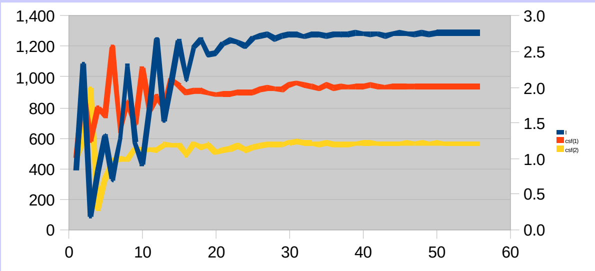
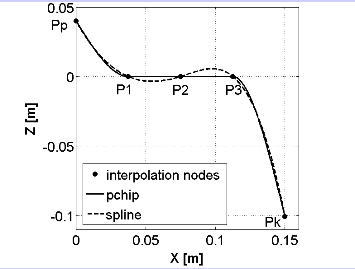
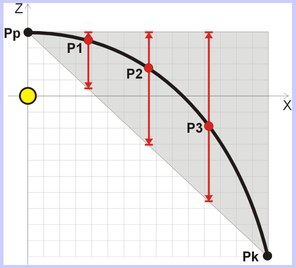
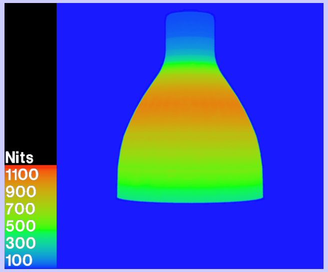
9th International
Radiance Workshop
Sep 20-21, 2010

Reflector profile optimisation using Radiance









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ARUP

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The idea

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Division of Lighting Engineering, Institute of Industrial Electrical Engineering
Poznan University of Technology, Poland, http://lumen.iee.put.poznan.pl/kw

Calculation of Luminaires Using Radiance

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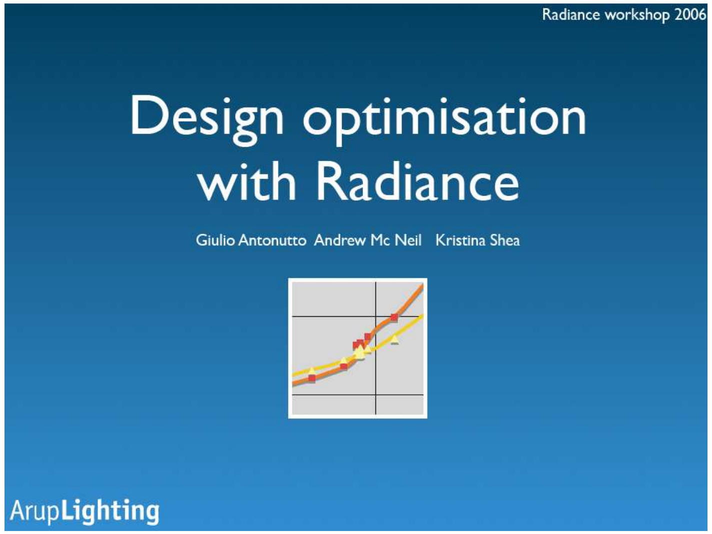
5th International Radiance Scientific Workshop
13-14 September 2006, De Montfort University, Leicester, UK

Room 0.09, Queens Building (#26 on the Campus map)

Organised by John Mardaljevic and Greg Ward
Hosted by the Institute of Energy and Sustainable Development



Reflector profile optimisation using Radiance

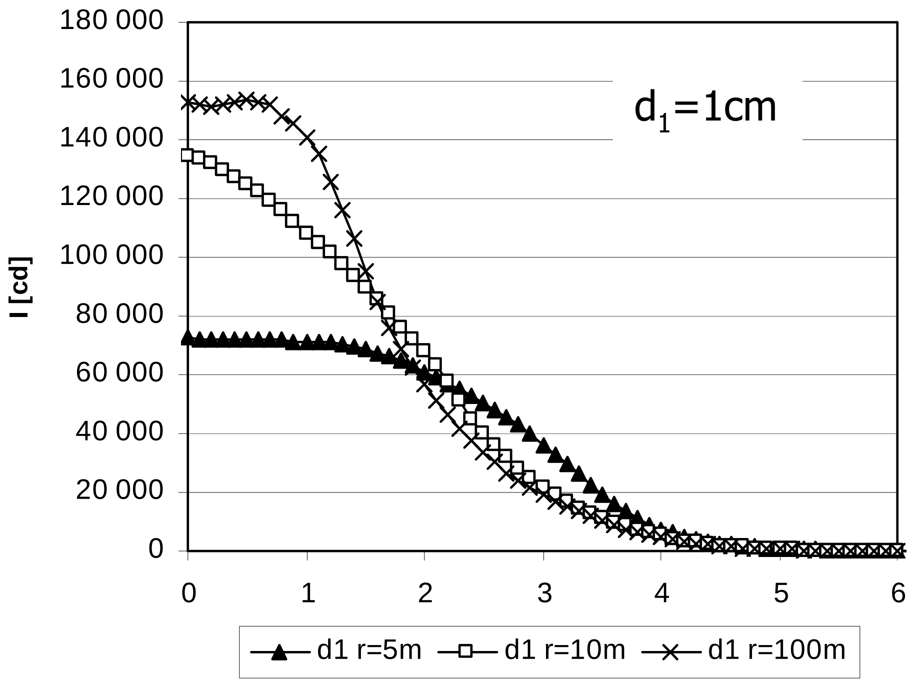
Giulio ANTONUTTO Krzysztof WANDACHOWICZ

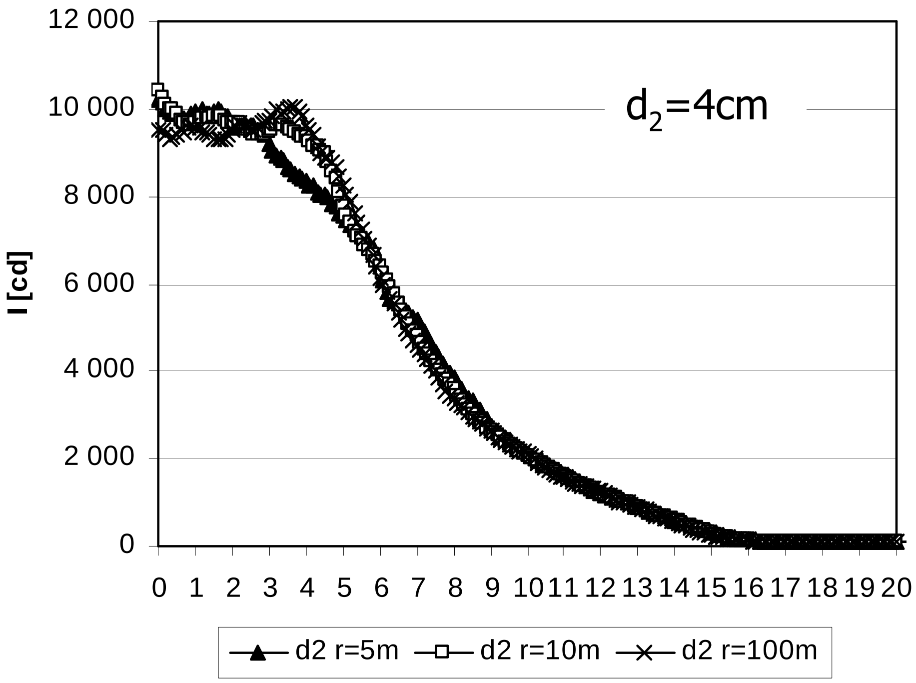
Calculation of luminaires using Radiance

Different examples: diffuse reflector and globe, specular reflector, semi-specular reflector.

Results compared with: the analytical solutions, laboratory measurements.

Example of specular, paraboloid reflector – compared with the analytical solution





luminous intensity changing in polar angles for light source diameter „d" and different distances „r" from light centre of the reflector

	Light source diameter d_1=1cm			Light source diameter d_2=4cm		
	Analytical solution	Radiance	Difference	Analytical solution	Radiance	Difference
Luminous flux [lm]	**929**	**950**	**2** %	**929**	**917**	**-1** %
Luminous intensity at the axis [cd]	**145 121**	**152 000**	**5** %	**9 072**	**9 600**	**6** %

Optimisation of luminaires vs calculation

Luminaire optical design

- determining the optimal luminous intensity distribution or optimal luminance distribution.

