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A Multi-Objective Evolutionary Algorithm for Optimization of Road Design Using A Random Key Genetic Algorithm

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Summary:

Multi-objective formulations are realistic models for many complex engineering optimization problems [1]. In a construction project, there are two main factors, such as project duration and project cost. The activity duration is a function of resources (i.e. crew size, equipments and materials) availability. On the other hand, resources demand direct costs. Therefore, the relationship between project time and direct cost of each activity is a monotonously decreasing curve. It means if activity duration is compressed then that leads to an increase in resources and so that direct costs. But, project indirect costs increase with the project duration. In general, for a project, the total cost is the sum of direct and indirect costs and exists an optimum duration for the least cost. Hence, relationship between project time and cost is trade-off [2].

There are two general approaches to multiple-objective optimization. One is to combine the individual objective functions into a single composite function. Determination of a single objective is possible with methods such as utility theory, weighted sum method, etc., but the problem lies in the correct selection of the weights or utility functions to characterize the decision-makers preferences [1].

The main difficulty with the single composite function is selecting a weight vector for each run. To overcome this drawback a GA based-approach to solving the time-cost optimization problem has been proposed. The idea is changing weights in the objective function by genes obtained from the genetic algorithm for each run.

The present approach provides a powerful alternative for the solution of the time-cost construction project scheduling problems when compared against others approaches including evolutionary algorithms.

In this paper is presented a multi-objective evolutionary algorithm (an area called multi-criteria of decision making [2]) using a random key genetic algorithm for optimization of

road design. An application to road design alternatives describing genetic algorithms developed specifically for these problems using multiple objectives is described. They differ from traditional genetic algorithms by using specialized fitness functions, introducing methods to promote solution diversity.

1 INTRODUCTION AND BACKGROUND

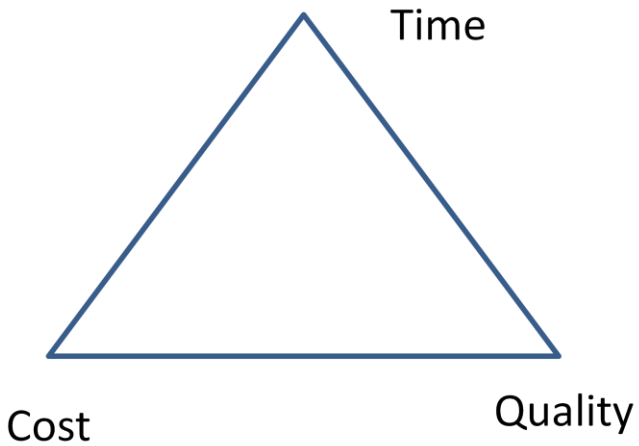
1.1 Project Management

According to the Project Management Institute, the discipline of project management can be defined as follows:

Project management is the art of directing and coordinating human and material resources throughout the life of a project by using modern management techniques to achieve predetermined objectives of scope, cost, time, and quality and participation satisfaction [42].

1.2 The Magic Triangle of Project Management

This project management model is also called Triple Constraint or the Iron Triangle. It helps to illustrate that no project related constraint is independent of the others. If one constraint is being changed, for whatever reason, it naturally impacts the other constraints and leads to changes in them as well.



The constraints are project time, cost and quality, each represented be one side or corner of the triangle.

- Time Constraint – refers to the amount of time available to complete the project
- Cost Constraint – refers to the budget allocated to the project
- Quality Constraint – refers to what must be done to achieve successful project delivery

As the constraints are usually competing, one side of the triangle cannot be changed without automatically affecting the other three sides.

Project management triangle is the expression of the three basic parameters which measure the success of the project that is the time, the project budget and the quality of project outputs.

Figure 1: Magic Triangle of Project Management [6].

1.3 Project Manager

Project Manager must ensure the integrity of that triangle and brings in practice usually various complications and it also relates to those best planned. In practice, then breach occurs in one of those parameters. The most commonly occurring is a project schedule delay (time), the cost overruns (project budget), is sometimes in an effort to adhere these two qualities deteriorates project outcomes. Each of these situations is bad for the customer: late-supplied result of the project, although it is good quality and original price can cause the same problems as poor quality output despite the fact that it is delivered on time.

