AUTOMATIC SHAPE OPTIMISATION OF HYDRO TURBINE COMPONENTS BASED ON CFD

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Abstract: Since hydro turbines are designed individually according to the local situation, this requires a huge engineering effort. In order to reduce this effort, automatic optimisation tools are necessary. In this paper the shape optimisation of a turbine draft tube is shown. Different optimisation algorithms have been applied and will be discussed. From the used algorithms, the one based on approximated gradients seems to be the fastest.

Keywords: mathematical optimisation, flow simulation, draft tube

1. Introduction

Hydro turbines are usually designed individually according to the local situation like head, discharge *etc.* Therefore it is necessary to optimise the shape of the different components according to the flow properties. This is even more important for rehabilitation or upgrading projects, where only selected parts of the turbine are exchanged and thus the interaction of the different components has to be optimised.

The shape optimisation is carried out today by means of CFD. However it requires a huge amount of manpower since many different shapes have to be investigated. The aim of this work is to introduce a mathematical algorithm in order to obtain an automatic optimisation.

In the field of aerodynamics for many years automatic shape optimisation procedures based on mathematical optimisation algorithms have been applied for the improvement of airfoil shapes. Recently there have been attempts to apply similar techniques for the optimisation of hydro turbine components, see [1–4]. At IFMHM, University of Stuttgart, a design tool for hydro turbine components has been developed, which allows the engineer a fast and intuitive shape optimisation of the different components [5, 6]. It is now intended to extend this tool by a mathematical optimisation algorithm.
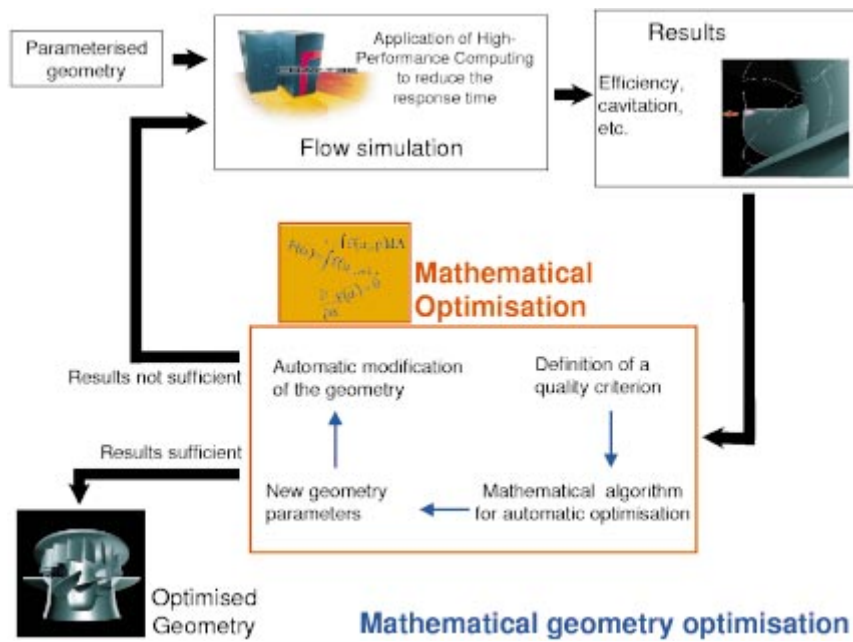
Figure 1. Mathematical optimisation loop

2. Optimisation

The general procedure of the automatic optimisation is shown in Figure 1. It consists of four major points:

- parameterisation of the geometry,
- CFD-simulation,
- quality function,
- optimisation algorithm.