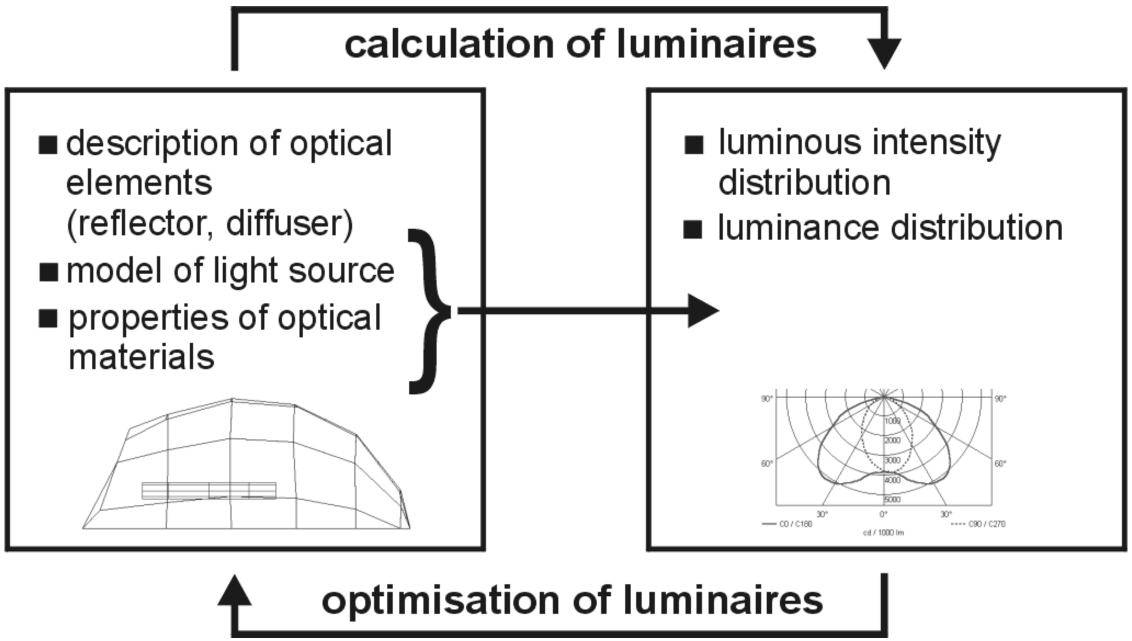
Constraints can include:

- the size of luminaire,
- the properties of material used,
- the overall cost of the solution proposed,
- the minimum efficiency that can be accepted, etc.

Optimisation of a luminaire: the goal is to meet a given luminous intensity distribution by adjusting:

- the geometry of the reflector,
- optical properties of the reflector material,
- position, power and geometry of lamps, material used are set,

Variables describe the geometry of the reflector



Optimisation of luminaires

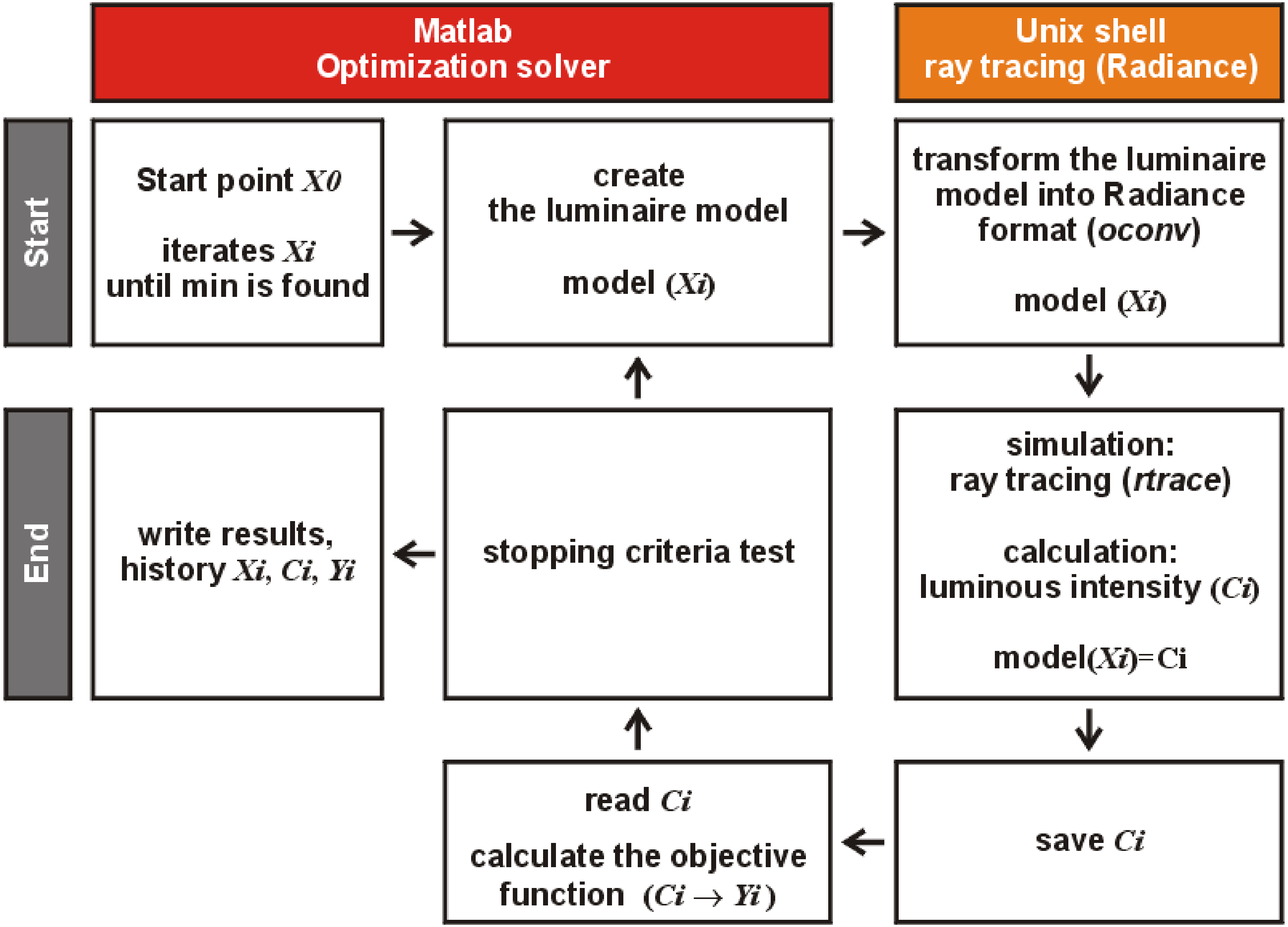
MATLAB – optimisation tool

- determining the optimum reflector shape to produce the luminous intensity distribution required,
- generation and evaluation of a succession of designs,
- each variation is derived from the previous by adjusting the design variables,
- variables are determining reflector shape,
- script creates Radiance geometry,
- an algorithm decides how and which variable needs adjusting and iterates the process until an optimal solution is found,
- stopping criteria are implemented.

RADIANCE – calculation tool

- calculation of illuminance at the distance „r” from the light centre of the reflector (`rtrace -I`),
- calculation of luminous intensity using inverse square law,
- `polygon` - surface for reflector and light source,
- `mirror` - material for reflector,
- `light` - material for light source,
- light source is small sphere consists of triangles,

