matching classes have very different amounts of components that are available for matching. This mismatch results in unused components and decreases the yield.
As detailed component information is available after measurement it is also possible to use the measurement data itself to find a matching partner. Classification is not necessary and merely used to simplify the search for matching components. Combinatorial matching (without classification) avoids much of the complications. It works for smaller production runs, available measurements are fully utilized and mismatching is not an issue.
Selective assembly can in many ways be looked at as a form of compensation. However, there are some peculiar differences. Selective assembly is only possible in discrete (and randomly changing) steps and it is executed without feedback such that every other tolerance can impact the matching.

3.2 Tolerance reduction through selective assembly

Being used as a compensator selective assembly can be employed to reduce tolerances of measured element properties. Precise manufacturing is replaced by precise measurements. If selective assembly is applied to very sensitive parameters (e.g. worst offenders) their tolerance effect can be significantly reduced. But this is not everything there is to selective assembly.

The application of selective assembly – or compensation in general – allows the designer to focus desensitization of a design on parameters that will not be used for compensation. An increase of the sensitivity of parameters used during selective assembly is – at least theoretically – not critical. If a few very sensitive parameters can indeed be excluded during desensitization it should be expected that the remaining sensitivities can be reduced even further. A different tolerance optimum can be found for the reduced set of disturbed parameters and hopefully the trade-off between nominal value and tolerance effect can be improved.
Figure 2 illustrates this idea. While the best compromise of nominal performance and tolerance effect during desensitization of the entire lens requires a significant increase of the nominal value to reduce the tolerance effect, a smaller increase is sufficient to find the optimal compromise for the reduced set of parameters. The selectively assembled system can thus be designed to have better nominal performance while a large part of the tolerances is reduced through selective assembly or matching as we say. It is important to note that the comparison between purely desensitized designs and designs desensitized for selective assembly is only as good as the desensitized solution. It might always be possible to find a desensitized design with even better as-built performance and the selective assembly design would have to be compared against this solution.

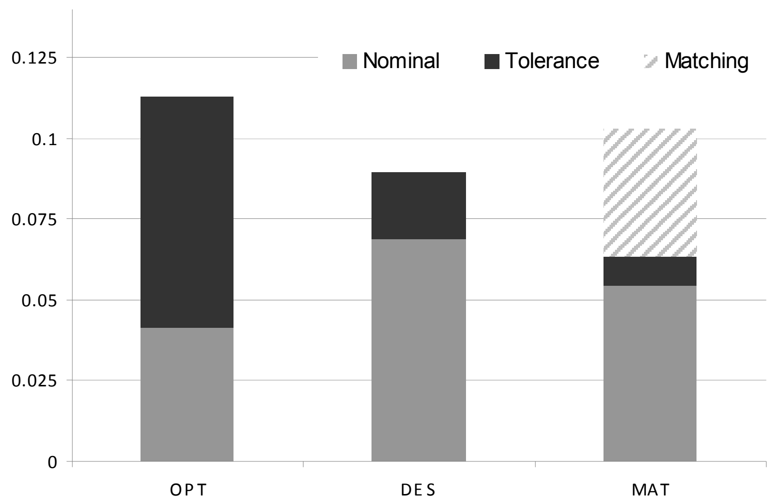

Figure 2: Tolerance reduction through selective assembly. Optimized design (OPT), desensitized design (DES) and selective assembly matching (MAT)

A couple of things are necessary for this idea to work. First, sensitivities will indeed tend to even out during tolerancing and can be redistributed such that parameters for selective assembly gain sensitivity, whereas other tolerances loose sensitivity. Second, a feasible matching between components must be possible and reduce most of the tolerance induced changes. Ideally, the sensitivities of selective assembly parameters entirely disappear due to the matching and only secondary tolerances exist. And third, secondary tolerances must not significantly disturb selective assembly. That is, the matching is insensitive to other tolerances and cross relations are small.

