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Retrofitting a Truss-Z Modular Pedestrian Ramp with Fully Automated Generation of the Spatial Configuration of the Modules

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Abstract

This paper presents a case study of retrofitting of a single branch of a Truss-Z (TZ) ramp structure in a given three-dimensional environment. The spatial configuration of modules is automatically generated, and the only input required are the coordinates of the initial unit, the target zone defined by a cuboid and the spatial configuration of the environment where the TZ structure is to be installed. The case study is done for the Musashikosugi railway station in Tokyo, where the pedestrian traffic flows through large stairs with 39 steps at only one intermediate landing and total elevation of over 6 meters. Since the system is modular, the creation and optimization of a TZ structure has a combinatorial nature. Preliminary solution created manually is demonstrated, followed by implementation of intensive search (backtracking) and heuristic (evolutionary algorithm) methods. The algorithm parameters are briefly described and calibration of some – explained. The results of experiments are presented and discussed.

Keywords: Truss-Z, modular skeletal system, organic design, discrete structural optimization, retrofitting, pedestrian ramp.

1 Introduction

Truss-Z (TZ) is a concept of a modular skeletal system for creating free-form transportation links and networks among any number of terminals in space [1,2]. TZ is intended for pedestrians, especially ones with strollers or carts, cyclists etc. In other words for people who have difficulties using regular stairs. The underlying idea of this system is to create structurally sound provisional or permanent structures at the minimal number of types of modular elements. The TZ structures are composed of only two units – R and L which are mirror reflection of each other. By rotation, they can be assembled in two additional ways (R2 – rotated R and L2 – rotated L) as shown in Figure 1.

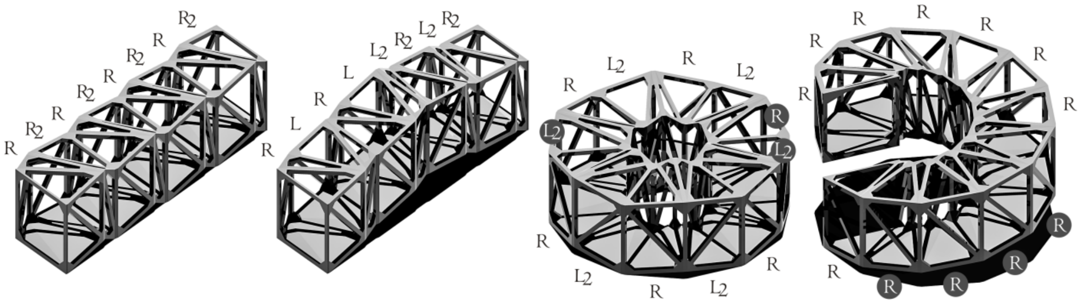

Figure 1: Some basic examples of TZ structures. From the left: “straight and flat” with 8 units, “straight up & down” (8), a flat ring (12), and a spiral (12).

Most importantly, TZ allows automated creation of optimal structural linkages for given terminals and obstacles [3]. The optimization criteria can be: the minimal number of units, in case of multiple branches – the minimal network distance etc. Effective algorithms for two-dimensional, single-branch TZ linkages in constrained environment have been demonstrated [4,5]. This paper presents the next step towards the practical implementation – the three-dimensional case study of retrofitting in an existing situation.

2 The case study

Musashikosugi railway station in Tokyo is one of great many public spaces where, euphemistically speaking, the pedestrian communication is not very comfortable. The traffic flows through large stairs with 39 steps at only one intermediate landing and total elevation of over 6 meters as shown in Figure 2.