1.4 Construction Management

Construction management is the process of planning, coordinating and providing monitoring and controlling of a construction project. This style of project management is designed for the, as the name implies, construction industry. There are few types of construction that use construction management; they are industrial, civil, commercial, environmental and residential. Each category has its own way of running projects, but all will follow the construction management methodology.

Construction management has five stages, where project management has five phases. The stages are design, pre-construction, procurement, build, and owner occupancy.

The time and cost are usually two objectives which are often tradeoff in project practices. When the construction time is shortened, the project cost should be added. The main objective of construction project management is to execute the project within the anticipated time while satisfying the minimum cost.

Several approaches to solve the time-cost optimization (TCO) problem have been proposed in the last years: mathematical, heuristic and search methods.

Several mathematical models such as linear programming (Hendrickson and Au [5]; Pagnoni [3]), integer programming, or dynamic programming (Robinson [8]; P. De et al. [23]) and LP/IP hybrid (Liu et al. [20]; Burns et al. [25]) and Meyer and Shaffer [27] use mixed integer programming. However, for large number of activity in network and complex problem, integer programming needs a lot of computation effort (Feng et al. [6]).

Heuristic algorithms are not considered to be in the category of optimization methods. They are algorithms developed to find an acceptable near optimum solution. Heuristic methods are usually algorithms easy to understand which can be applied to larger problems and typically provide acceptable solutions (Hegazy [26]). However, they have lack mathematical consistency and accuracy and are specific to certain instances of the problem (Fondahl [19]; Siemens [22]) are some of the research studies that have utilized heuristic methods for solving TCO problems.

Some researchers have tried to introduce evolutionary algorithms to find global optima such as genetic algorithm (GA) (Feng et al. [6]; Gen and Cheng [21]; Zheng et al. [10]; Zheng and Ng [9]; Mendes [16, 18] and Parveen and Saha [32]) the particle swarm optimization algorithm (Yang [10]), ant colony optimization (ACO) (Xiong and Kuang [28]; Ng and Zhang

[24]; Afshar et al. [2]) and harmony search (HS) (Geem [29]). In this paper, the optimal time and cost generated by the GA techniques are compared with those produced by other techniques through some problems obtained from literature.

This paper is organized as follows. Section 2 describes the multi-objective optimization problem. Section 3 presents the approach. The case study and results are presented in Section 4. Finally, conclusions and future work are outlined in Section 5.

2 MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization deals with solving optimization problems which involve multiple objectives. We can say that there are two types of methods for solving problems with multi-objective optimization: the classical methods and methods based on evolutionary algorithms.

The disadvantages of the classical methods are shown in [31]:

- Only one non-dominated solution is obtained by each execution of the algorithm. It means that in order to get a set of solutions; it should be run many times.
- Some of them require some kind of information of the problem treated.
- Some of them are sensitive to the shape of the Pareto frontier, so in non-convex ones, they cannot find solutions.
- The dispersion of the founded Pareto solutions depends on the efficiency of the monocriteria optimizator.
- In problems that contain stochasticity, classical methods are not appropriate.
- Problems with discrete domain cannot be solved by classical methods, neither in the multi-objective case. Consequently, the problem treated in the present article, discrete, could not be solved by this kind of methods.

All this disadvantages are overcome with evolutionary multi-objective methods such as genetic algorithms (MOEA) [30].

With evolutionary algorithms being used for single-objective optimization for over two decades, the incorporation of more than one objective in the fitness function has finally gained popularity in the research [33].

The approach presented in this paper is based on a random key based genetic algorithm to perform its optimization process, so this approach aims to stipulate multiple search directions at each generation without using any additional parameters.

2.1 Linear Combination of Weights

The classical approach to solve a multi-objective optimization problem is to assign a weight w_i to each normalized objective function $z_i^{'}(x)$ so that the problem is converted to a single objective problem with a scalar objective function as follows [35]:

$$\min z = w_1 * z_1^{'}(x) + w_2 * z_2^{'}(x) + ... + w_n * z_n^{'}(x) \quad (1)$$

where $z_i^{'}(x)$ is the normalized objective function of $z_i(x)$ and $\Sigma w_i = 1$. The main difficulty with this approach is selecting a weight vector for each run.

2.2 Linear Combination of Genes

Linear Combination of Weights also called the weighted sum method (WSM) is the simplest approach and probably the most widely used classical method. This method scalarizes the set of objectives into a single objective by multiplying each objective with a user supplied weight.