3.3 Distributing sensitivities

If the tolerance effect of separate parameters is observed for different lenses during desensitization it becomes obvious that sensitivities are shifted. Different solutions will show different sensitivity distributions. It is frequently possible to reduce one or more parameters in their sensitivity to a tolerable value, but at the same time sensitivities of other parameters will increase. A simultaneous reduction of all sensitivities seems almost impossible. Desensitization will rather result in sensitivities that are more evenly distributed over the system thereby reducing the overall tolerance effect. If a root sum square estimate is assumed to represent the estimated performance change this becomes clear. The largest values dominate the performance change and a considerable decrease can be achieved if the worst offenders are treated.
If desensitization results in a design with manageable tolerances, this is fine. If however, sensitivities are distributed over the entire system and every component needs more than a moderate degree of attention this can be a highly undesirable result. It would often be easier to take good care of only a few critical tolerances and neglect the majority.

This idea has driven us to the question whether selective assembly could be used to take care of some critical tolerances while the remaining tolerances can be reduced even further.
In order to compare the effect of single parameters on system performance the sensitivity needs to be defined. Merely looking at a change table for positive and negative tolerances can be very deceiving. As a root sum square method is often used to judge the cumulative effect of multiple tolerances it seems more appropriate to look at the change of this measure that can be apportioned to a specific parameter. Let S_k be the sensitivity as it is usually defined: the performance change at tolerance boundaries of a parameter k. Another sensitivity measure S_1 can then be defined as follows:

$$S_{1,k} = \frac{\sqrt{\sum_i S_i^2} - \sqrt{\sum_{i,i\neq k} S_i^2}}{\sum_k \left(\sqrt{\sum_i S_i^2} - \sqrt{\sum_{i,i\neq k} S_i^2} \right)} \tag{1}$$

This kind of measure has the advantage that the sum of the sensitivities corresponds to the root sum square estimated change. An even more accurate measure could similarly be derived from monte-carlo analyses.
Figure 3 compares the sensitivities of curvatures and thicknesses of the three systems shown in Figure 4. The important thing to note here is that systems that underwent a desensitization process tend to display a more even sensitivity distribution. High peaks are reduced whereas lower sensitivities are increased. Note for example the relative importance of the sensitivities of curvatures three and four.

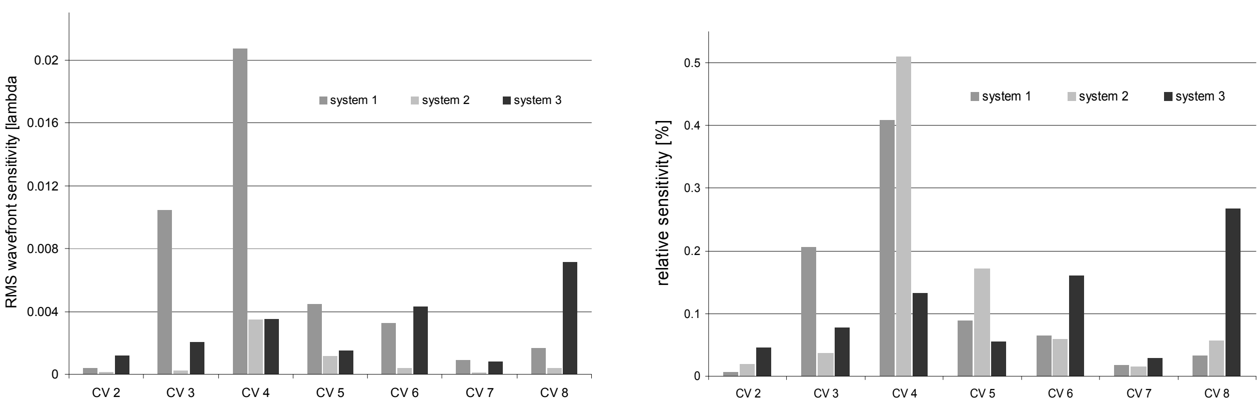

Figure 3: Sensitivity balancing. Absolute sensitivities (left) and relative sensitivities (right) for curvatures (CV) and thicknesses (T) of the lens designs in Figure 4.