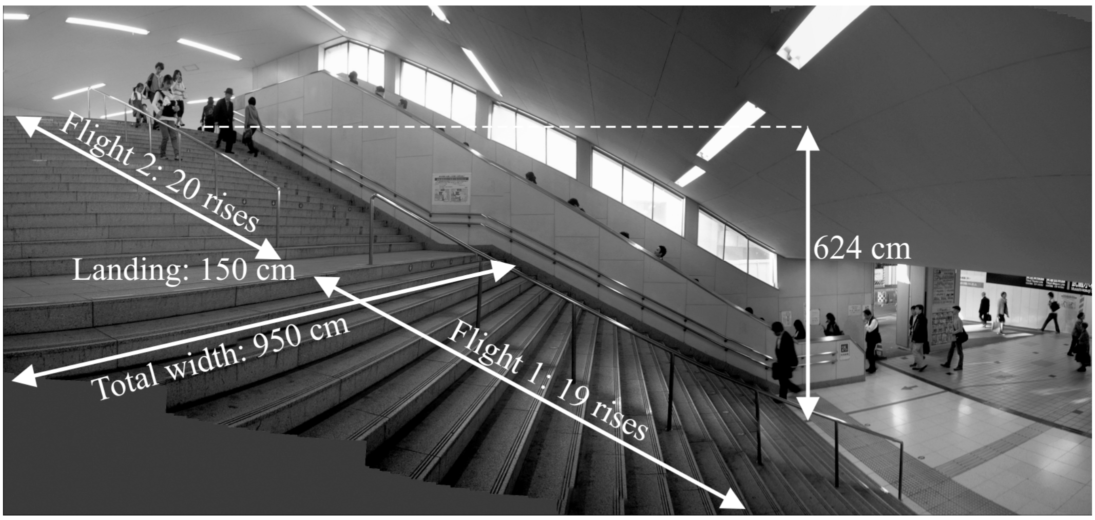

Figure 2: The stairs at Musashikosugi Railway Station where the retrofitting of a TZ structure is proposed.

In fact, the building regulations in many countries would not allow such an arrangement. For example according to the British Standards [6], a railway station qualifies as an “assembly building”, and in such a case at least the following rules are violated:

1. The flight width is much wider than allowable 180 cm.
2. The number of rises exceeds the maximum allowable value of 16 (here: 19 & 20).
3. Stairs of more than 36 rises (here: 39) shall have at least one change of direction between flights of at least 30°.
4. The going of a landing shall be not less than the width of the flight. (here the going of the landing is 150 cm and the width of the flight: 475 cm).

Such a communication path poses tremendous effort on pedestrians, especially elders and persons with mobility problems. There are also an escalator and elevator, however, in case of a fire or a major earthquake, they can not be used, and in such a case the evacuation may become very difficult. This case represents a large class of pedestrian communication problems which can be solved by retrofitting of a TZ ramp structure. The recommendations for the geometry, in particular – slopes of ramps depend on the intended use and local regulations. For instance, the Americans with Disabilities Act (ADA) requires a 1:12 (8%) slope for wheelchairs and scooters for business and public use [7], the British guidelines as recommended by the Disability Discrimination Act (DDA) and Disability Rights Commission (DRC) are 1:6 (16%) for temporary ramps for assisted wheelchairs, 1:12 for temporary ramps for self-powered wheelchairs, and 1:15 (7%) for permanent and semi-permanent ramps [8]. In the proposed TZ configuration, the slope of a modular unit is rather steep as shown in figure 9. Therefore the unassisted use by persons on wheelchairs would be problematic. However, it could still serve the purpose for persons with less severe mobility problems, cyclists, etc.