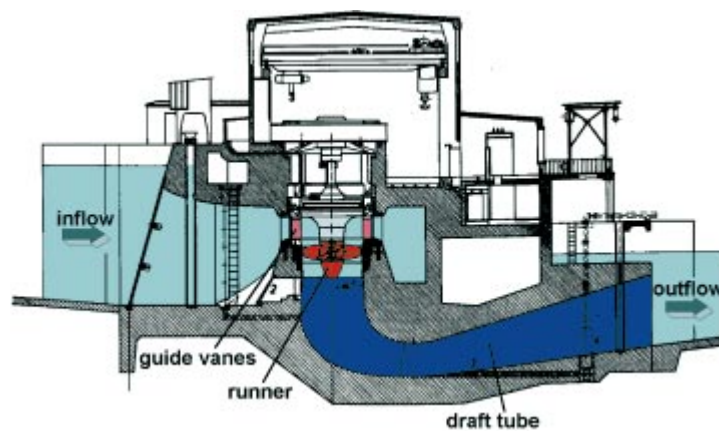In the following, these points are shortly discussed.

Figure 2. Typical low head power plant

3. Geometry parameterisation

As an example the optimisation of the draft tube is presented. Figure 2 shows a typical low head water turbine with draft tube, which is frequently installed in rivers. The aim of the draft tube is to recover the kinetic energy after the runner and to convert it into a pressure drop which increases the power output.

The shape of the draft tube is represented by a variable number of cross-sections. Each cross-section can have a different location, orientation and shape. The outer surface can either be obtained by a straight connection of the different cross-sections with sharp corners or by a smooth shape based on a B-spline approximation. Figure 3 shows a draft tube with its defined cross-section. The outer shape shows a straight connection.
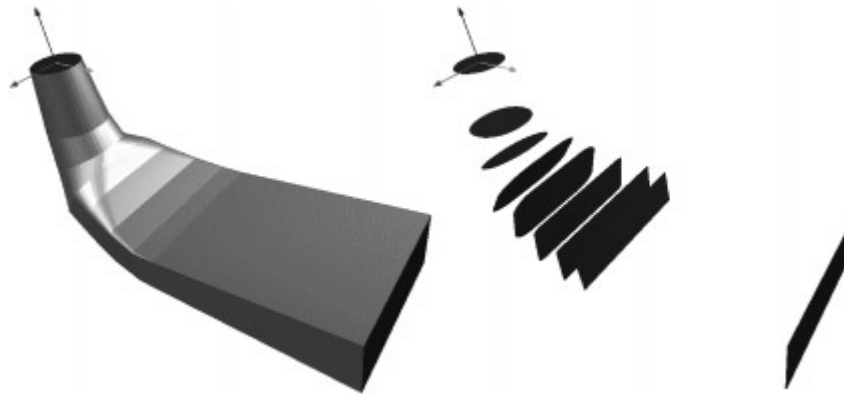

Figure 3. Draft tube and its representation by cross-sections

Each cross-section is again represented by a number of parameters. This set of parameters can vary according to the degrees of freedom wanted by the user. For example, the user can specify the cross-section be symmetrical, and the parameter set is reduced automatically. In Figure 4 an easy parameter set is shown. It consists of width, height, radius at the top and radius at the bottom.

Figure 4. Cross-section parameters

3.1. Flow simulation

The flow simulation is carried out by the Finite-Element code FENFLOSS, which has been developed at the University of Stuttgart. It is based on the Reynolds-averaged Navier-Stokes equations. For the shown application the turbulence is taken

into account by the k-ε model. For details of the simulation code the reader is referred to [7].

In order to carry out the flow simulation an automatic grid generation is necessary. For a fast grid generation the grid topology is kept unchanged. Therefore the modification of the geometry is restricted. However, this is not a real limitation since usually a starting configuration, selected based on experience, is relatively close to the optimum.

3.2. Quality function

The most difficult point of an automatic optimisation is the definition of a suitable quality function, which has to be minimized (or maximized). The quality function depends very much on the specific situation and requires a lot of experience. Often it contains not only fluid dynamical parameters but also economical aspects. In the draft tube case, *e.g.* an increase of the depth may increase the draft tube efficiency. However, the cost of civil engineering work would also dramatically increase. Consequently, the definition of the quality function should contain all these aspects and must be specified individually for each problem.