Implementation of the computational optimisation workflow



Modelling the reflector geometry

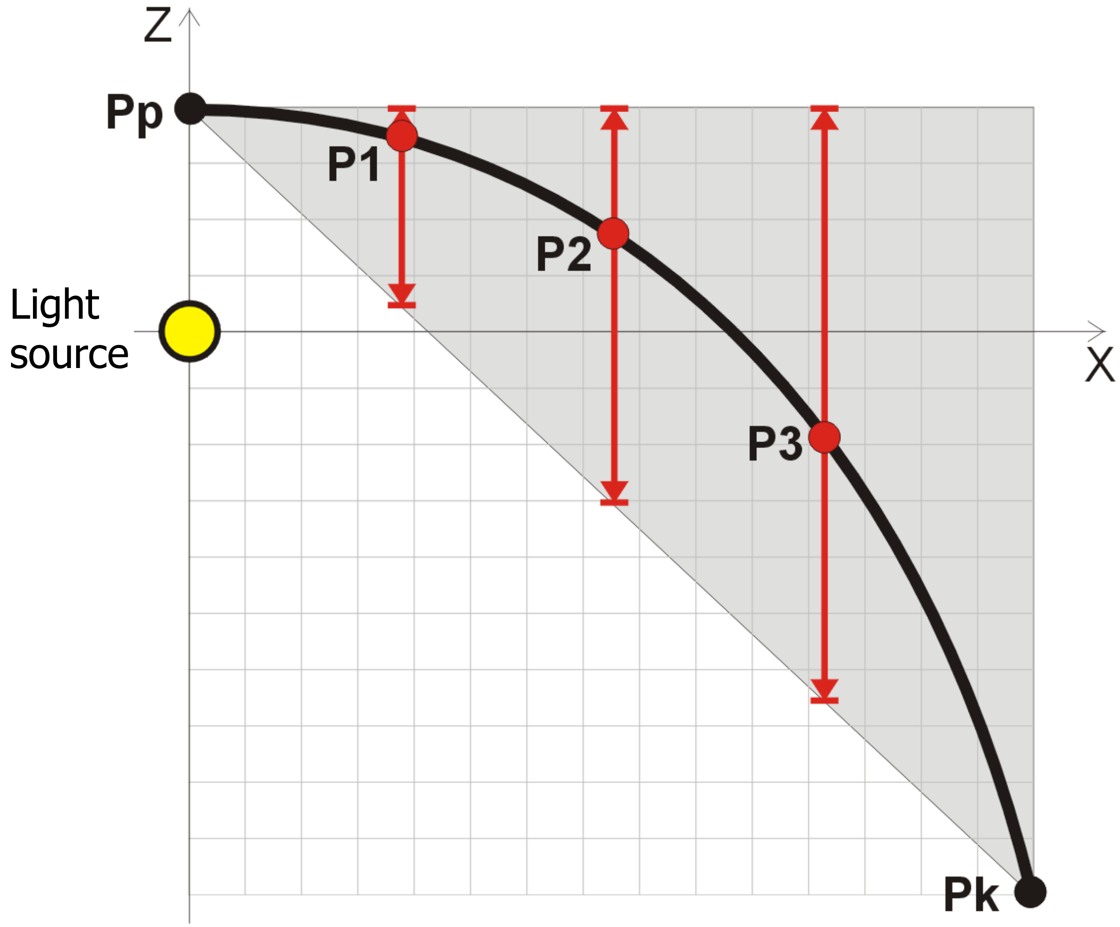
Rotationally symmetrical surface. Reflector shape profile revolving around Z axis.

Pp, Pk – fixed points, determine the maximum reflector dimensions.

P1, P2, P3 – points that have fixed X coordinates while Z coordinates can be adjusted within a range. Surface of revolution will be concave.

Variables are recorded together as a single vector with three dimensions:
Xi = [P1 P2 P3]

The vector **Xi** is used by the optimisation algorithm to adjust the reflector shape.



The reflector profile is **interpolated** using a **piecewise cubic Hermite polynomial** strategy and it is constrained to points Pp, P1, P2, P3, Pk.

Hermite polynomial interpolation

MATLAB **spline** and **pchip** function.

Spline piecewise interpolation method is class C^2 (second derivative is continuous).
A function generated with this approach has smooth shape but doesn't preserve monotonicity.

Pchip monotone interpolation can be accomplished using cubic Hermite splines with the slopes modified. In this case the function is class C^1 (only first derivative is continuous).
A discontinuous second derivative implies discontinuous curvature, but this method guarantees shape preservation and local monotonicity.

The monotone interpolation method available is the Fritsch–Carlson which allows calculating slopes and to preserve shape (it is used in the MATLAB function **pchip**).