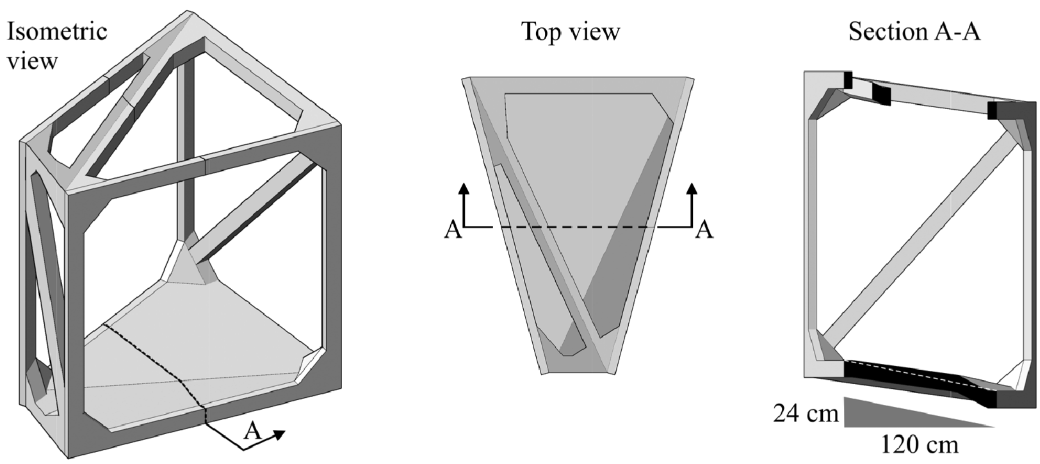

Figure 3: The section through a TZ module. The slope is 24/120 = 1:5 (20%).

In principle, the slope of TZ module shown in Figure 3 can be reduced to meet any requirements, however at the expense of the “flexibility” of the system. For instance, if the slope was to be reduced below 16% (20/120), the applicability of vertical spirals would be limited.

The model of space of the considered situation is shown in Figure 4.

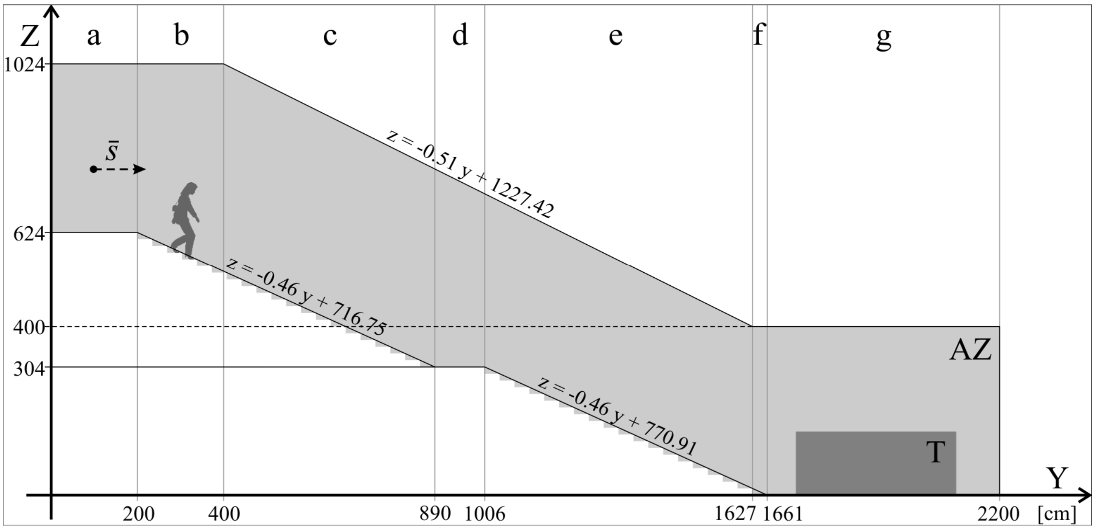

Figure 4: All vertices of TZ modules must lay within the allowable zone (AZ) given as geometric constraints, indicated in light gray. In the XY plane: $0 \leq x \leq 950$. All the values are in cm. AZ is divided into 7 sections a, b,..., g and implemented as a set of inequalities. The target area (T) is indicated in dark gray, the position and direction of the initial vector $\bar{s}$ of the TZ structure are shown respectively (explained further in text).

The intention is to create a three-dimensional TZ linkage within the allowable zone (AZ) that starts from the given point and reaches the target zone T with the least number of units, as shown in Figure 4. At first, a preliminary solution was manually created by trial and error as shown in Figure 5.