Based on the WSM idea, this paper proposes an application of linear combination of genes where $z_i^{'}(x)$ is the normalized objective function of $z_i\ (x)$, with the following formulation:

$$\min z = gene_1 * z_1^{'}(x) + gene_2 * z_2^{'}(x) + ... + gene_n * z_n^{'}(x) \tag{2}$$

where $z_i^{'}(x)$ is the normalized objective function of $z_i\ (x)$ and $0 < \sum gene_i < n,$ each $gene_i$ is randomly generated for individual solution ***x*** during the selection phase at each generation.

3 THE GA-BASED APPROACH - MOEA

The algorithm used in our study is based on a idea of a multi-objective evolutionary algorithm (MOEA) [37], which starts with a set of random solutions known as the initial population. Each individual (chromosome) in the population represents a solution to the optimization problem. In each generation, individuals are evaluated with a fitness function (fitness). Based on this value, certain individuals (parents) are selected. The probability of selecting an individual is related to its adaptability, which means that there is a greater probability of selecting the best individuals. Then, a number of genetic operators are applied to the parents to produce new individuals that will be part of the new population. This process continues in an effort to obtain increasingly better solutions until a stopping criterion is satisfied.

The objective of this paper is to present the development of an advanced multi-objective optimization model that supports minimizing construction time and cost, while maximizing its quality.

In many real-life problems [1], objectives under consideration conflict with each other, and optimizing a particular solution with respect to a single objective can result in unacceptable results with respect to the other objectives. A reasonable solution to a multi-objective problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution.

For each chromosome the following main phases are applied:

1) Generation of parameters by genetic algorithm;
2) Schedule parameters allocation - this phase is responsible for allocation of the chromosome parameters supplied by the genetic algorithm into the priorities of the activities and delay time;
3) Schedule generation Schemes - this phase makes use of the priorities, delay time and constructs schedules[40];

This study considers both project total cost and time. For effective time-cost optimization the approach proposes an objective function with the following formulation:

$$Z_1^{'} = Z_{time}^{'} = \frac{(Z_t^{\max} - Z_t)}{(Z_t^{\max} - Z_t^{\min})} \tag{3}$$

$$Z_2^{'} = Z_{cost}^{'} = \frac{(Z_c^{\max} - Z_c)}{(Z_c^{\max} - Z_c^{\min})} \tag{4}$$

and finally:

$$\min f(x) = Gene_t \frac{(Z_t^{\max} - Z_t)}{(Z_t^{\max} - Z_t^{\min})} + Gene_c \frac{(Z_c^{\max} - Z_c)}{(Z_c^{\max} - Z_c^{\min})} \tag{5}$$

where,

$Z_c^{\max}$ = maximal value for total cost in the current chromosome;
$Z_t^{\max}$ = maximal value for time in the current chromosome;
$Z_c^{\min}$ = minimal value for total cost in the initial population;
$Z_t^{\min}$ = minimal value for time in the initial population;
Z_c = represents the total cost of the x^{th} solution in current chromosome;
Z_t = represents the time of the x^{th} solution in current chromosome.

3.1 GA-Decoding

Each chromosome represents a solution to the problem and it is encoded as a vector of random keys (random numbers). Each solution encoded as initial chromosome (first level) is made of 2+*mn*+*n* genes where *n* is the number of activities and *m* is the number of execution modes, see Figure 2 [16, 18].

Genes for Activity 1	Activity 1	Mode 1	$Gene_{11}$
		Mode 2	$Gene_{12}$
		...	...
		Mode m	$Gene_{1m}$
		Delay 1	$Gene_{1m+1}$
Genes for Activity 2	Activity 2	Mode 1	$Gene_{21}$
		Mode 2	$Gene_{22}$
		...	...
		Mode m	$Gene_{2m}$
		Delay 2	$Gene_{2m+1}$
....	...		...
Genes for Activity n	Activity n	Mode 1	$Gene_{n1}$
		Mode 2	$Gene_{n2}$
		...	...
		Mode m	$Gene_{nm}$
		Delay n	$Gene_{nm+1}$
Genes for Objective Function	OF	Time	$Gene_t$
		Cost	$Gene_c$

Figure 2: Chromosome structure.

To decode each chromosome a schedule generation scheme (SGS) based on the idea of parameterized active schedules is applied [11, 14, 16]. This type of schedule consists of schedules in which no resource is kept idle for more than a predefined period if it could start processing some activity [16] and employs operators described in [15, 16].