The lens designs under test for the diagrams in Figure 3 are different solutions of a desensitization process of a Tessar lens. Root sum square average angles of incidence have been continuously reduced during desensitization. This is basically the procedure suggested by Isshiki[3,7].

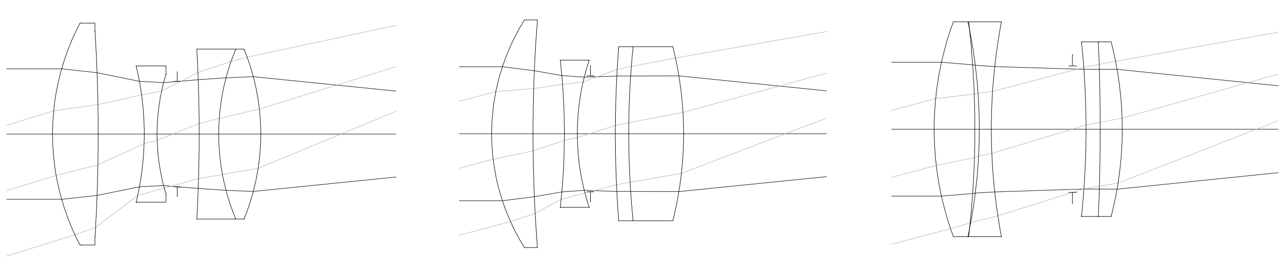

Figure 4: Desensitized lens designs. System 1 (left), system 2 (center) and system 3 (right).

Furthermore it is often possible to specifically reduce the sensitivity of selected surface, either by reducing the angle of incidence or by making the surface aplanatic. The designs are shown in Figure 4 and were limited to similar design forms. Glass materials and stop position with respect to the elements were not variable.

3.4 Secondary tolerances

One of the main drawbacks of selective assembly is the fact that parameters other than those used to determine matching components can negatively impact the desired benefit. Ideally, selective assembly would be executed such that other tolerances have no effect on the matching procedure. That is, the matching procedure is insensitive to remaining system tolerances.
Conversely, if desensitization of a lens design is intended, insensitivity to a fixed matching of component parameters is sufficient for selective assembly whereas insensitivity to a random matching is necessary for classical assembly. In other words a degree of freedom is gained and can be used for desensitization. The tolerance reduction from selective assembly is thus twofold.
In order to investigate the effect of secondary tolerances two observations are being made. First, we plot lens performance along the perfect matching determined for an undisturbed system. Then secondary tolerances are introduced and the performance along the original matching is observed. Second, we look how the optimal matching changes in parameter space, which is intuitive for two dimensional matching.
Ideally, secondary tolerances are simply added to the matching and do not disturb the matching itself. That is, no cross terms between parameters used for selective assembly and secondary tolerances exist. This is the optimum. As a result, some tolerances may impact the matching more than would be assumed from their sensitivity alone.

4. OPTIMIZATION FOR INSENSITIVITY AND SELECTIVE ASSEMBLY

As an example to illustrate the effect of selective assembly on tolerance desensitization we analyse an imaging lens at unit magnification (Figure 5). The lens is monochromatic with 2 degrees field of view. Because finding a cost optimal tolerance allocation while simultaneously desensitizing the design is a complex task a set of fixed tolerances has been assumed. This set of tolerances serves as a basis for the comparison of different designs. Because we want to show that inexpensive tolerances are feasible a set of relatively coarse tolerances has been chosen. Curvatures are tolerated with 10 fringes, element thicknesses with +/- 0.2mm and air spaces with +/- 0.1mm. Limits have been set for the various thicknesses to prevent the system from getting too long. In order to simplify the discussion, only the right half of the symmetrical lens has been analysed.