For the cases shown, here simply the pressure recovery factor is applied as a cost function. It is defined by:

$$c_p = \frac{\Delta E_p}{E_{\text{kin Inlet}}},$$

where ΔE_p – pressure energy difference between outlet and inlet $\Delta E_{\text{kin Inlet}}$ – kinetic energy at the inlet.

Apart from the shape of the draft tube the pressure recovery also depends on the inlet boundary condition, which changes according to the point of operation of the turbine. Therefore the final shape is a compromise between the optimised shapes for the different operation conditions.

3.3. Optimisation algorithms

In this project three different types of optimisation algorithms are investigated:

- based on search directions (approximation of the gradients),
- discrete SIMPLEX-type methods,
- genetic methods.

The first investigated algorithm is the EXTREM method [8]. The working principles are illustrated in Figure 5 for an example with 2 parameters. Starting with an initial search direction the quality function along this direction is approximated by a polynomial through three points (1-3). Along this approximation the minimum of the quality criterion is searched (4). The search than is continued in a perpendicular direction. Again the minimum (7) will be evaluated by approximating the criterion along this direction by a polynomial through three points (4, 5, 6). Then a new search direction will be generated by a linear connection of the starting point and the last found minimum. In this manner the search is continued until the minimum is found.

This method works fairly fast if the parameters can be varied in a large range. However, if the quality function shows local minima the method can stop there and does not find the total minimum. Since the quality function along the search
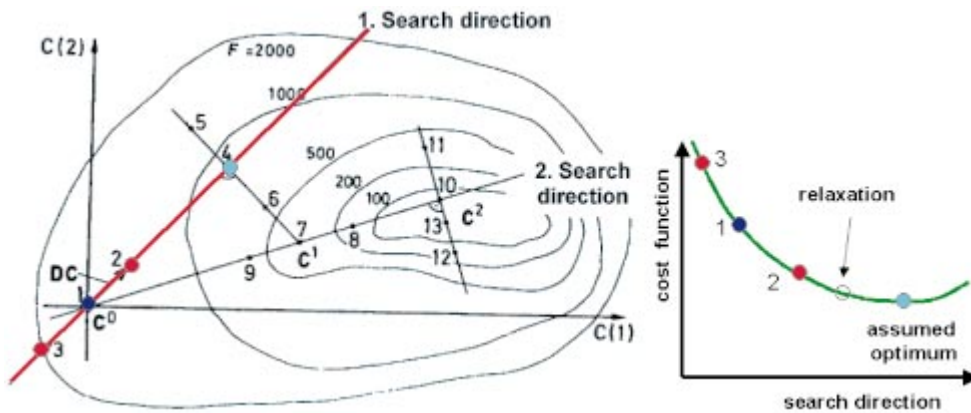
Figure 5. Automatic minimisation of a function by the EXTREM method [8]

directions is continuously approximated, this method can be interpreted as a semi-discrete method.

The second investigated optimisation method is of SIMPLEX type [9]. This is a completely discrete method, it starts with a set of points, at least one point more than the number of parameters to be optimised. The method tries to substitute the worst point by a better one by the operations of reflection, expansion or contraction. These three operations are explained in Figure 6. Initially, the worst point is reflected at the centre of the other points. In the case the new reflected point is located in the range of the other points, it substitutes the old (worst) point. If however the new point is the best point, this search direction seems to be promising and an new extension point (in the same direction) is evaluated and the best of these two points is used to substitute the old point. On the other hand, if the new reflection point is the worst of all other points a new contraction step is carried out and a new point is evaluated between the centre and the old point. By these basic operations the set of points moves towards the minimum. This method however can also not solve the local minimum problem. An improvement of the method is that if all points are gathered on a minimum, all points except the best point will be substituted by randomly distributed points. This leads to the COMPLEX algorithm [10], which can overcome local minima and eventually find the global minimum.
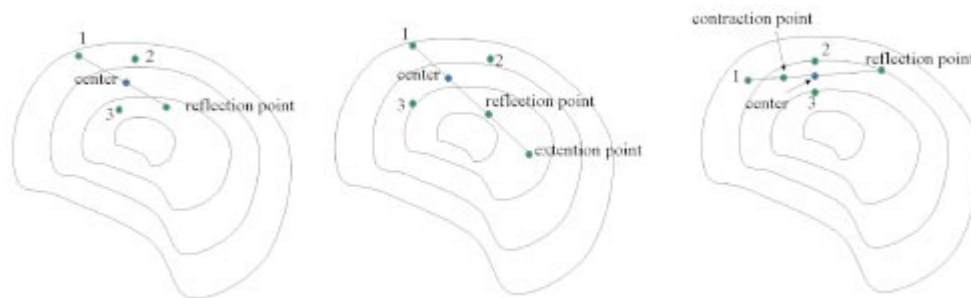