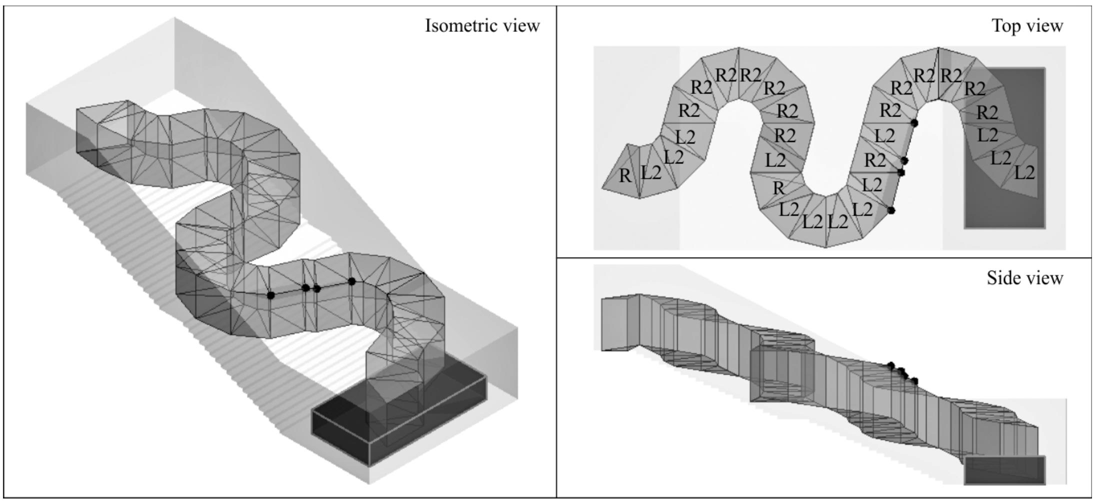

Figure 5: The preliminary, manual solution is not acceptable since there are four vertices of the structure that violate AZ, as indicated by black dots. AZ and T are shown in light and dark gray respectively.

Although the preliminary solution, which is composed of 29 units, is not acceptable, it was assumed, that if an allowable solution exists, the number of units will be in the same range of magnitude. This information allows estimating the size of the search space. Since there are four variations of a unit at each position, for the sequence of 29 units there are 4^{29}=288,230,376,151,711,744 possible configurations. It is clearly unrealistic to inspect every solution, however, backtracking [9] is a simple and efficient method that usually gives good results in reasonable time, especially for highly constrained problems, as in this case.

3 Backtracking

In this implementation of the backtracking, each partial solution must meet two types of geometrical constraints – all the units must lie within AZ and the TZ units must not collide with each other. The procedure starts from the given point in a given direction with a single unit (R, L, R2 or L2). At each step, all four options are evaluated against the aforementioned criteria, and the next unit is chosen from the set of allowable options. The selection is based on the minimal distance to T. If at a certain step, the set of allowable choices is empty, the process retracts to the previous step that had more than one possible option, selects a different one than previously, and erases the unit (module) that lead to the "dead end". In the given conditions, it was only possible to construct the linkage starting from unit of type R. The result was produced rather fast, that is after only 2389 iterations of the algorithm (Figure 6). When starting from L, L2 or R2, which are the cases where allowable solutions do not exist, the algorithm terminated within 5000 iterations.