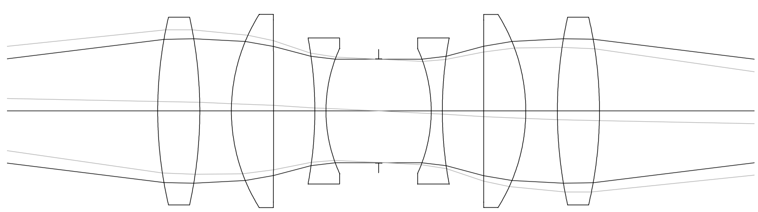

Figure 5: Imaging lens optimzed for selective assembly

In a first step the optimal as-built performance design for the given set of tolerances has been determined using desensitization. We adopted a method by Isshiki and continuously decreased the root of the sum of squared angles of incidence. The results are shown above in Figure 1 and have been used to illustrate the effect of trading nominal performance for tolerance effect. The lens with an average angle of 13.5 degrees displays the best performance considering 98% of the systems. This lens will be used as a reference for designs optimized for selective assembly. As stated earlier, the desensitized design so found may not be the design with the best as-built performance but it is the best we could find.
A look at the sensitivities of this system shows a dominance of the thicknesses of element one (the negative element) and two (the approximately plano-convex element) as well as of the airspace between them. It thus seems logical to use these parameters for selective assembly.

A linear matching function between the airspace and the element thickness linking these two values has been established and the design optimized. Back focus is used as an additional compensator. Subsequent desensitization focuses on the remaining parameters. Because sensitivities of thicknesses and air spaces in this example are much related to ray angles the root sum square angle has been reduced until a solution was found having better nominal performance and better overall performance after selective assembly than the best desensitized design.
The designs optimized for selective assembly show the same balancing effect of nominal performance and tolerance effect that can be observed for desensitization. The difference being that the nominal performance can be significantly better than before and that much of the tolerance effect can be reduced by selective assembly. Results are compared in Figure 6.
How much of the theoretically possible difference is attainable in reality needs to be verified. A simulation will be shown in the next section.

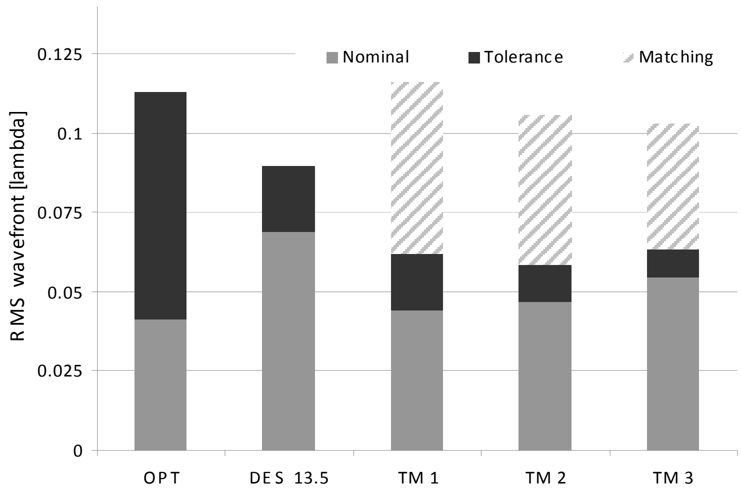

Figure 6: Tolerance reduction through selective assembly

Figure 7 shows the sensitivities of curvatures and thicknesses not used for selective assembly for an optimized design, a desensitized design and a design optimized for selective assembly. While desensitization is able to reduce the sensitivity of thickness 1 (element thickness of negative element) and increase of the curvature sensitivities with respect to the optimized system can be observed. The design optimized for selective assembly has smaller sensitivities than the desensitized design for most of the parameters.