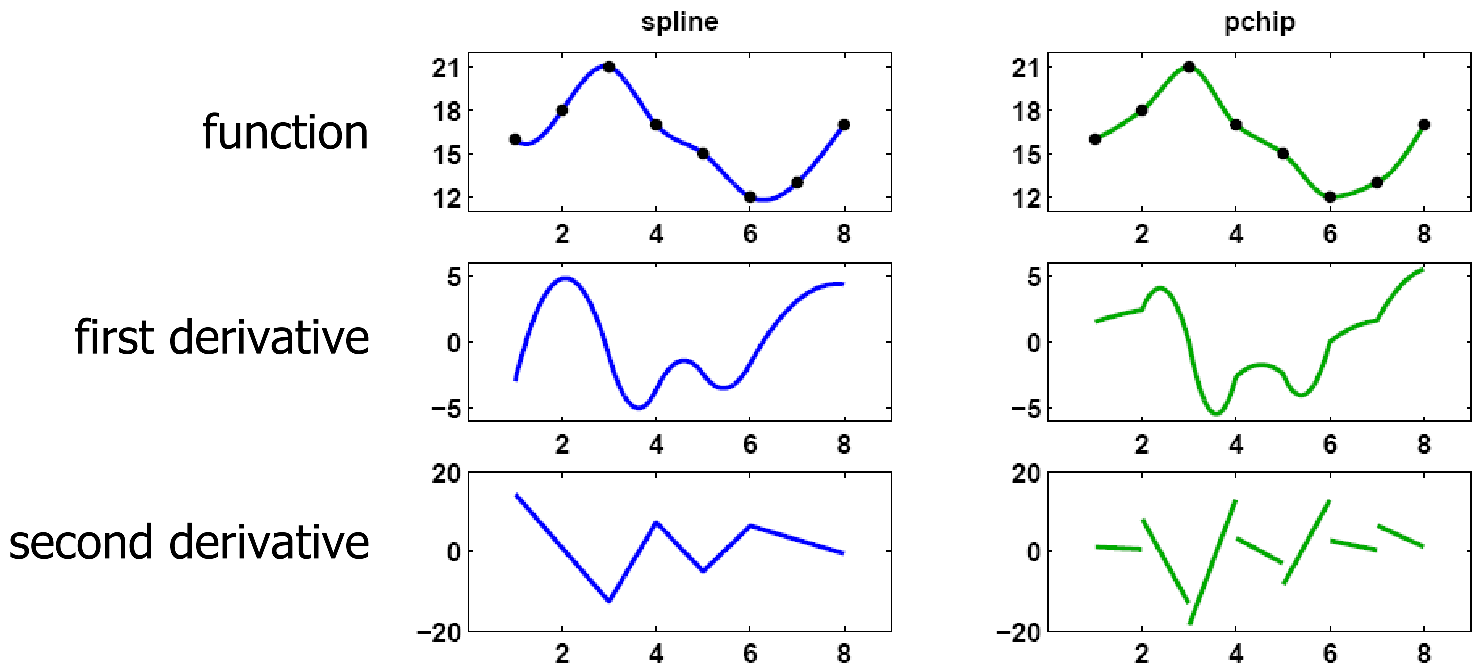


Figure from
C. Moler: *Numerical Computing with MATLAB*

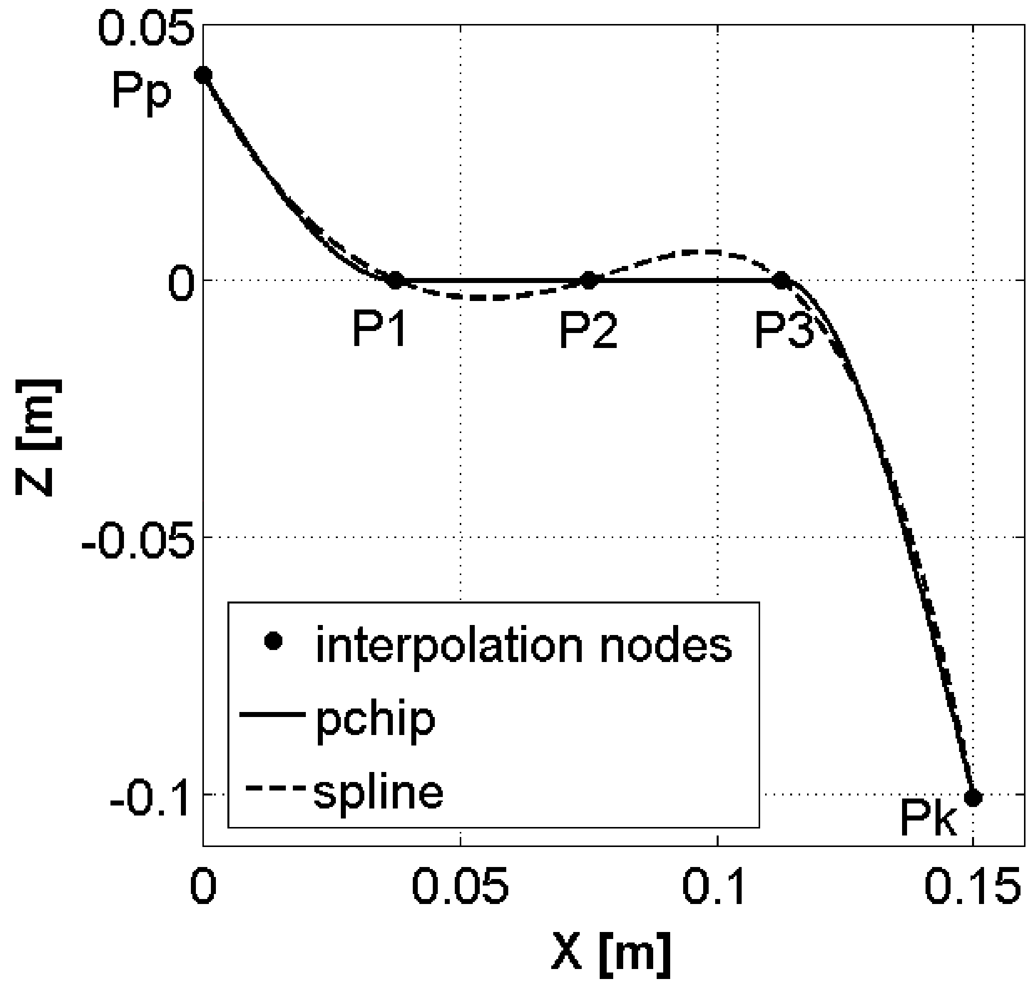
Hermite polynomial interpolation

Comparison of the results of the reflector geometry interpolation using the **spline** and **pchip** function.

In the middle area of the curve between points P1 and P3 the **spline** function is not monotonic.

spline – piecewise cubic interpolation

pchip – monotone Fritsch-Carlson piecewise Hermite polynomial interpolation



Implementation of the computational optimisation workflow

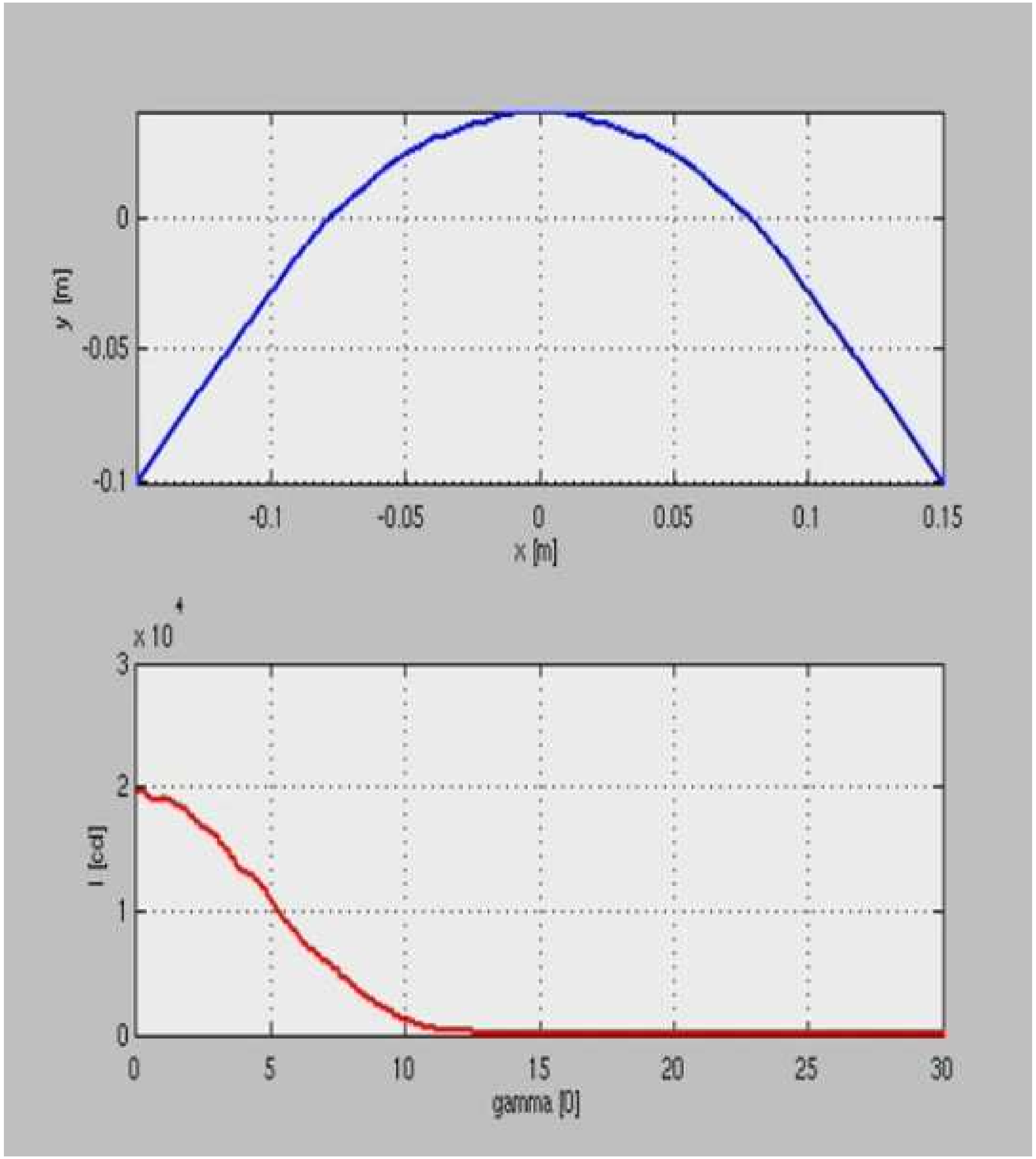
Animation
R_I_PARmax05-debug-15.mov

4 frames per second

1 frame = 1 iteration

reflector profile

luminous intensity distribution calculated for above reflector profile (using Radiance)



Computational optimisation strategies (algorithms)

MATLAB optimisation algorithms (find minimum):

Pattern search - direct search method for solving optimization problem that doesn't require any information about the gradient of the objective function. The algorithm search a set of points, called mesh, around the current point $\mathbf{X_i}$ (the current reflector configuration). To avoid being trapped in local minima the strategy that selects random starting points $\mathbf{X_0}$ is used.

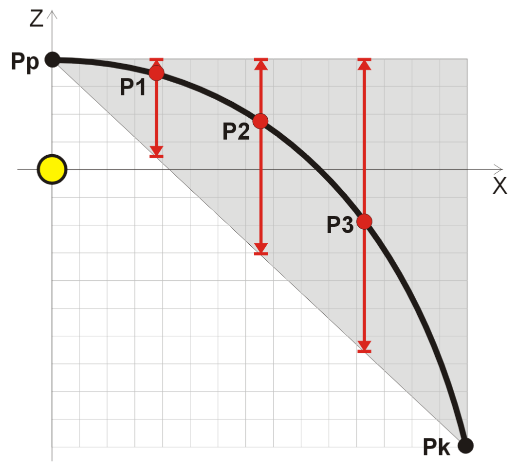
Simulated annealing is a method for solving unconstrained and bound-constrained optimization problems. The method models the physical process of heating a material and then slowly lowering the temperature to decrease defects.

Genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection. The algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. The main difference from other algorithms is that the genetic algorithm generates a population of points at each iteration instead of generating single point.

Case study A – optimisation of luminous intensity for a given direction

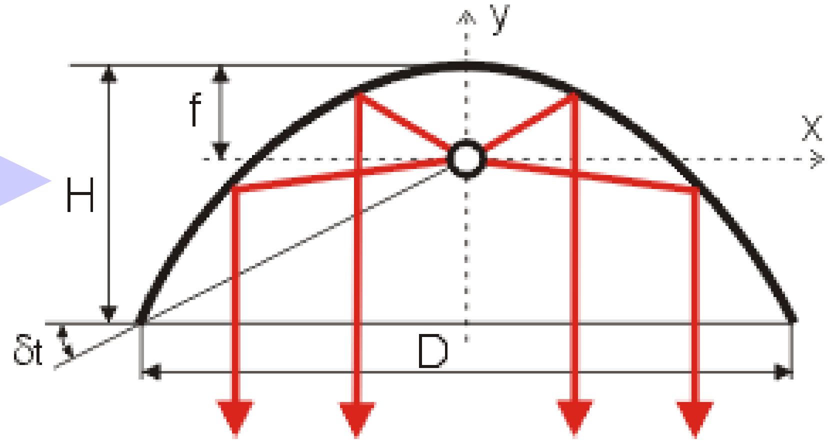
Variables: Z coordinate of points P1, P2 and P3
Constrains: (-0.9375 x + 0.04) < P1,P2,P3 < 0.04
Objective function *F(X)*: maximum luminous intensity at $\gamma=0^0$ (at the axis)

$$F(X) = -I_{\gamma=0}$$



As the **analytical solution** to the problem is known, it is possible to compare the different approaches.

