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Using Genetic Algorithms for Optimizing and Modelling Time, Cost and Quality Trade Offs of Construction Projects

KEYWORDS: Construction, Project Management, Genetic Algorithm, project planning, time-cost-quality trade-off.

The well-known "iron triangle" and its attributes, time, cost and quality has still importance as a framework of basic objectives of construction projects. In practice, construction project managers can optimise time and costs with the well-known time/cost trade-off approach, but quality optimization versus cost and time performances in construction project is usually pursued in a rather intuitive manner based upon Project Manager's experience. The research behind this paper is proposing a specific approach where three possible estimates for time, cost and quality form starting points for the optimisation of project performance. The estimates are based on characteristic of alternative technical solutions such as possible commercial products to be used or assembled. The effectiveness of various combinations is evaluated with an optimisation procedure based upon Genetic Algorithms. A simple pilot study of a renovation project of two residential apartment is presented to test the proposed approach. The gained results are demonstrating the possibilities of genetic algorithms for such trade off analyses.

INTRODUCTION

Quality in construction projects is of prime importance for the final client. Time and cost are other main points of interest, but the desired quality of an important construction project can be an outstanding result to achieve. Project Manager's objectives are often described as the "Iron Triangle" (Atkinson, 1999), meaning time, cost and quality or project scope. Generally speaking, quality can be defined as the fitness for purpose, while more stringent definition is the degree of conformance of the outputs and process (APM, 2015) and the level of accomplishment of a product or a process to a set of performance requirements (ISO 9000:2005). ISO standards define quality as the degree to which a set of inherent characteristics fulfill requirements. Quality assessment in construction can be divided into three main components: quality of products, quality of design and quality of processes. Quality of products can be understood primarily as a technical quality whereas quality of design is about meeting the needs of client and end users successfully.

The quality of processes refers all activities throughout the life-cycle of building construction project (Bragadin, Kahkonen, 2013).

Traditional project control techniques are built around time and cost, where estimates of costs and durations of work packages and finally over the total project are forming the control baseline. The integrated project control of time and costs generally is addressed with the Earned Value Method (Moder et alii, 1983, Rasdorf and Abudayyeh, 1991, ANSI/EIA, 1998). Time-cost trade-off is a well known method of project management (Fondhal, 1962; Harris, 1978; Moder et alii, 1983; Reda, Carr, 1989; Fan, Lin 2007, Agdas et alii, 2018) that aims at optimising project results in terms of cost and timing, mainly by evaluating the ratio between the differences of crash cost and normal / minimum cost and crash duration and normal duration of activities on a critical path.

Nevertheless, few optimisation approaches that entails also quality can be found in literature (Minchin, Smith, 2001; El-Rayes, Kandil, 2005, 2006; San Cristobal, 2009; Monghasemi, Nikoo, Fasaee, Adamowski, 2015). Project quality is surely interdependent with time and costs, but a general mathematical equation that links the three KPIs can be difficult to find, or at least, can be different changing from case to case. Project Managers, actually, optimise quality versus costs and time with a rather intuitive manner.

Framing the quality and integration of the quality aspect with the time and cost aspects have been long-term topics of interest both to the industry and academia. The quality of construction is closely relating to the value and performance concepts. Solutions such as value engineering and management, Quality Management Systems (QMS) together with key performance indicators (KPI) represent solutions in practice that are framing quality and providing some linkage to time and cost. Modelling of interplay between time, cost and quality has been a long term arena of interest particularly for academia.

Quality assessment in management of construction projects can be successfully delivered with quality based KPIs (Minchin, Smith 2001; El-Rayes, Kandil, 2005, 2006), and the objective of the presented research work is to propose Genetic Algorithms to purse time-cost-quality trade-offs in construction projects.

PREVIOUS WORK

Few researchers focused the problem of the evaluation of the global quality of a project or a system by means of a quality indicator, and the development of a time-cost-quality trade-off procedure. Atkinson (1999) introduced the concept of the project manager's iron triangle, meaning the need of integrating time, cost and scope, or quality project objectives. The integration of cost, schedule and performance data was addressed by Cho, Russell and Choi (2013) building on the traditional Work Breakdown framework.

In the field of Information Technologies Mishra and Mahanty (2014) indicate that the optimisation of project cost, schedule and quality for a software development project in an outsourcing environment, can be studied with a system dynamics simulation approach.