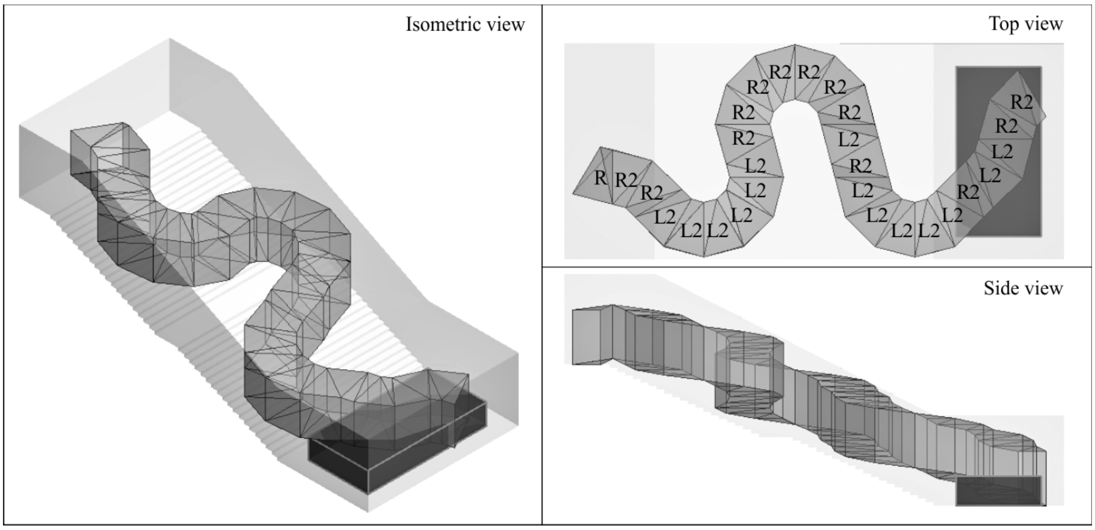

Figure 6: The solution produced by backtracking. It is not only allowable since there are no violations, but it also seems very good, perhaps even ideal. The number of units is 28.

Since the search space is enormous, it is natural to apply heuristic method in order to investigate whether better or alternative configurations exist.

4 Evolutionary algorithm

The implementation of a classic evolutionary algorithm (EA) requires the following:

1. encoding of the solution into a genotype, that is a list of symbols, usually integers,
2. formulation of the fitness function, which should consistently give higher (for maximization) or lower (for minimization – as in this example) values for better candidates,
3. selection method,
4. operation of crossover,
5. operation of mutation.

The aforementioned items are briefly described below.

4.1 Genotype

In this case, a candidate solution is encoded in the most straightforward way, that is as a list of units: $\{u_1, u_2, \ldots u_i, \ldots\}$, where u_i:{R,R2,L,L2}. Different sequences can reach T with a different number of units. In order to maintain the constant length of genotype, the units that "go away" from the closest proximity of T are ignored. The length of all the genotypes was set to 33, that is 5 extra units to the length of the solution produced by backtracking (figure 6).

4.2 Fitness (cost) function

Formulating the fitness function, which for minimization, as in this case, is called the cost function (CF) is usually the most challenging part of the EA implementation. It does not only require the knowledge particular to the considered problem, but it is also necessary to give univocal, usually numerical, evaluation of each candidate solution, including the unacceptable ones. CF in the given environment E for the sequence of TZ units S is expressed as follows:

$$CF_S^E = Minimize\,(w_1 n_v + w_2 v_i + w_3 Min[d_i] + w_4 m) \quad (1)$$

where,
n_v is the number of vertices violating AZ,
v_i is the mean of the distances between T and the vertices violating AZ,
d_i is the distance from an i^{th} unit of the TZ structure to T,
m is the index of the unit u_m which is located the closest to T, in other words it is the effective length of the sequence of units – the part of the structure that is evaluated,
w_1, w_2, w_3, w_4 are the parametric weights.

In order to calibrate the weights $w_1 ... w_4$, a set of representative solutions was prepared as shown in Figure 7.