Figure 6. Operation in the SIMPLEX method

The third investigated algorithm belongs to the evolution strategy methods. In this method a starting population, consisting of various individuals (*i.e.* sets of parameters which have to be optimised) will be changed by the elementary processes

- mutation (varies parameters),
- reproduction (increases number of individuals),
- selection (reduces number of individuals by selecting the best).

The mutation and reproduction processes contain a stochatic selection of the parameters for the newly created individuals. This guarantees that the method can eventually find the global minimum, even for complex quality functions with many local minima. For details on the evolution strategy the reader is referred to [11, 12].

It has to be mentioned that the flow simulation code needs a huge amount of computational time. Therefore it is essential to have a fast optimisation algorithm. On the other hand the experience usually provides good initial guesses. Thus the algorithm does not have to search in a wide range of parameters.

4. Applications

4.1. Axially symmetric diffuser

The behaviour of the different algorithms is tested at an axially symmetric diffuser. The only parameter (degree of freedom), which will be optimised, is the length of the diffuser, see Figure 7. In Figure 8 the calculated pressure recovery factor c_p is plotted against the length of the diffuser.
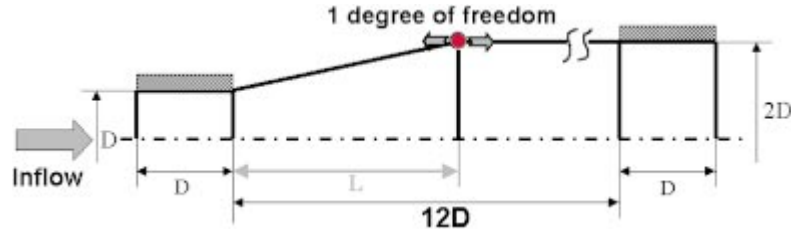

Figure 7. Axis symmetrical diffuser with one degree of freedom
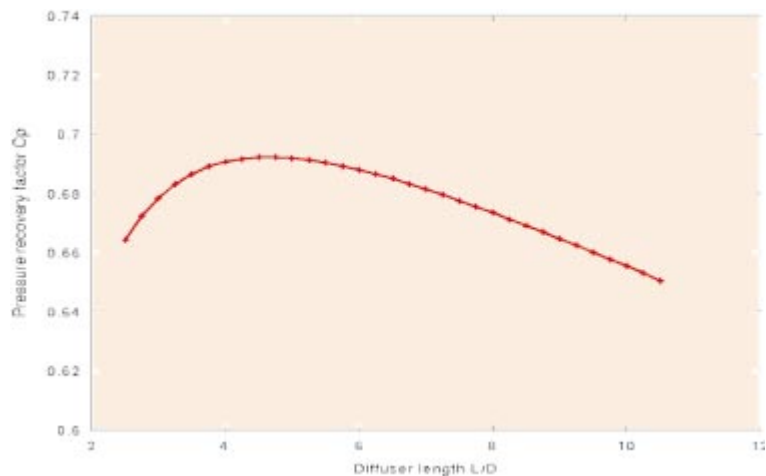