3.2 Evolutionary Strategy

The GA based-approach uses an evolutionary strategy identical to the one proposed by Goldberg [7]. To breed good solutions, the population is operated by a genetic algorithm.

There are many variations of genetic algorithms obtained by altering the reproduction, crossover, and mutation operators.

In this approach reproduction is accomplished by first copying some of the best individuals from one generation to the next, in what is called an elitist strategy.

The fitness proportionate selection, also known as roulette-wheel selection, is the genetic operator for selecting potentially useful solutions for reproduction. The characteristic of the roulette wheel selection is stochastic sampling.

The fitness value is used to associate a probability of selection with each individual chromosome. If f_i is the fitness of individual i in the population, its probability of being selected is,

$$p_i = \frac{f_i}{\sum_{i=1}^{N} f_i} \quad , \qquad i = 1, \ldots, n \tag{6}$$

A roulette wheel model is established to represent the survival probabilities for all the individuals in the population. Then the roulette wheel is rotated for several times.

After selecting, crossover may proceed in two steps. First, members of the newly selected (reproduced) chromosomes in the mating pool are mated at random. Second, each pair of chromosomes undergoes crossover as follows: an integer position k along the chromosome is selected uniformly at random between *1* and the chromosome length l. Two new chromosomes are created swapping all the genes between k+1 and l, see Mendes [17].

The mutation operator preserves diversification in the search. This genetic operator is applied to each offspring in the population with a predetermined probability. We assume that the probability of the mutation in this paper is 0.1% [17].

4 CASE STUDY

The case study is the road construction project for the "Strada Provinciale n°4 - Galliera (SP4)" in ITALY. It includes the construction of a new axis road that bypasses the towns of Castel Maggiore and Funo. The project essentially consists of a main axis at ground level, with some underpasses/overpass. The focus was only on the construction of the Main Axis [35].

In this study two objective functions are studied: the first with cost and duration and the second includes the quality constraint.

$$\text{GA1-OBJECTIVE} \quad \textit{Minimize} \;\; C = \sum_{i=1}^{n} C(i) + C_i \times T_a - k \times (T_t - T_a) \tag{7}$$

where,

C = project total cost;
$C(\mathrm{i})$ = actual direct cost of activity i;
C_i = project daily indirect cost 1500 €;
T_t = project target duration 355;
T_a = project actual duration;
k_i = incentive ratio when (Tt - Ta) > 0 1000 € /day;
k_p = 5* 10^7 €/daily penalty ratio when (T_t - T_a) < 0;

4.1 Time- Cost-Quality Original project

ACTIVITIES	OPTIONS	COST	TIME	Ai	Qi
1. Construction excavation	1	€ 132.740	38	0,5	94%
	2	€ 139.013	29		96%
	3	€ 140.345	23		98%
2. Enbankment	1	€ 18.344	3	12	93%
	2	€ 18.566	2		94%
	3	€ 18.618	1		96%
3. Geotextile	1	€ 9.235	6	9,5	93%
	2	€ 10.238	5		93%
	3	€ 10.420	4		95%
4. Enbankment: recycling soil	1	€ 372.093	59	14	94%
	2	€ 375.735	47		95%
	3	€ 377.397	38		96%
5. Enbankment: cement/lime soil	1	€ 1.247.091	193	14	93%
	2	€ 1.259.298	154		94%
	3	€ 1.264.870	122		96%
6. Road fondation: cement stabilized soil	1	€ 386.245	20	10	82%
	2	€ 386.866	18		84%
	3	€ 387.378	14		85%
7.Road fondation: crushed concrete	1	€ 286.375	13	10	88%
	2	€ 287.144	11		89%
	3	€ 287.494	9		89%
8. Tout Venant	1	€ 5.066.702	45	10	54%
	2	€ 5.072.297	38		55%
	3	€ 5.077.093	31		57%
9. Protection layer: Sami	1	€ 153.725	7	9	82%
	2	€ 154.503	6		83%
	3	€ 155.169	5		85%
10. Wearing course	1	€ 1.065.325	32	11	64%
	2	€ 1.068.000	26		65%
	3	€ 1.071.272	21		68%

Table 1. Detailed data of the original project.