El Rayes and Kandil (2005, 2006) presented a method aimed at facilitating the measurement and quantification of the global construction quality by estimating quality performances of each project activity thorough the definition of a Quality Index. The method was applied in the field of highway construction. The definition of a quality KPI, termed Quality index, is achieved by the creation of a Quality Breakdown Structure (QBS) of the project. The Construction Quality Index (CQI) is a rating of quality of materials and workmanship on highway projects completely objective (Minchin, Hammons and Ahn, 2008).

The QBS developed approach builds on the "Quality – Based Performance Rating System" of the American National Cooperative Highway Research Program (NCHRP) (Anderson and Russel 2001, Minchin and Smith 2001) for contractors' qualification. QBS aims at evaluating the final quality of the products of the construction process, with a performance-based approach. Therefore, a set of quality indicators are detected to evaluate the final product quality.

An automated optimisation system for construction resources termed MACROS, was developed (El Rayes and Kandil, 2005, 2006), and the time, cost and quality trade-off algorithm is developed by Genetic Algorithms.

The use of Genetic Algorithms (GAs) was introduced by J. H. Holland (1975) as a research method based on the mechanics of natural selection and natural genetic of Darwin's Evolutionary Theory. Later, Goldberg (1989) developed further the GAs approach in the field of automation engineering. GAs have been implemented in many engineering and operations research problems, for instance the Travelling Salesman Problem (Razali, Geraghty, 2011).

San Cristobal (2009) proposed an Integer Programming model which enables meeting quality output standards and time and cost objectives respectively, while Monghasemi et alii (2015) propose a

Multi-criterion decision-making approach that identifies all global Pareto optimal solutions by a multi-objective Genetic Algorithm. Sorrentino (2013) applies GAs to a time, cost and quality optimisation problem for project scheduling of road construction and finally Tiene (2017) investigated a similar application for the selection of design alternatives for a building envelope.

GENETIC ALGORITHMS FOR TIME, COST AND QUALITY TRADE-OFF

Owners and Government agencies have placed an increasing pressure on decision makers in the construction industry to design and plan new construction projects minimizing construction costs and time while maximizing its quality (San Cristobal, 2009). A custom Genetic Algorithm (GA) is developed and used to solve the time- cost and quality trade-off problem.

Genetic Algorithms (GAs) are a global and stochastic research method termed "genetic" because of the mutual terminology from genetics, a branch of biology. Genetic algorithms are probabilistic search procedures designed to work on large spaces involving states that can be represented by mathematical strings (Goldberg & Holland, 1988). Genetic algorithms can be used with the aim of planning and controlling the activities of a project as they are search and optimization tools that assist decision makers in identifying optimal or near-optimal solutions for problems with large search space.

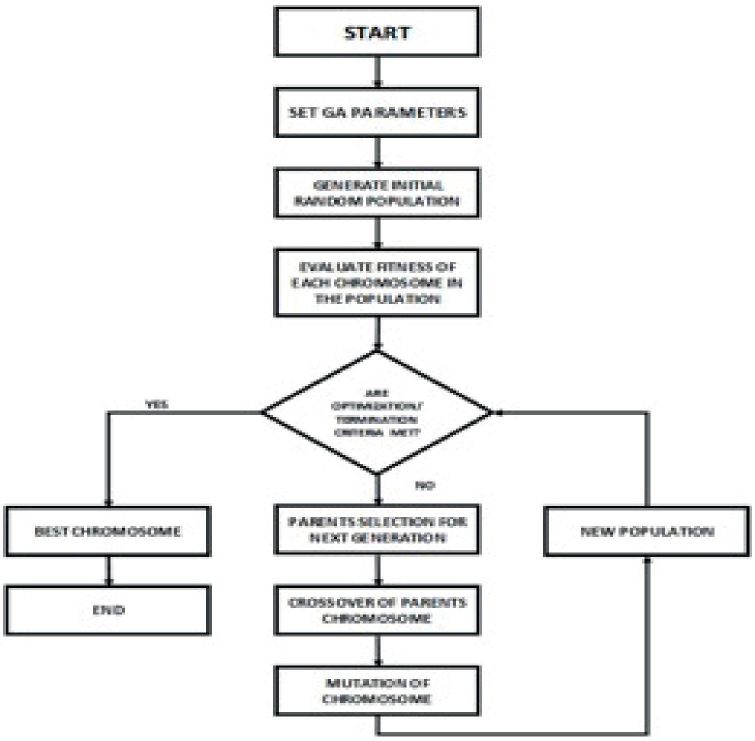
One fundamental advantages of GAs from traditional methods is that they work from a rich database of solutions simultaneously (a population of chromosomes), climbing many peaks in parallel, thus the probability of finding a false peak is reduced over methods that go solution to solution, like the "brute-force" method. The basic structure of a genetic algorithm involves cyclic operation that simulates the evolutionary process of a population. Each loop represents one generation and each new population generated is formed by better and better individuals. Five phases are considered in a Genetic Algorithm: initial population; fitness function; selection; mating (crossover / mutation); termination.