Figure 8. Pressure recovery factor

In Figure 9 the optimisation runs for the EXTREM and the SIMPLEX method are shown. After 10 calculations of different shapes the EXTREM algorithm obtained the optimum. The SIMPLEX algorithm – starting from a randomly generated initial parameter set – obtains the optimum after 15 runs. The generic algorithm – also starting from a randomly generated population – needs 25 runs to find the optimum. But all three algorithms find the same optimum in the range of computational accuracy.
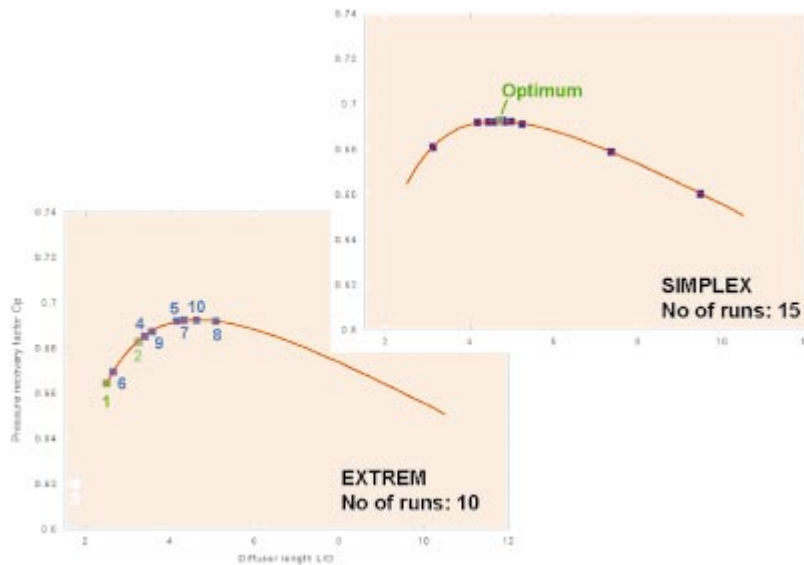

Figure 9. Results from EXTREM and SIMPLEX algorithms

As a second test example, again an axially symmetric diffuser is investigated. Now two parameters are optimised. The flow domain is shown in Figure 10 starting at the inlet with a fixed pipe of given diameter D. The diffuser opens into an outlet pipe with the diameter 2D. In Figure 11 the hill chart of the pressure recovery against the two parameters P1 and P2 is plotted. Also shown are the search directions of the EXTREM algorithm. Starting at the position S one can see the search along the first direction and the following search in the perpendicular direction. Finally, after the simulation of 23 different shapes the optimum is reached. For the same problem the SIMPLEX algorithm needed 28 runs and the genetic algorithm 44 runs.
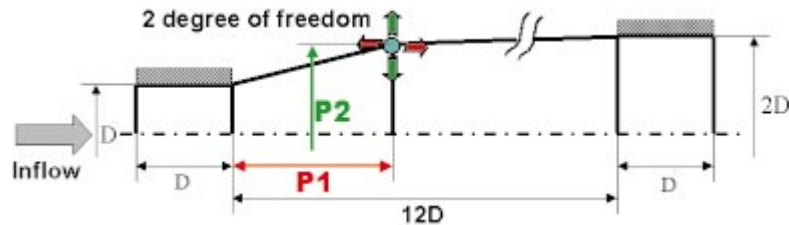

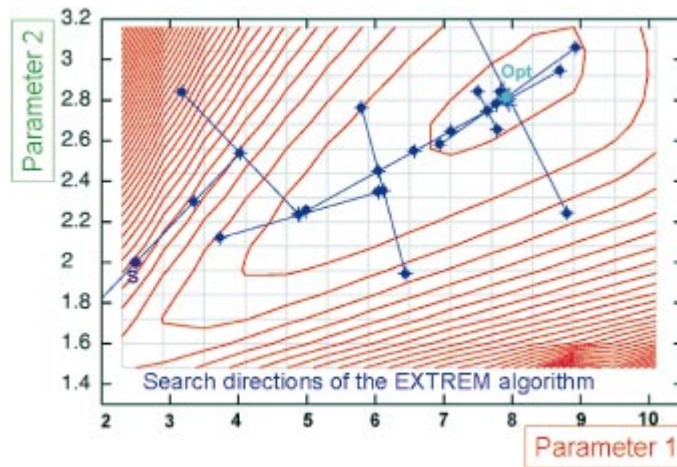**Figure 10.** Axis symmetrical diffuser with two degrees of freedom