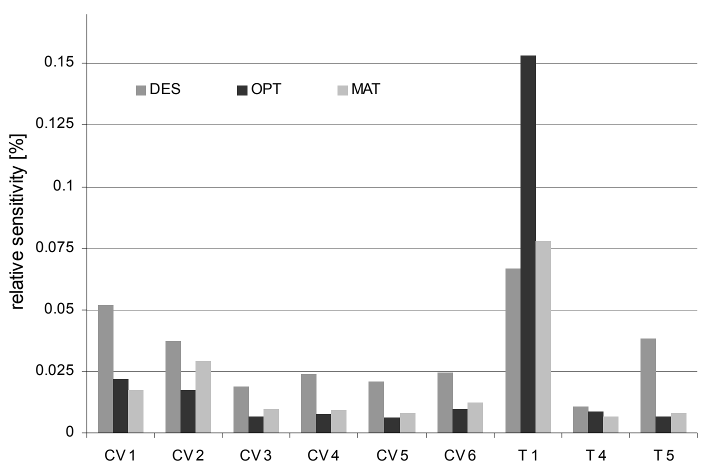

Figure 7: Sensitivities of different desensitized designs

It is understood that additional mechanical tolerances (decentration, tilt) play an important role as they will induce coma. However, the example shows that desensitization and selective assembly can greatly benefit from each other because critical tolerances can be disarmed through selective assembly.
We believe that more complex lens designs can equally benefit from an application of selective assembly if additional parameters are considered. Modern production environments and the large availability of measured element properties minimize the additional cost and an increased performance might justify the approach.

5. SIMULATION OF SELECTIVE ASSEMBLY

To analyze expected performance we have developed a statistical tolerancing tool for selectively assembled optical systems. The matching procedure is executed in simulation and production yield for production runs of arbitrary size can be estimated. The results of desensitized designs optimized for the application of selective assembly can thus be accurately analyzed.
Figure 8 shows a comparison of the matching success for different production sizes. A matching of 10 systems (e.g. ten elements of every type are available and will be used to assemble ten lenses) is compared to a matching with 50 systems and the ideal matching (e.g. infinite number of systems). As a reference the best desensitized design is shown as well representing the solution with the best performance at a cumulated probability of 98% that can be achieved without selective assembly.