In fact, the maximum luminous intensity, which can be only obtained with a **parabolic reflector**, can be calculated using the following equation:



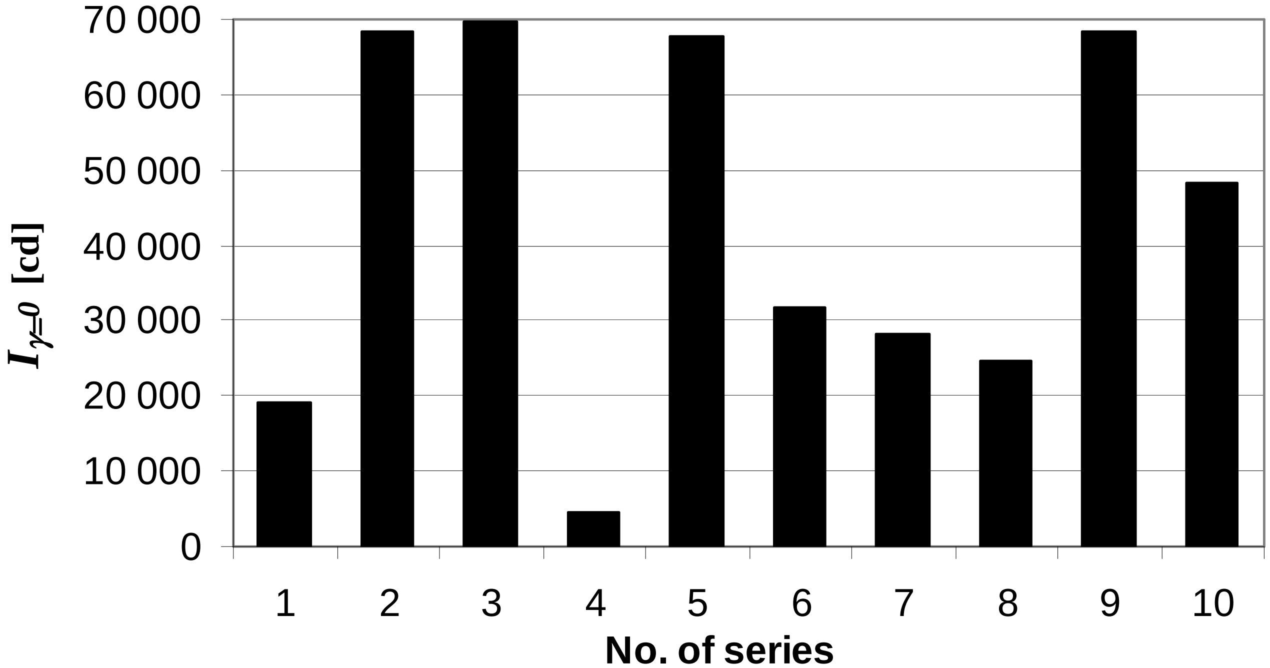
$$I_{\gamma=0} = I_{light\_source} + I_{reflector} =$$
$$= \frac{\Phi}{4\pi} + \frac{\pi D^2}{4} L_g \rho =$$
$$= \frac{1000}{4\pi} + \frac{\pi \cdot 0.3^2}{4} 1065294 \cdot 0.9 =$$
$$= \underline{67850 \ [cd]}$$

where: γ- polar angle, Φ- luminous flux (1000 lm),
D-diameter of the reflector (0.3 m),
Lg – luminance of light source (1065294 cd/m^2),
ρ - reflectance of reflector's surface (0.9)

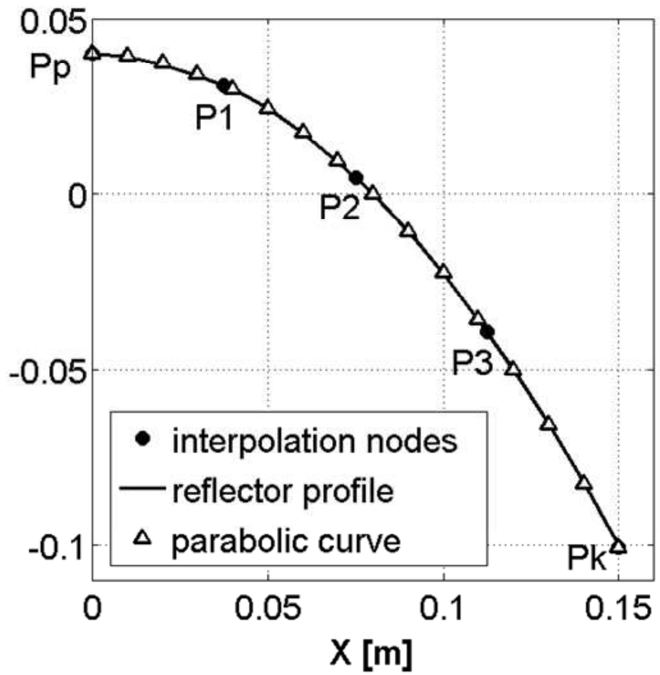
Case study A – Pattern search

10 starting points have been used, of which 4 got nearly the same best solution.

Calculated reflector profile is almost identical to parabolic curve, therefore it can be said that **algorithm have found optimum solution**.



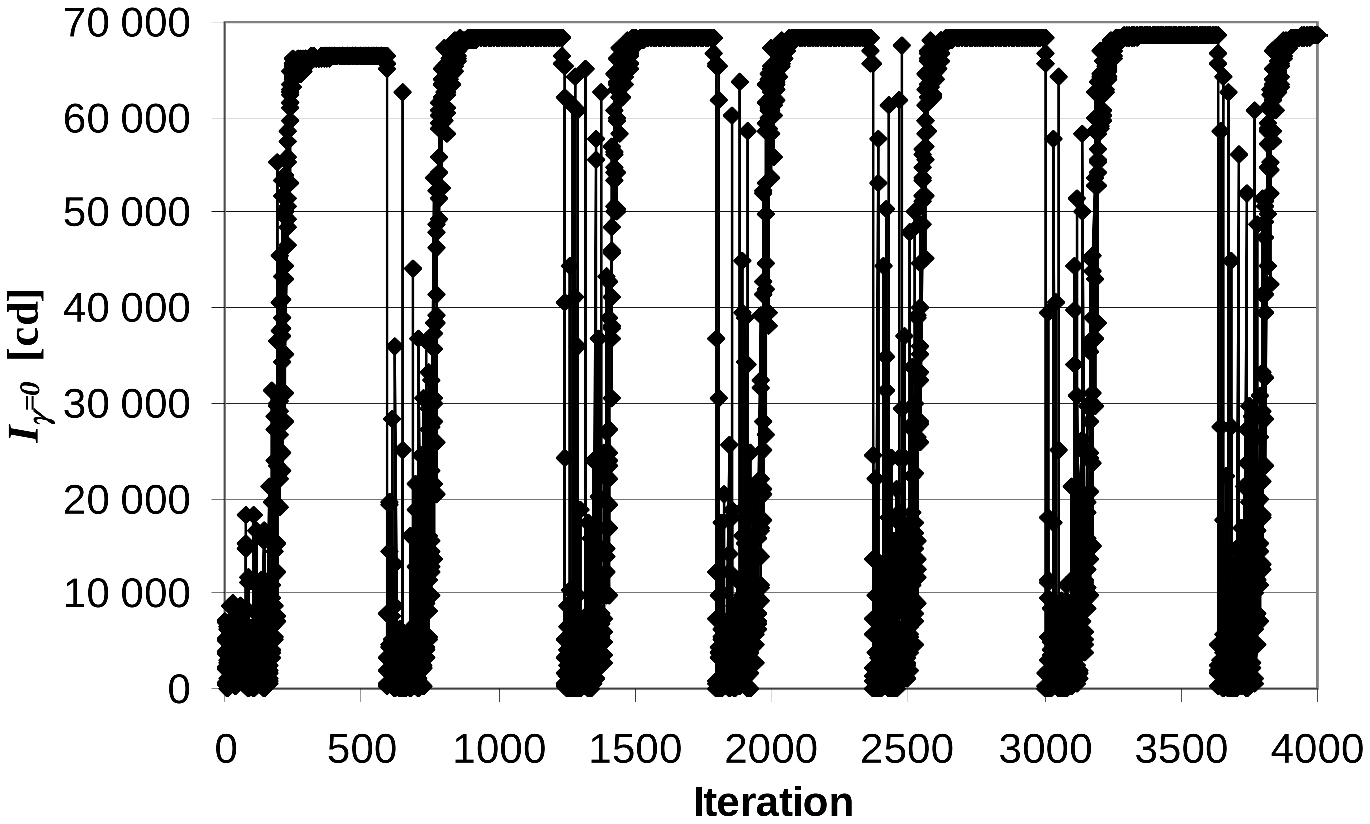
Luminous intensity distribution in the reflector's axis.
Final results for each of the 10 series.