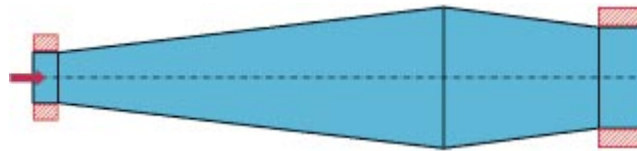**Figure 11.** Search directions of the EXTREM algorithm

Figure 12. The optimum shape

In Figure 12 the optimum shape is depicted. The algorithm detects the maximum opening angle which can be applied without flow separation. The fast deceleration of the flow leads to a reduction of the wall friction.

4.2. GAMM draft tube

As a further example, the distribution of cross-sectional areas of the elbow draft tube is optimised. The initial geometry is taken from the GAMM-Workshop [13]. The draft tube consists of 7 circular cross-sections, see Figure 13. The inlet area and the centre line of the draft tube are kept constant. Consequently, one obtains 6 degrees of freedom. The optimisation is started from an initial area ratio, shown in Figure 14. The initial shape of the draft tube together with the computational grid, which consists of approximately 20 000 nodes is also plotted in Figure 14.
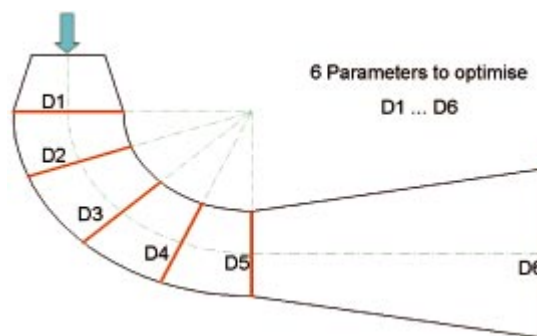

Figure 13. Optimisation parameters

After 68 iterations (computational runs) the EXTREM algorithm finds the area ratio distribution shown in Figure 14. At the inlet of the optimised form a larger opening shows, whereas in the bend flow separation is suppressed by means of flow acceleration. The obtained outlet area is smaller, to avoid re-circulation in the diffuser outlet.
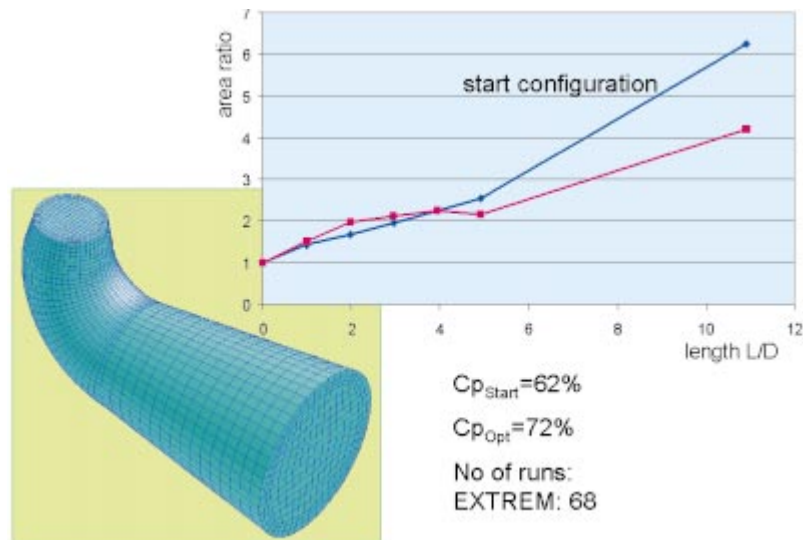

Figure 14. Mesh and results

4.3. Draft tube

The last example is a typical elbow draft tube. At the inlet the shape of the cross section is circular and at the outlet it is rectangular. The centre line of the draft tube is kept fixed in order to avoid that the optimisation algorithm would find a geometry with a huge elbow. This would seriously increase the civil engineering costs. To obtain the optimum for a real problem these costs have to be included in the cost function. This has to be done individually for each problem. Because here only a general performance of the algorithm is investigated, these economical aspects are neglected.