A typical genetic algorithm starts generating randomly an initial population of possible solutions, called individuals. Every individual in the population (or whatever solution is desired) is coded in the form of a string, called the Chromosome. Each member of the current population is assessed by calculating its fitness value by the objective function (fitness), and an appropriate sorting of these individuals is determined on the basis of the fitness values: The most promising individuals are selected as parents, creating a sequence of new populations or generations.

After selecting an n number of individuals, the genetic algorithm emulates the sexual reproduction that occurs naturally in biology and re-combines the genetic material of the parents, giving birth to the children or to the future generation of solutions. The re-combination is carried out by genetic operators of Cross Over (by appropriately combining the characteristics of a couple of parents) and Mutation (by making random changes on a single parent). The new generation of solutions takes the place of the previous generation, from which it was born for re-combination. The process is repeated a great number of times until one of the stop requirements is fulfilled (termination), for example when an acceptable approximation of the solution to the problem is reached, or the maximum number of iterations has been performed.

In figure n. 1 a flow chart summarizes the operating principles of GAs. The GA approach is set on a population that generates a set of possible solutions. Subpopulations are possible, and subpopulation structures termed species can be defined with different approaches.

Genetic algorithms do not ensure that an optimal solution is found but contribute to a set of solutions superior to the source solutions. From the same problem and from the same set of possible starting individuals at each new population



generation the individuals evolve towards different and better new solutions. Because of this the GAs are used in the study of artificial intelligence. In many situations, there are more than one relevant goal to minimize (or maximize), in this case a multi-objective genetic algorithm is defined. A multi-objective GA pursues multiple objectives simultaneously, in the sense that an individual is considered more or less suitable in relation to multiple criteria. In this case the problem to be addressed is not simply reduced to the search for a local (or global) maximum or a minimum for a given function, but to the analysis of multiple criteria at the same time. In this kind of problems the various objectives are often conflicting, meaning that a solution that minimizes or maximizes an objective will generally not minimize or maximizes others. In a multi-objective optimization problem, there is a need to find a solution that is optimal at the same time for all objective functions that describe the problem.

GA MODEL IMPLEMENTATION: PROPOSED APPROACH

The GAs implementation is based upon a table that reports the needed data for genetic algorithm implementation. A table summarizes for each project activity the alternatives related to activity duration, activity cost and quality (table 1).

Therefore, each project activity includes three possible options for its development that creates a search space of thousands of possible solutions. GA – based algorithm has been implemented with Matlab®. This application is able to explore the solution space very quickly and can identify a set of optimal solutions. The pilot study has 21 work packages (WP), and each has three possible alternative of time, cost and quality to create project activities. The possible combinations of these alternatives create a large space of search, where each solution in this space can be a possible option for project delivery.

Nevertheless, the search space is not 321 because different subpopulations, termed species, constitute the structure of base data of the problem. In fact, project modelling can be represented with a time-oriented networking approach (fig. 2). Therefore, each possible path from project start to project finish constitutes a species. Within species, i.e. single path, permutations of different WP alternatives are possible, after satisfaction of precedence relationships between succeeding WP. No alternative permutations are possible between different species because of the structure of chromosomes, i.e. the number of WP of each network path. Every project activity can be represented by a 3-by-3 matrix reporting the options in terms of time-cost-quality.

Therefore, the whole project is represented by a set of matrices divided into different species that constitutes a data array from which activity performance data are selected to create the chromosome of a single species.

The chromosome of a species is created by time, cost and quality data of each chosen WP alternative belonging to a network path.

An initial random selection of options for each activity is performed and the corresponding objective function is computed. Next, GA uses genetic operators such as crossover, which divides two initial solutions exchanging their chromosomes in order to generate new solutions, and mutation, that simulates the effect of random errors. The new solution is computed again and the results of the objective function are compared with the previous ones. The best solutions are selected in order to improve the fitness function. Each solution has a fitness value different from the others and best solution are selected for future generations while worse solutions are set aside.