Reflector profile and parabolic curve

Luminous intensity in the reflector's axis $I_{\gamma=0}$		Difference
Theoretical best solution	Optimization algorithm (series no. 3)	
67 850 cd	69 550 cd	2.5 %

Case study A – Simulated annealing

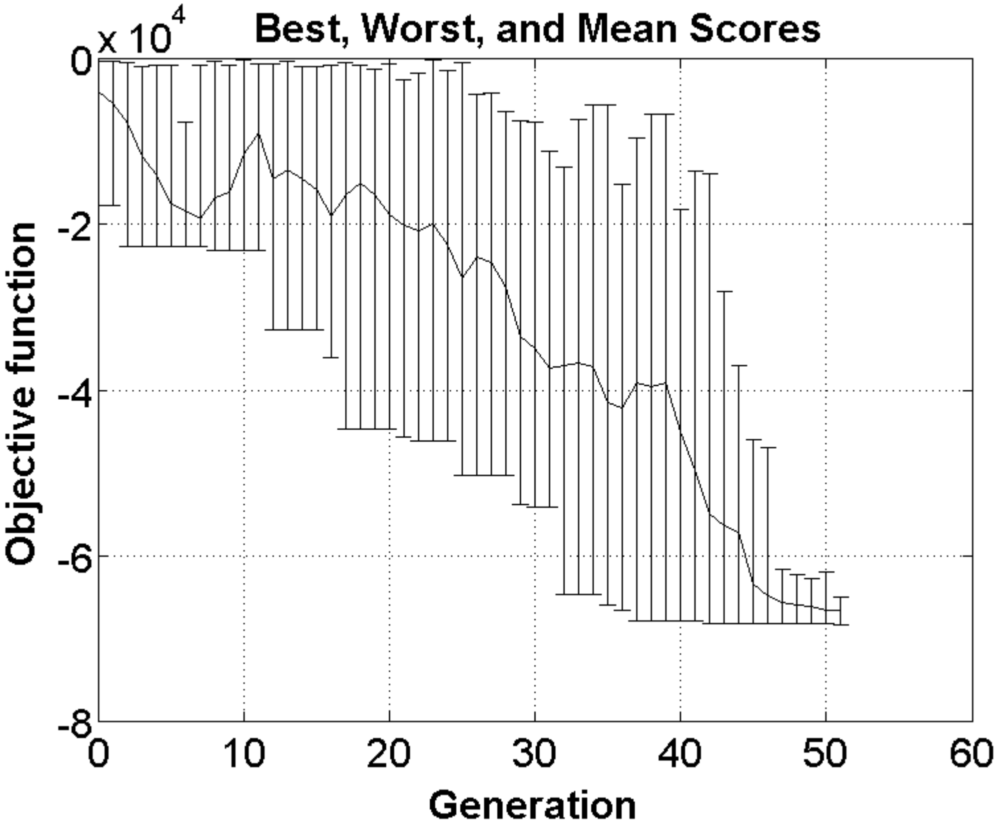


Changes in luminous intensity in the reflector's axis in consecutive iterations.

The effect of the **re-annealing** technique is clear: the temperature raises after a certain number of new points have been accepted, and starts the search again at the higher temperature. This technique avoids local minima.

Luminous intensity in the reflector's axis $I_{\gamma=0}$		Difference
Theoretical best solution	Optimization algorithm	
67 850 cd	68 539 cd	1.0 %

Case study A – Genetic algorithm



The plot shows a vertical line at each generation. This line represents the range of the objective function values within a generation. Reducing the amount of mutation decrease the diversity of subsequent generations. Diversity is important to the genetic algorithm because it enables the algorithm to search a larger region of the space (no of population is 20).

The objective value changing in subsequent generations. The lower objective value, the higher luminous intensity in the reflector's axis.

Luminous intensity in the reflector's axis $I_{\gamma=0}$		Difference
Theoretical best solution	Optimization algorithm	
67 850 cd	68 359 cd	0.7 %

Case study A – summary

	Pattern search	Simulated annealing	Genetic algorithm	Analytical solution
Luminous intensity $I_{\gamma=0}$ [cd] Difference	69 557 2.5 %	68 539 1.0 %	68 359 0.7 %	67 850
Best solution *P1* (Z coordinates) *P2* *P3*	0.030768 0.004435 -0.039320	0.031228 0.004764 -0.038838	0.030926 0.004735 -0.039275	0.031211 0.004844 -0.039102
No of iteration	2 585	4 044	1 040	-
Iterations / time elapsed [s] (Intel Core Duo T2450 2.0 GHz)	2 585 / 7 610 [s] = 0.34	4 044 / 12 396 [s] = 0.33	**1 040 / 2 425 [s] = 0.43**	-
Success percentage: no of solution within 95% of the theoretical best	562 / 2585 = 22%	**2 510 / 4044 = 62%**	174 / 1024 = 17%	-

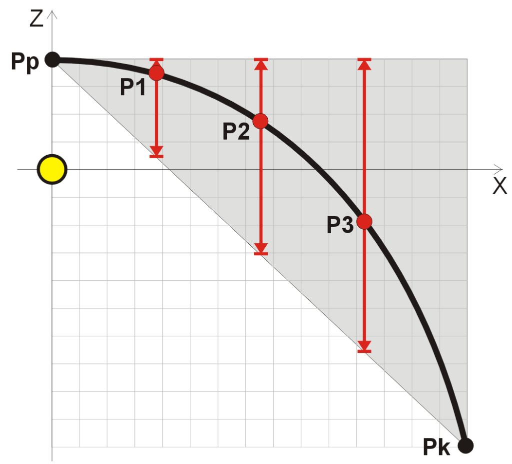
Simulated annealing and **genetic algorithm** methods return slightly different results each time when are run. This is because they both use random number generators.

Patternsearch also returns random solution as the starting points $\mathbf{X_0}$ are defined randomly.

Case study B – optimization of luminous intensity meeting a set distribution

Variables: Z coordinate of points P1, P2 and P3
Constrains: (-0.9375 x + 0.04) < P1,P2,P3 < 0.04
Objective function *F(X)* with penalty:

1. maximum luminous intensity at $\gamma=0^0$ (at the axis),
2. half-peak divergence value is $\delta=5^0$, the ratio R=0.5



$$R=\frac{I_{\gamma=5}}{I_{\gamma=0}}=0{,}5$$

$$F(X)=-\frac{I_{\gamma=0}}{m}+f_k$$

m - coefficient reducing luminous intensity to the level of the penalty function f_k.

$$f_k=\begin{cases}\left(100\left(\left|\frac{I_{\gamma=5}}{I_{\gamma=0}}-0{,}5\right|-tol\right)\right)^2 & \text{if } \left(\left|\frac{I_{\gamma=5}}{I_{\gamma=0}}-0{,}5\right|-tol\right)>0\\ 0 & \end{cases}$$

If tolerance **tol** is set at 0.05, this means that all results with the ratio **R** within the range from 0.45 to 0.55 are accepted without penalty (f_k = 0).