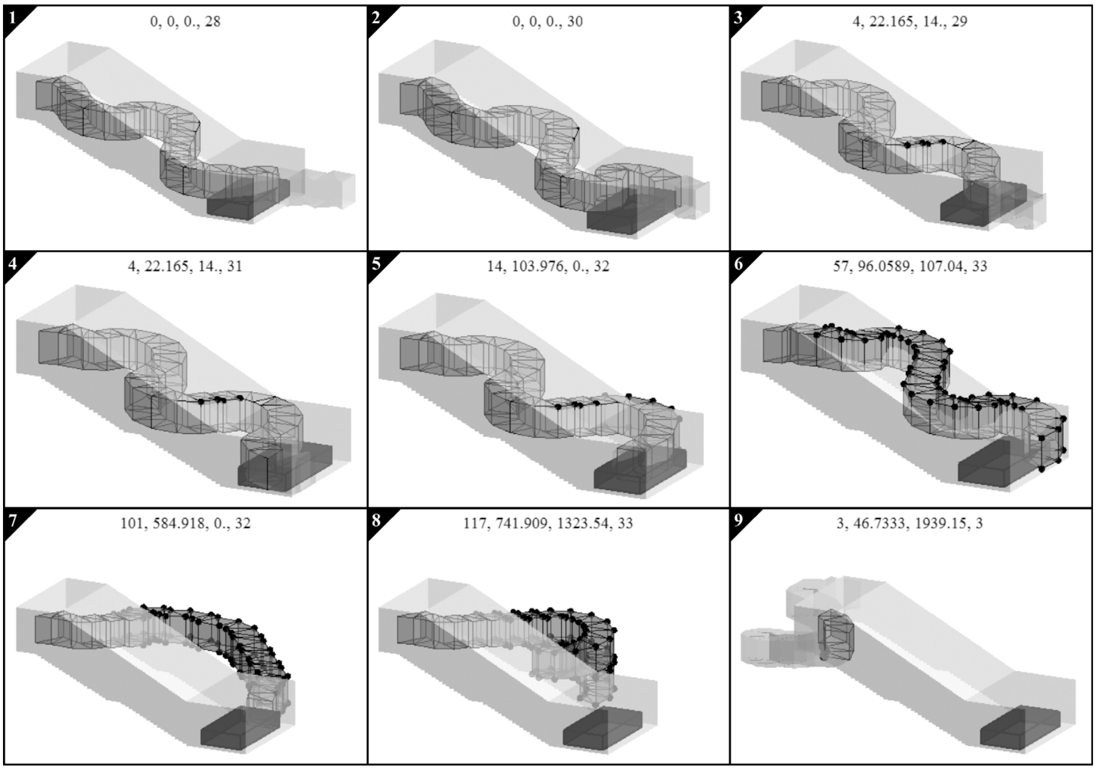

Figure 7: 9 solutions of decreasing quality from the best known (1) to a very dissatisfactory one (9). The sorting was done intuitively according to the number of constraint violations and the "general performance" of a solution. Four values above each solution indicate: the number of vertices violating AZ, the mean distance between T and the vertices violating AZ, the distance between T and the unit *m*, and the effective length of the structure. Modules beyond *m* are shown with lower opacity and without edges.

The weights $w_1 ... w_4$ were calibrated, so that CF grows monotonically for the examples from Figure 7. The values were assigned as follows: $w_1 = 1$, $w_2 = 0.2$, $w_3 = 0.6$, $w_4 = 1$.

4.3 Selection

Selection is the stage when parent solutions are chosen from a population for further breeding. The most common selection methods are the Tournament (TS) and Roulette (RS), also called fitness proportionate selection. TS is based on random selection of two candidates and choosing the better one for a parent. In RS, the parent solutions are randomly selected from the population with the probability proportional to the quality of a solution. The difference in selection pattern is visualized in Figure 8.

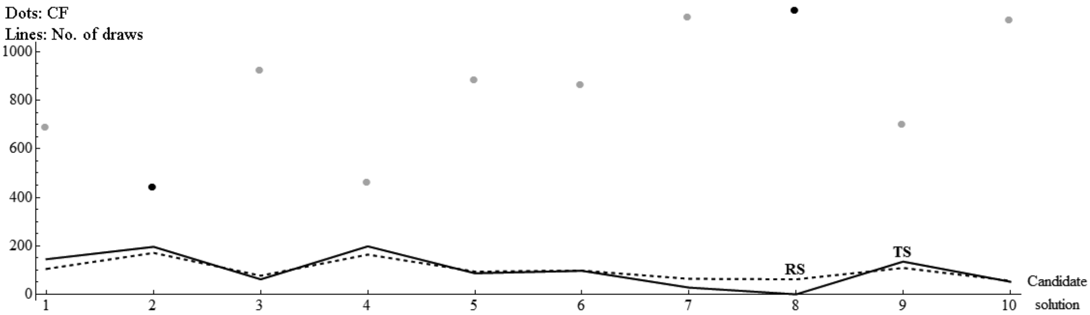

Figure 8: Randomly generated population of 10 solutions. CF for each one is shown with a dot. Black dots indicate the extreme values. 100 draws using RS and TS were performed. The probability of selection is more even in RS, where even the worst candidate has nonzero chance to be drawn – which is impossible with TS.

It cannot be generalized that one of the methods is always better than the other. The decision should be made for an individual problem.