Final evaluation of the found solutions can be performed by comparison with maximum and minimum set limits of the three parameters, termed Cmax, Cmin, Tmax, Tmin, Qmax and Qmin. Anyway, the objective of the optimisation is to find a solution that minimises times and costs, while maximises quality. Therefore, the proposed fitness function depends on the three WP parameters (time, cost and quality) weighted . The following equation (1) is proposed.

$$Fitness = \max\left(\frac{Ci \times Kc + Qi \times Kq + Ti \times Kt}{3}\right)$$

Where Ci is defined by the following:

$$Ci = 1 - \frac{\sum Cj - Cmin}{Cmax - Cmin}$$

Where ΣCj is total cost of each j work package of the project (j = 1, 2, 3, ….n) of each i generation (i=1, 2, 3, ……m) and m the number of generations.

Qi can be found by the following equation:

$$Qi = \frac{\sum Qj}{n}$$

Where ΣQj is the total sum of quality indexes of each j work package of the project (j = 1, 2, 3, ….n) for the generation i and n the total number of work packages of the project.

Ti is the time parameter found for the i generation, defined by the following:

$$Ti = 1 - NTd$$

Where NTd is the normalized total duration:

$$NTd = \frac{TDi - Tmin}{Tmax - Tmin}$$

Where TDi is the total project duration found by network diagramming and critical path computation for the generation i. TDi is the maximum duration found by critical path analysis comparing each total duration TDik of a single species k of the generation i composed by the work packages j belonging to the k network path.

TDi = max TDik

The weighting parameters kc, kq and kt can range from 0 to 1 for cost, quality and time, respectively. Aiming at balancing the three parameters the following values has been set: kc = 1; kq=1; kt=1.

PILOT STUDY APPLICATION

A simple pilot study of a renovation project of two residential apartment has been imp to test the proposed approach. For each work package, three different commercial product options has been considered and corresponding activity durations, costs and quality performances have been detected from a public works price list (Regione Lombardia, 2008). Quality indexes has been evaluated straightforwardly as product quality and its suitability for the use. Therefore, the proposed time – cost – quality trade-off procedure has been implemented using Genetic Algorithms, with the aim of finding a set of optimal solutions for the building construction project. Found data for each work package are presented in table 1a and 1b.

A project model has been implemented with network diagramming. Therefore, critical path analysis can be performed and total project duration can be found for each project alternative of the pilot project (fig. 2).

Firstly, the limits of possible solutions concerning different WP alternatives have been selected. Minimum and maximum total values of the three project parameters, time, cost and quality, have been computed by selecting the corresponding alternative for each WP (table 2).

Secondly, the Matlab application has been set for the specific problem. The network diagram and the working options of the pilot study have been formalized in Matlab® using two classes (one for describing the work package and one for the work package options). Beyond class attributes like code and description, other network attributes, such as the set of successors of each work package, or the set of option belonging to each work package were added. The whole problem has been translated into the Matlab® code. The maximum number of generation has been set to 100 and the stall condition to 50 generations. After running, the GA correctly converges to optimal solutions, reaching the best fitness scores generally just after 60-70 generations (see Figure 3). Both the fittest individual (Figure 3 –