For the optimisation, 8 cross section areas are chosen as the degrees of freedom. As a start configuration, a linear distribution of the cross section areas has been selected. In an industrial environment the start configuration is usually closer to the optimum due to the designer's experience.

The optimising algorithm needs 170 CFD runs to accomplish the task. Figure 15 shows all tested area distributions. The optimiser detects very fast that an early increase of the cross-section area leads to good results. Also typical curves for the distribution over the tube length could be seen. In the elbow part, the area is gradually decreased to avoid separation. In the straight outlet, it is increased again to recover the kinetic energy.

Figure 16 shows on the left axis the relative pressure recovery against the CFD runs (red graph). The optimised geometry shows a gain of approximately 13%.
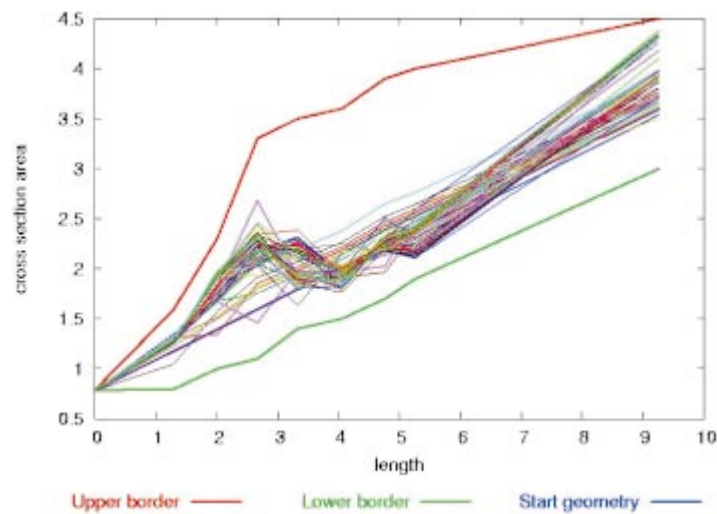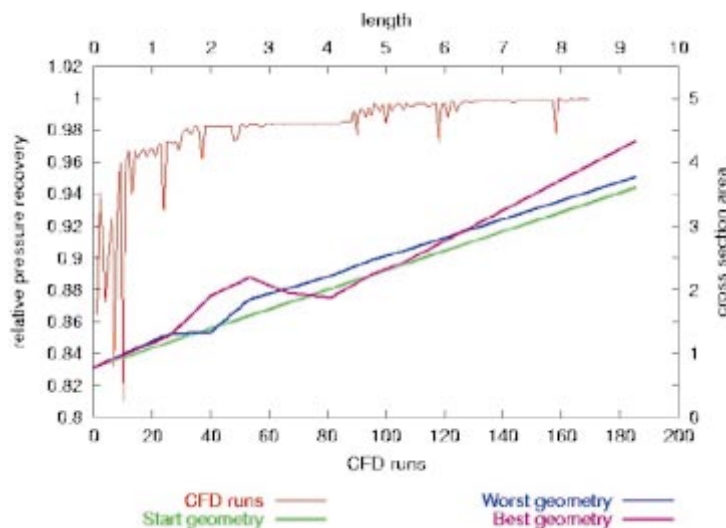
Figure 15. Areas for all tested cases

Figure 16. Results from EXTREM algorithm

5. Conclusion

Several optimisation algorithms have been presented in this paper. The EX-TREM algorithm has proved to be the fastest in terms of optimisation runs. However, a decisive drawback is that it can lead to detection of a local minimum instead of the global minimum. Nevertheless, we did not encounter this problem with good initial guesses. On the other hand the genetic algorithm shows a very robust behaviour, but it requires a distinctly more optimisation cycles and computational time.

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