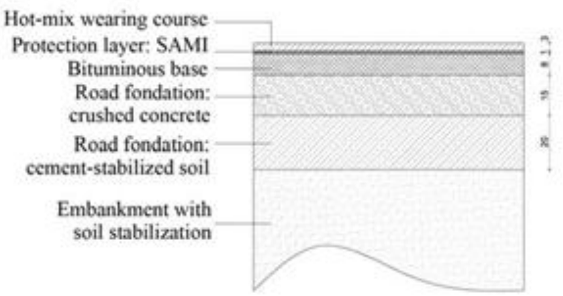


Figure 2: Structural original project

The original project and the variant have various activities. Each activity has several construction modes, which reflect different ways of performing the activity, each mode having a different impact on the duration and total cost of the project. The present approach provides an attractive alternative for the solution of the construction multi-objective optimization problems. The developments made in this paper provide guidelines for designing and implementing practical GA applications in the civil engineering domain and gives to construction managers a tool to balance critical construction resources in the competitive construction industry and is codified as

GA1-OBJECTIVE $$C = \sum_{i=1}^{n} C(i) + C_i \times T_a - k \times (T_t - T_a) \qquad (7)$$

4.2 Time- Cost-Quality Variant project

where,

C = project total cost;
C(i) = actual direct cost of activity i;
C_i = project daily indirect cost 1500 €;
T_t = project target duration 355;
T_a = project actual duration;
k_i = incentive ratio when (Tt - Ta) > 0 1000 € /day;
k_p = 5* 10^7 €/daily penalty ratio when (T_t - T_a) < 0;

Let´s consider also the third constraint of the magic triangle the quality introduced in a global model. The idea is to minimize time and cost while maximizing its quality. The objective function used is:

4.3 Time- Cost-Quality Original project

GA2-OBJECTIVE

$$Minimize\ \ C = \sum_{i=1}^{n} C(i) + C_i \times T_a - k \times (T_t - T_a) \qquad (7)$$

$$Maximize\ \ Q = \sum_{i=1}^{n} A_i \times Q_i \qquad (2)$$

4.4 Time- Cost-Quality Variant project

GA2-OBJECTIVE

$$Minimize\ \ C = \sum_{i=1}^{n} C(i) + C_i \times T_a - k \times (T_t - T_a) \qquad (7)$$

$$Maximize\ \ Q = \sum_{i=1}^{n} A_i \times Q_i \qquad (8)$$

Q_i = quality performance for the activity options;

A_i = The weight of activity within the overall project;

OPTIONS	COST (€)	TIME	Ai	Qi (%)
1	132.740	38	0,5	96%
2	139.013	29	0,5	96%
3	140.345	23	0,5	98%
1	18.344	3	12	93%
2	18.566	2	12	93%
3	18.618	1	12	95%
1	9.235	6	9,5	94%
2	10.238	5	9,5	95%
3	10.420	4	9,5	96%
1	372.093	59	14	93%
2	375.735	47	14	94%
3	377.397	38	14	96%
1	1.247.091	193	14	87%
2	1.264.870	154	14	88%
3	477.291	122	14	89%
1	478.573	21	12	94%
2	479.157	17	12	95%
3	443.741	14	12	96%
1	445.268	13	12	96%
2	446.268	11	12	97%
3	446.577	9	12	99%
1	9.145.926	56	13	96%
2	9.152.919	47	13	97%
3	9.251.722	38	13	99%
1	1.148.643	32	13	97%
2	1.151.319	26	13	98%
3	1.154.591	21	13	99%

Table 2. Detailed data of the variant project.

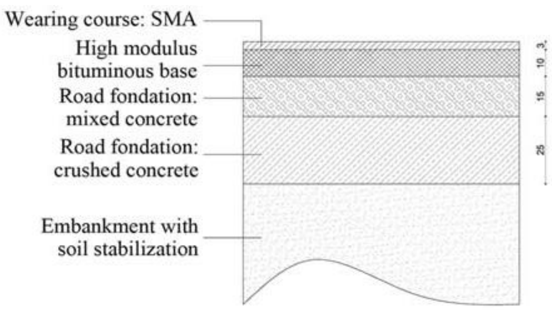


Figure 3: Structural variant project

An improved alternative structural (called variant project with nine activities) was proposed by Professor A. Simone (see Figure 1 and Figure 2).

Table 2 shows the new values for time-cost-quality).