This example has not analytical solution which can be easily evaluated

Case study B – Pattern search

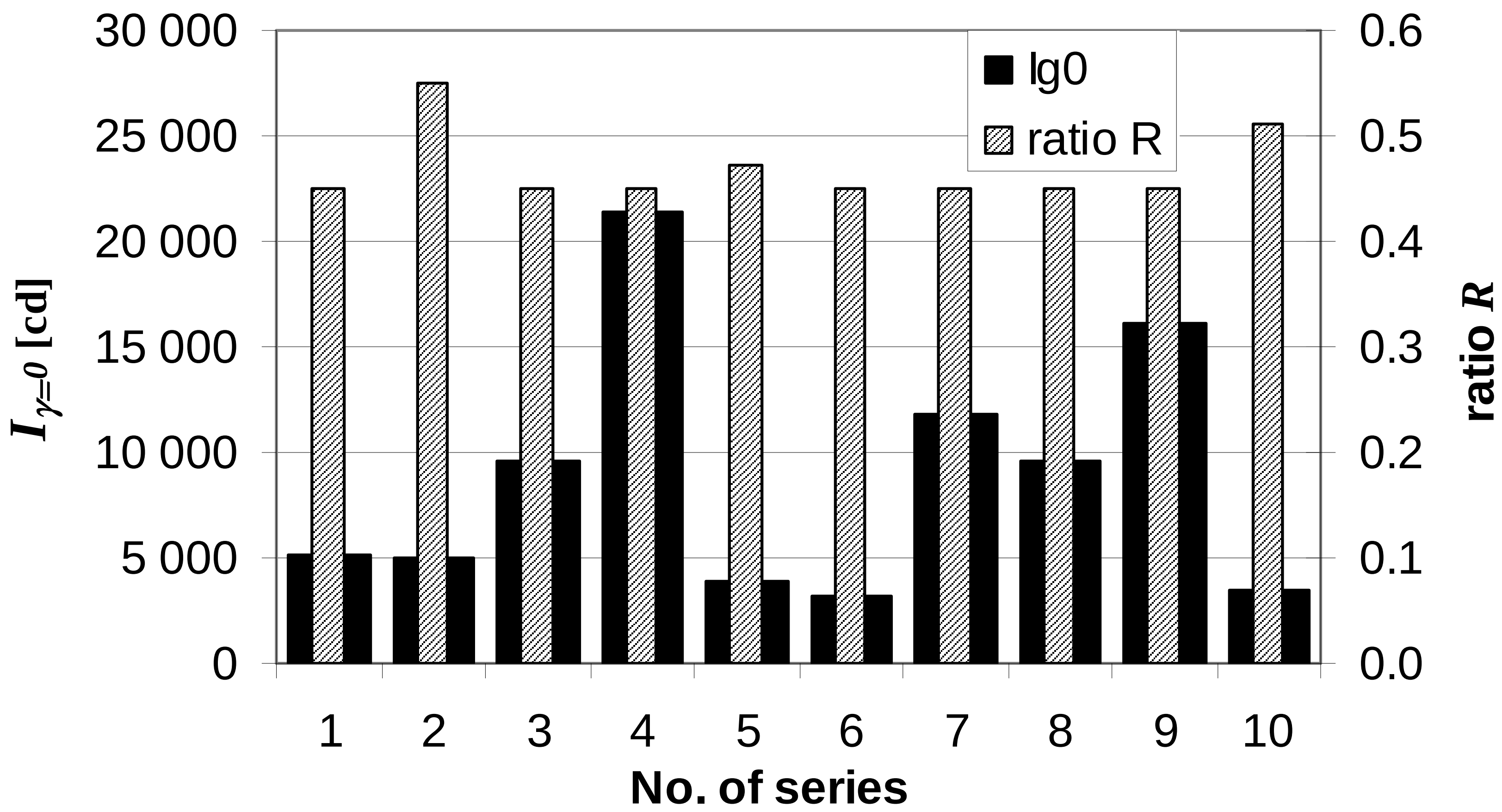


Figure shows luminous intensity in the reflector's axis (Ig0) and ratio R as a final result for each of the 10 series.

Luminous intensity must be as much as possible, ratio R should be within the range 0.45÷0.55

Only one series (no. 4) is close to the optimum.

Case study B – Simulated annealing

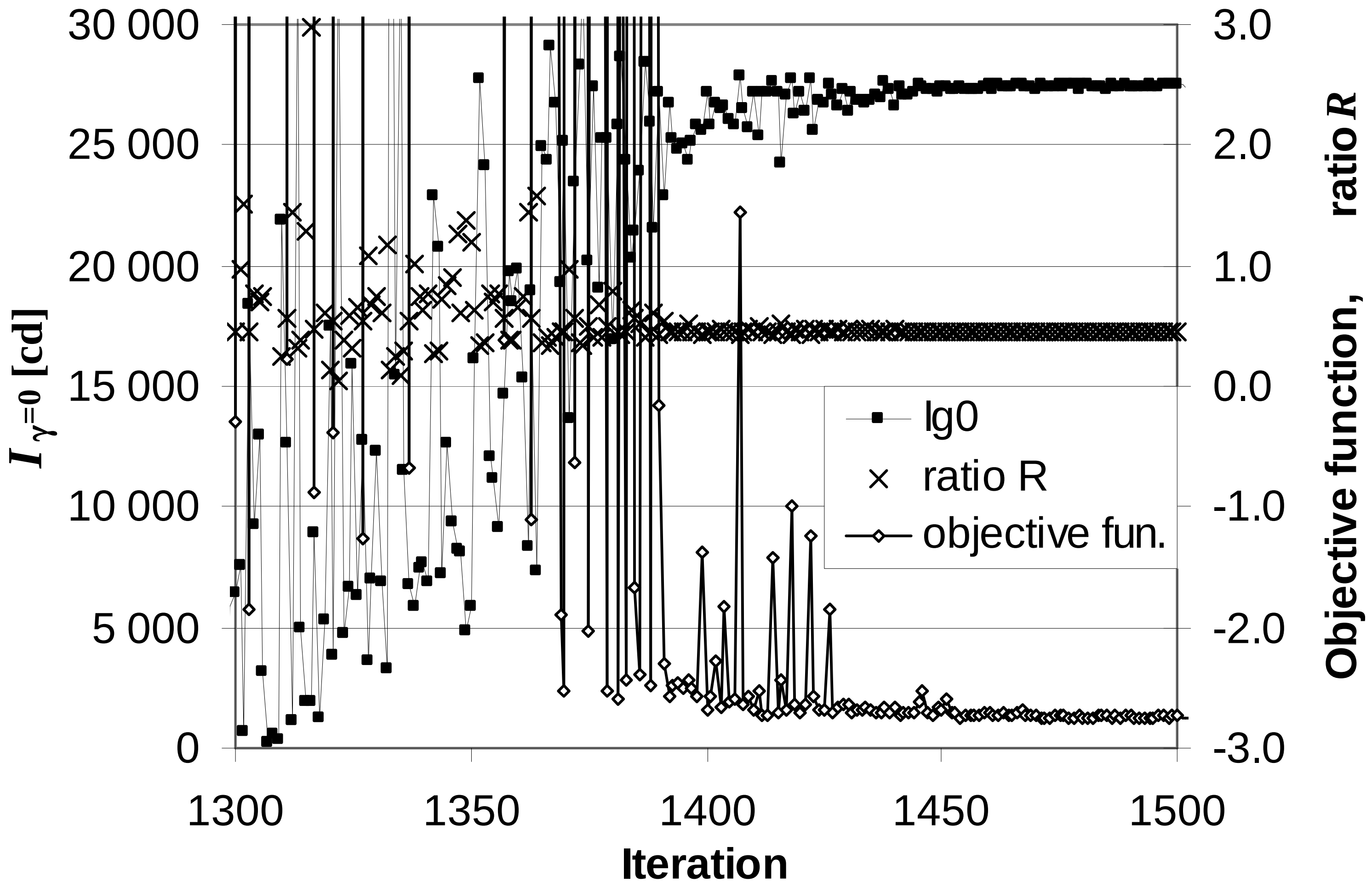
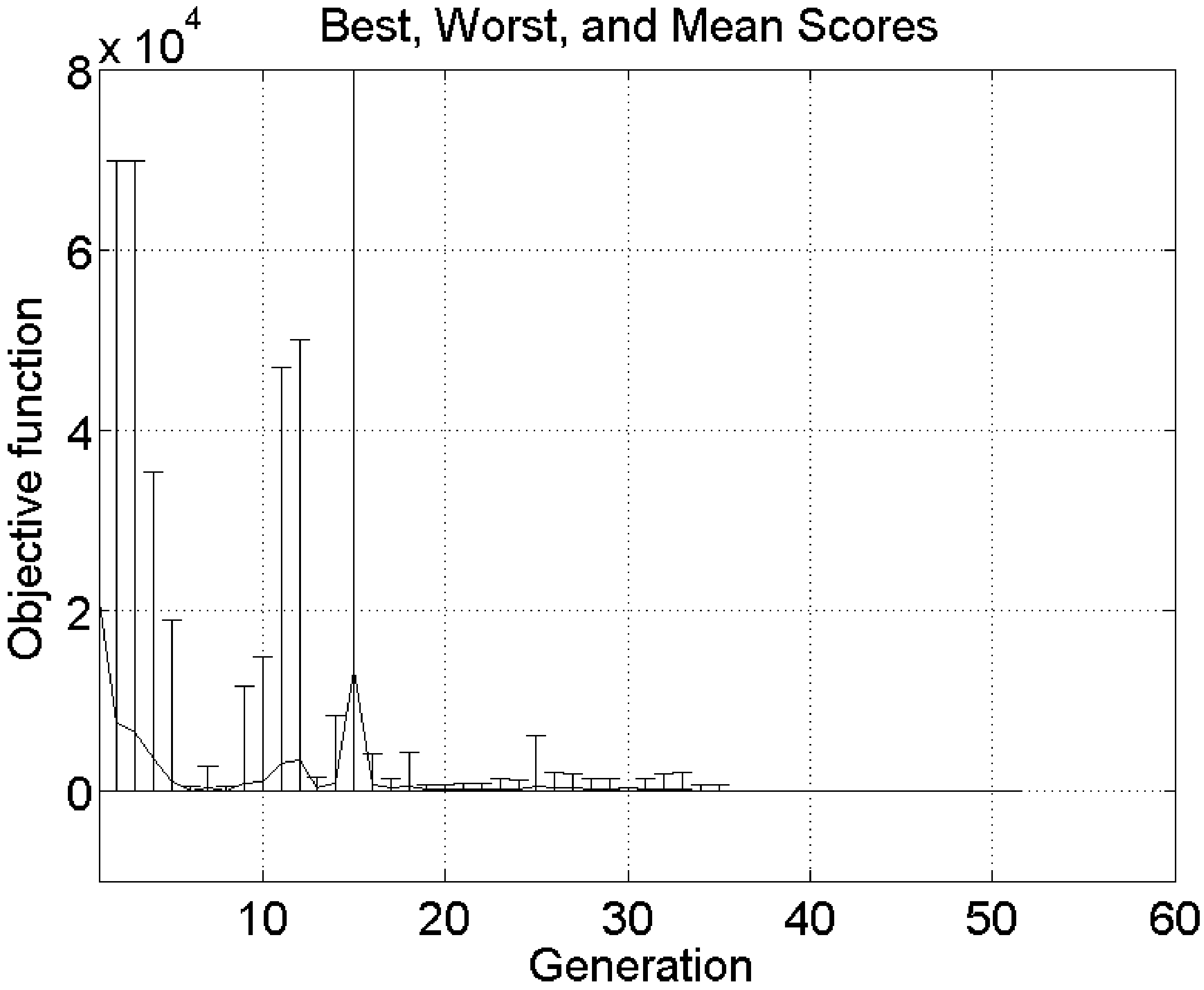