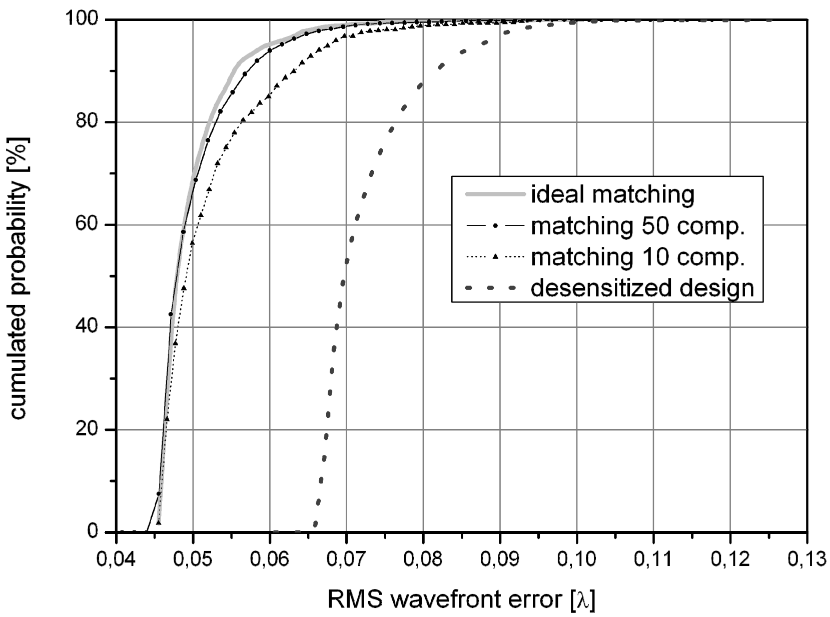

Figure 8: Cumulated probability plots of selectively assembled system

For a production of 50 lenses the ideal matching is closely resembled while for a matching of 10 lenses the matching related tolerance reduction cannot be fully employed. Nevertheless, a considerable reduction is already possible even for the assembly of ten lenses. The comparison to the desensitized design further highlights that the nominal performance could be increased. A comparison of the yield is also very instructive. For a limit of 0.07λ RMS wavefront error the desensitized lens would give a 50% yield whereas for the design using selective assembly 98% of the lenses are within this limit.
The simulation used to generate these results is based on a monte carlo approach[9]. Random parameter values are generated according to given tolerance distributions. Sets of multiple random components are then created and the best matching for this set is determined by the program. As an optimality criterion we chose to reduce the variance within a

set of components. In order to generate a statistical result the procedure of generating sets of random components is repeated. In this example we conducted analyses with 100 repetitions of random set generation. For selective assembly of 50 elements of every kind a total of 5000 random systems have thus been evaluated. Tolerance distributions are Gaussian and tolerance limits correspond to twice the variance.

6. CONCLUSION

Designing manufacturable lenses is a difficult task and depends on design forms that are ideally insensitive to tolerances and contain elements that can be easily fabricated. Desensitization is attempted through a number of strategies relying on the inclusion of performance prediction in the optimization error function or the introduction of new design elements.

This paper focuses on introducing selective assembly as an alternative assembly strategy to deal with difficult-to-manage tolerances and relies on desensitization of the remaining ones. A further degree of freedom to distribute tolerances is achieved through the application of selective assembly in addition to the compensation effect through selective assembly. Both aspects help to further relax tolerances and increase performance.

Further tolerance reduction of parameters not used during selective assembly has been demonstrated and a significant increase in system performance is supported by statistical simulation of the matching procedure. Simply using measurement data that is available after component manufacture lens performance can be increased at little cost.

7. ACKNOWLEDGEMENTS

The authors would like to thank the German Research Foundation (DFG) for its support within the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” at RWTH Aachen University.

REFERENCES

[1] John R. Rodgers, “Using global synthesis to find tolerance-insensitive design forms”, International Optical Design Conference, Proceedings SPIE Vol. 6342 (2006)

[2] James P. McGuire, “Designing easily manufactured lenses using a global method”, International Optical Design Conference, Proceedings SPIE Vol. 6342 (2006)

[3] Masaki Isshiki, Leo Gardner, G. Groot Gregory, “Automated control of manufacturing sensitivity during optimization”, Optical Design and Engineering, Proceedings SPIE Vol. 5249 (2004)

[4] Donald D. Dilworth, “New tools for the lens designer”, Current Developments in Lens Design and Optical Engineering, Proceedings SPIE Vol. 7060 (2008)

[5] S. J. Dobson, A. Cox, ”Automatic desensitization of optical systems to manufacturing errors”, Measurement Science Technology 6, pp.1056-1058 (1995)

[6] Jessica DeGroote Nelson, Richard N. Youngworth, David. M. Aikens, “The cost of Tolerancing”, Optical system alignment, tolerancing and verification III, Proceedings SPIE Vol. 7433 (2009)

[7] Masaki Isshiki, Douglas C. Sinclair, Seiichi Kaneko, “Lens design: Optimization of both performance and tolerance sensitivity”, International Optical Design Conference 2006, Proceedings SPIE Vol. 6342 (2006)

[8] Alexander Epple, Hexin Wang, “”Design to manufacture” from the perspective of optical design and fabrication, OSA (2008)

[9] Max C. Funck, Peter Loosen, ”Statistical simulation of selectively assembled optical systems”, Optical Modelling and Performance Predictions, Proceedings SPIE Vol. 7427 (2009)