The time necessary by RKTCO to obtain the optimal solution is highly promising and shows that a good implementation can be critical to the success of the genetic algorithms.

This computational experience has been performed on a computer with an Intel Core 2 Duo CPU T7250 @2.33 GHz and 1,95 GB of RAM. The algorithm proposed in this work has been coded in VBA under Microsoft Windows NT.

5 RESULTS

Table 3 and 4 shows the results of the present approach and other methods [35, 36] for GA1-Objective.

Table 5 shows the results of the present approach and other methods [35] using MathLabR for GA2 - objective.

Direct comparison shows that RK-TCQ provided the best time, cost and quality.

Figure 4 shows the cost evolution with generation number.

Additionally we can also state that the RK-TCQ approach produces high-quality solutions quickly once needed only 2 seconds to complete 20 generations.

Table 3: Comparison of approaches for GA1-Objective – original project

Author	TEST	Generation Number	Cost	Time
J. Magalhães-Mendes	1	20	9,105,056	268
M. Sorrentino	4	100	**9,133,790**	269

Table 4: Comparison of approaches for GA1-Objective – variant project

Author	TEST	Generation Number	Cost	Time	Quality
J. Magalhães-Mendes	1	20	9,105,056	279	86.140%
M. Sorrentino	4	100	**9,133,790**	280	86.125%

Table 5: Comparison of approaches for GA2-Objective – variant project

Author	TEST	Generation Number	Cost	Quality	Time
J. Magalhães-Mendes	1	1	13.494.414,00 €	94,778	331
		2	13.494.414,00 €	94,778	331
		3	13.464.519,00 €	95,000	316
		4	13.401.816,00 €	95,333	286
		6	13.401.816,00 €	95,333	286
		7	13.401.816,00 €	95,333	286
		8	13.394.900,00 €	95,444	283
		9	13.394.900,00 €	95,444	283
		10	13.391.085,00 €	95,667	281
		11	13.391.085,00 €	95,667	281
		12	13.395.811,00 €	95,333	283
		13	13.395.811,00 €	95,333	283
		14	13.391.085,00 €	95,667	281
		15	**13.387.394,00 €**	**95,778**	**279**
		17	13.387.394,00 €	95,778	279
		18	13.387.394,00 €	95,778	279
		19	13.387.394,00 €	95,778	279
M. Sorrentino	4	-	**13.389.712,00 €**	95,405	281,73
			13.484.281,00 €	**95,725**	279,92
			13.394.310,00 €	95,475	283,52
			13.479.683,00 €	95,655	**278,13**
			13.401.062,00 €	95,585	285,92

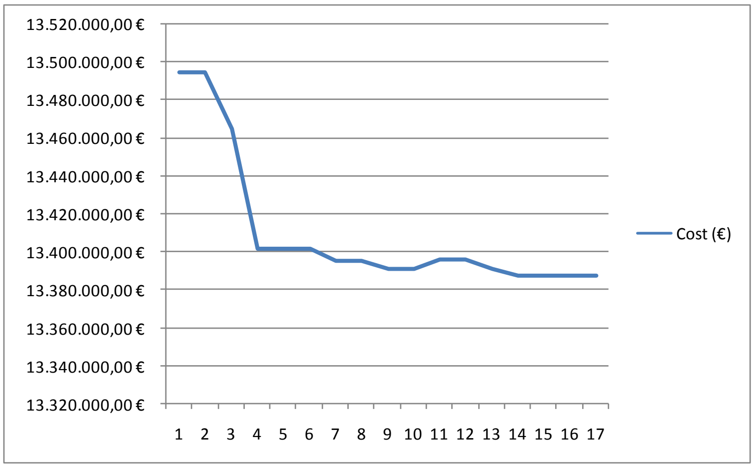


Figure 4: Cost (€) vs generation number for GA2-Objective - variant project

6 CONCLUSIONS AND FURTHER RESEARCH

A new GA based-approach to solving the time-cost optimization for construction projects has been proposed. The project activities have various construction modes, which reflect different ways of performing the activity, each mode having a different impact on the duration and cost of the project. The present approach provides an attractive alternative for the solution of the construction multi-objective optimization problems. The developments made in this paper provide guidelines for designing and implementing practical GA applications in the civil engineering domain and gives to construction managers a tool to balance critical construction resources in the competitive construction industry.

Further research can be extended to others multi-objective problems with relationships between cost, time and quality in the construction industry.

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