4.4 Crossover

The core idea of EA is the assumption that the desired qualities of the individuals can be carried out and augmented by selective breeding throughout the reproduction process. The most commonly used methods are one-point (OPX) and uniform (UX) crossovers. With OPX a single crossover point on both parents' genotypes is selected. All data beyond that point in either one is swapped between the two parents. With UX, the genes of one parent at selected points of the genotype (called *loci*) are replaced with the genes at the same *loci* of the other parent. In this paper the number and positions of *loci* are random. As with selection method, the most suitable type of crossover depends on a specific problem.

4.5 Mutation

As crossover maintains the general direction of the improvement towards the optimal solution, the operation of mutation prevents the population from degenerating, which is excessive decrease of diversity of the individuals. In other words, it prevents the process from "getting stuck" in local optima. Mutation alters one or more gene values in a genotype from its initial state. In this case each gene can have one of four values {R,R2,L,L2}. Mutation rate is controlled by two parameters – m_P which controls the probability of the occurrence of a mutation, and mutation intensity (m_I) which determines the number of genes to be mutated. In general, the mutation rate should be relatively low. The fine tuning is usually done by experimentation.

4.6 The preliminary experiments

In order to set up the parameters for EA, a number of small experiments with the size of population 20 at 10 generations have been performed. The results are collected in Table 1.