Figure shows a selected portion of the simulated annealing optimization (one re-annealing step).

Even if there are higher values of luminous intensity, they are not accepted because of the constrain at 5° (ratio R = 0.45÷0.55). The final solution is reached when the objective function is minimized.

Case study B – Genetic algorithm



High differences in objective function are a result of the penalty which increase the objective function value when ratio R is outside the range 0.45÷0.55.

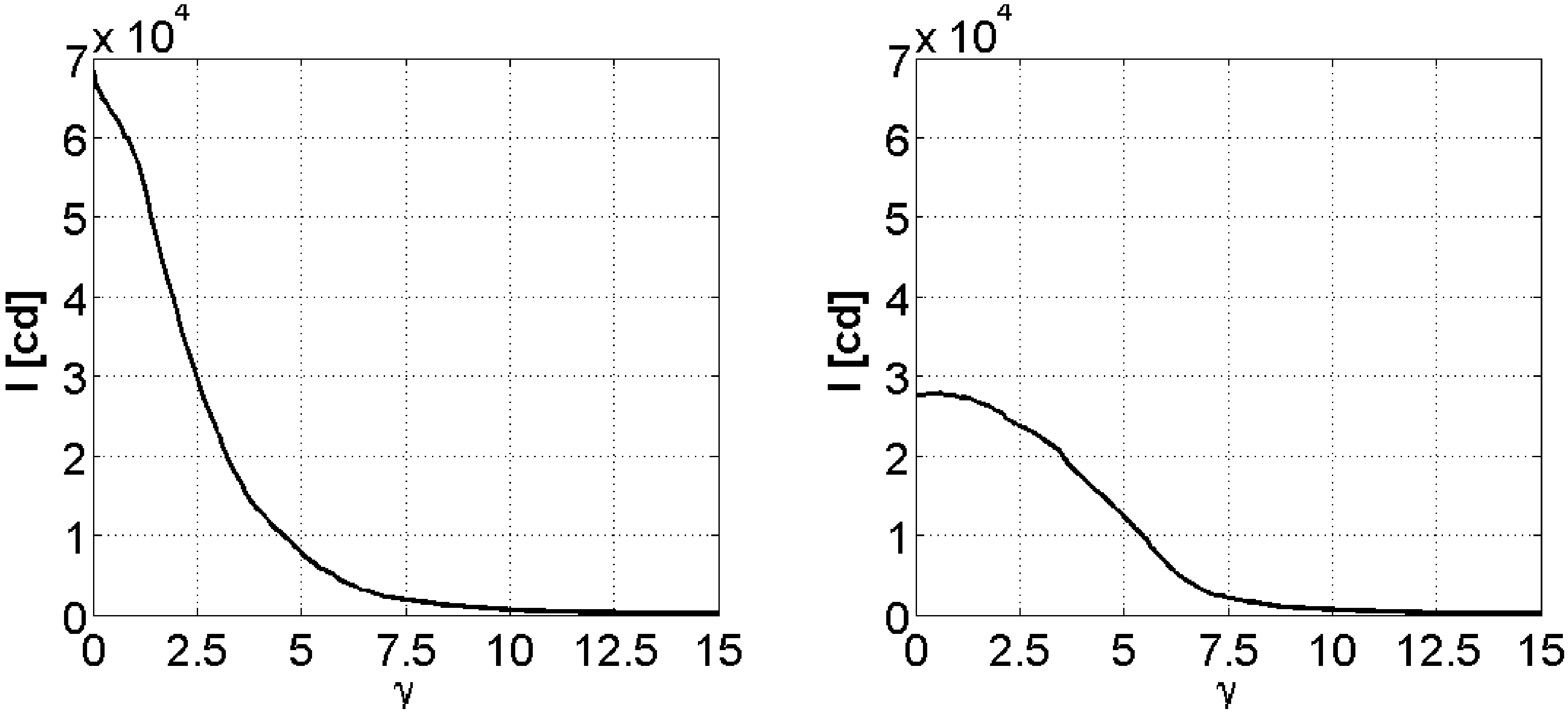
The objective value changing in subsequent generations. The lower objective value, the higher luminous intensity in the reflector's axis.

Case study B – summary

	Pattern search	Simulated annealing	**Genetic algorithm**
Best objective value	- 2.139	- 2.750	- 2.751
Best solution *P1* (Z coordinates) *P2* *P3*	0.027139 -0.002332 -0.046742	0.027664 0.000392 -0.043739	0.030268 0.003355 -0.043066
Luminous intensity $I_{\gamma=0}$ [cd]	21 399	27 514	27 514
Ratio *R*	0.4501	0.4497	0.4503
No of iteration	1 740	3 082	1 040
Iterations / time elapsed [s] (Intel Core Duo T2450 2.0 GHz)	1740 / 5 390 [s] = 0.32	3082 / 9 930 [s] = 0.31	**1040 / 3 030 [s] = 0.34**
Success percentage: no of solution within 95% of the theoretical best	40 / 1 740 = 2 %	316 / 3 082 = 10 %	**174 / 1 040 = 17 %**

The shorter calculations were performed by **genetic algorithm** and this method has also the best ratio of success percentage.

Case study A and B – summary



(a) (b)

Figure presents the luminous intensity curve of a reflectors which profiles were calculated using **genetic algorithm** method for:

(a) simply objective function (case study A),

(b) and objective with penalty (case study B).

Conclusions

Computational design optimisation can successfully be used to optimise simple reflector geometry to meet luminous intensity criteria.

The methodology used is general and can be easily applied to more complex scenarios.

In regards to the case studies shown, of the method used, **simulated annealing** and **genetic algorithm** seem to be the most promising techniques. They both show a good ratio of iterations per second and a high percentage of solution within the 5% best.

Pattern search shows a more cleaner convergence but it is often confused by local maxima/ minima.