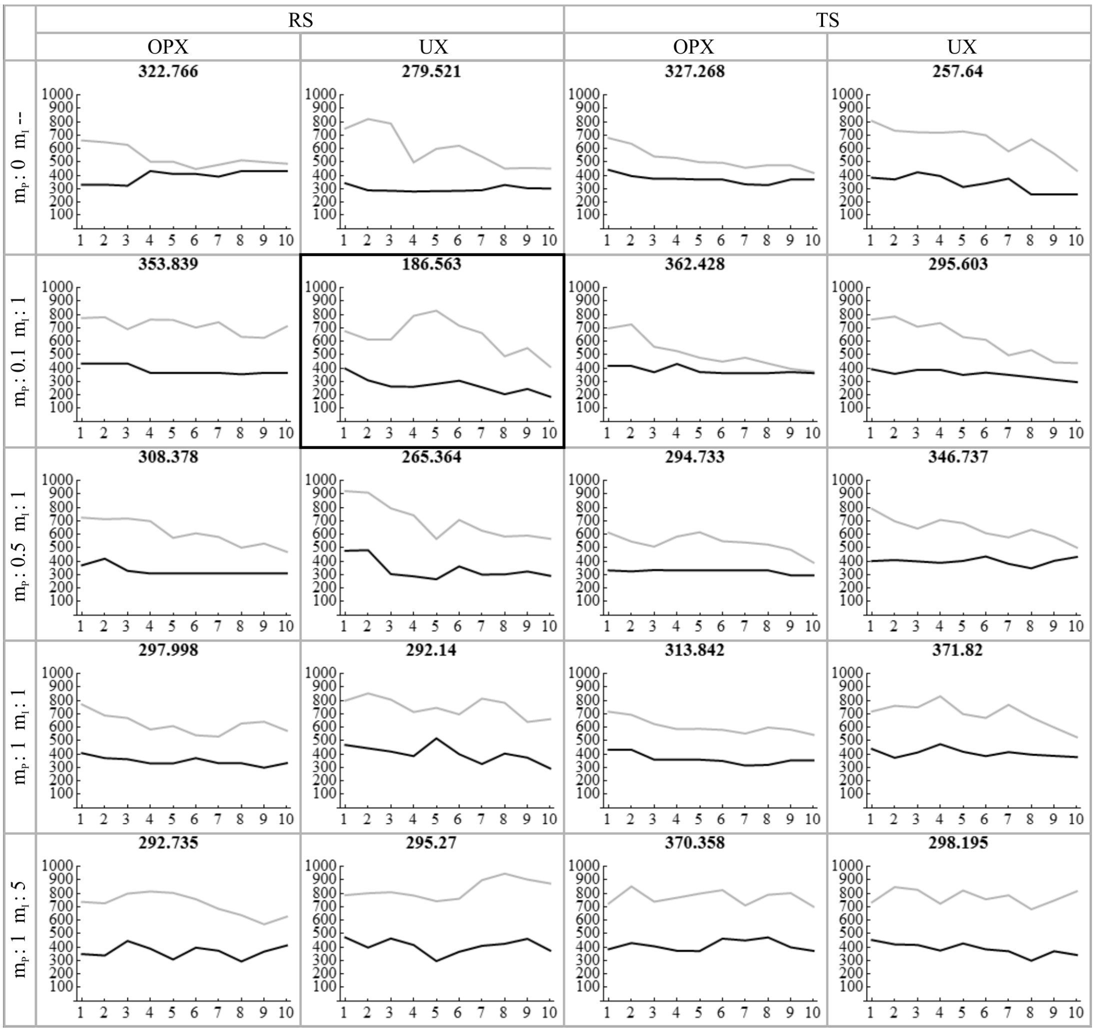

Table 1: Combinations of selections: RS and TS and crossovers: OPX and UX with various mutation parameters in a series of experiments. The minimal and mean CF values in each generation are shown in gray and black respectively. For each plot the minimal CF is shown. The experiment which produced the smallest value of CF (186.563) is framed in black.

4.7 The final experiment

As Table 1 indicates, the best results were produced with RS, UX with $m_P = 0.1$ and $m_I = 1$. A larger experiment, with population 1000 at 150 generations with the same settings was performed. It took 4.6 hours on an Intel core i7 PC. The results are shown in Figure 9.

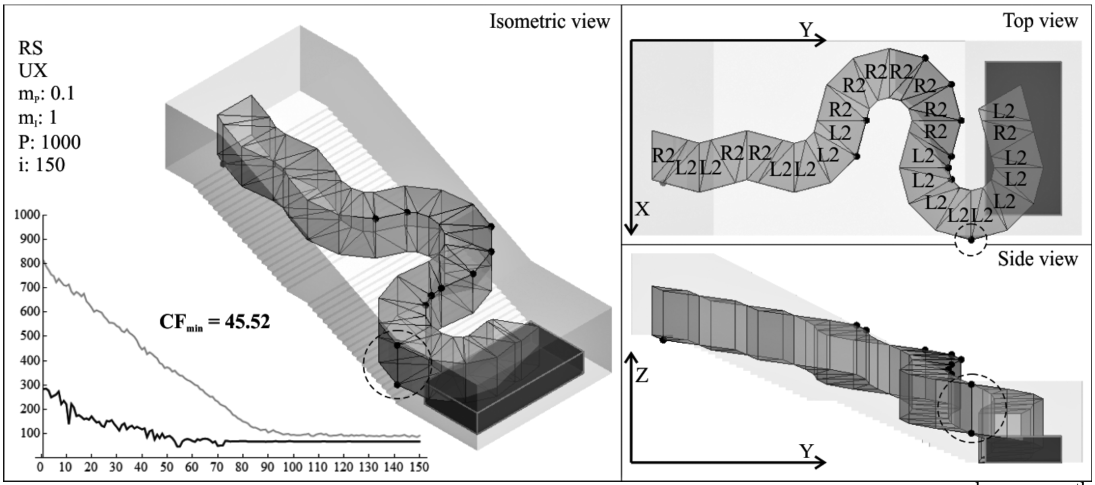

Figure 9: The best result of the final experiment appeared already in the 53rd and 54th generations. There are 12 vertices that violate AZ, however, two of them, marked with dashed circle, can be “fixed” by translation of the entire structure by -24 cm along X axis. This would reduce CF to 44.12.

5 Conclusions

Although the result produced by the EA is not allowable, since some of the vertices protrude out of the given spatial limitations, it can be considered quite good. Although, as Figure 9 indicates, the algorithm converges satisfactorily, the constraints seem to be too stringent for more effective application of stochastic-based algorithms. Backtracking, which is a variation of an intensive search method produced the best solution. However, if the position and direction of the initial unit was not arbitrarily set, the EA would most likely produce much more competitive results. This approach is presently under consideration.

Acknowledgments

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