A	C	D		E	O
No. / WP alternatives	WBS	Work Package description	Quality index (%)	Cost (€)	Duration (h)
1	A.01	demolizioni e rimozioni			
A		demolizioni e rimozioni A	90%	€ 15.174,00	177
B		demolizioni e rimozioni B	100%	€ 15.345,85	177
C		demolizioni e rimozioni C	110%	€ 15.409,35	179
	A.02	murature			
2	A.02.01	riparazione scuci cuci di murature			
A		mattoni pieni	100%	€ 18.225,22	248
B		mattoni semiartigianali tipo antico	110%	€ 30.846,14	307
C		mattoncini realizzati a mano tipo antico	90%	€ 35.972,56	308
3	A.02.02	tramezzi in mattoni forati cm 8			
A		mattoni a sei fori 8 x 14 x 28	100%	€ 592,08	8
B		foratelle a dieci fori 8 x 25 x 25	90%	€ 572,64	7
C		tramezzature di gesso in pannelli spess. Cm8	120%	€ 738,24	8
4	A.02.03	tramezzi in mattoni forati cm 10			
A		mattoni a sei fori 10 x 14 x 28	100%	€ 1.540,59	19
B		tramezzature di gesso in pannelli sp. cm10	110%	€ 1.839,02	20
C		tramezzature latero-gesso pann. Sp. Cm 10	120%	€ 2.304,46	21
	A.03	Sottofondi - massetti			
5	A.03.01	massetto isolante alleggerito polistirene espanso			
A		massetto isolante alleg. polistirene espanso	105%	€ 3.379,20	34
B		massetto isolante alleg. sughero naturale	100%	€ 4.878,40	34
C		massetto isolante alleg. vermiculite espansa	90%	€ 5.156,80	33
	A.04	Intonaci			
6	A.04.01	intonaco premiscelato per interni			
A		intonaco civile interni malta bastarda	100%	€ 4.994,08	83
B		intonaco civile interni malta di calce spenta	110%	€ 4.877,60	82
C		intonaco civile interni malta di cemento	90%	€ 4.994,08	82
	A.05	Pavimenti Rivestimenti			
7	A.05.01	pavimento in gres porcellanato 40x40 granigliato			
A		pavimento in gres porcellanato 40x40 tin. Unita	100%	€ 2.837,97	18
B		pavimento in gres porcellanato 60x60 tin. Unita	110%	€ 4.874,85	14
C		pavimento in gres porcellanato 20x20 tin. Unita	90%	€ 2.497,11	18
8	A.05.02	rivestimento in piastrelle ceramica mono. 20x20			
A		rivestimento in piastrelle ceramica mono. 20x20 tinta unita pastello	90%	€ 6.261,71	49
B		rivestimento in piastrelle ceramica mono. 20x20 effetto marmorizzato	100%	€ 3.632,72	49
C		rivestimento in piastrelle ceramica mono. 10x10 effetto pietra	110%	€ 7.433,79	60
9	A.05.03	zoccolino battiscopa in gres			
A		zoccolino battiscopa in gres 10x20	110%	€ 2.504,80	21
B		zoccolino battiscopa in klinker 8x24 smaltato	100%	€ 1.700,00	17
C		zoccolino battiscopa legno prever. Ciliegio 75x10mm	80%	€ 1.201,60	9

A	C	D		E	O
No. / WP alterna-tives	WBS	Work Package description	Quality index (%)	Cost (€)	Dura-tion (h)
	A.06	infissi e porte			
10	A.06.01	fornitura e posa struttura metallica di sostegno porte scorrevoli - scrigno			
A		Struttura metallica sostegno porte scor.scrigno	100%	€ 511,28	3
11	A.06.02	fornitura e posa controtelai porte larghezza fino 11 cm			
A		controtelaio in abete sp. 2,5 cm largh. 11 cm	100%	€ 93,60	1
12	A.06.03	fornitura porte in legno tamburato anta cieca liscia noce			
A		porte interne anta cieca liscia noce tanganika	90%	€ 2.412,84	8
B		porte interne anta cieca liscia noce nazionale	120%	€ 3.855,00	7
C		porte interne anta cieca liscia rovere naturale	100%	€ 3.209,88	8
	A.07	impianto elettrico			
13	A.07.01	impianto elettrico			
A		impianto elettrico opzione A	100%	€ 2.200,00	21
	A.08	impianto idrico sanitario			
14	A.08.01	fornitura e posa di vaso igienico monoblocco a pavimento			
A		vaso igienico vetrochina in opera escluso op.mu.	100%	€ 473,50	5
B		vaso igienico vetrochina sospeso escluso op.mu.	110%	€ 629,10	5
C		vaso igienico vetrochina sospeso cromato escluso op.mu.	120%	€ 1.034,08	6
15	A.08.02	fornitura e posa di bidet			
A		Bidet in porcellana vetrochina escl. Op. murar.	100%	€ 469,26	4
B		Bidet in porcellana sospeso NP	110%	€ 625,10	5
C		Bidet in porcellana sospeso cromato NP	120%	€ 1.030,08	6
16	A.08.03	fornitura e posa di lavabo 65x50			
A		lavabo in vetrochina 70x55	100%	€ 687,84	5
B		lavabo in vetrochina 65x50	95%	€ 643,20	5
C		lavabo in vetrochina 70x55 con colonna	105%	€ 842,06	6
17	A.08.04	fornitura e posa scarichi in pvc per bagno			
A		rete di scarico per bagno in pvc	100%	€ 629,12	8
18	A.08.05	rete generale di distribuzione acqua calda/fredda			
A		rete d. acqua calda/fredda polibutilene	100%	€ 967,00	9
B		rete d. acqua calda/fredda acciaio zincato	95%	€ 1.156,64	18
C		rete d. acqua calda/fredda polietilene reticolato	105%	€ 1.366,44	17
	A.09	assistenze murarie			
19	A.09.01	assistenze impianto idrico sanitario - esecuzione tracce e fori	100%	€ 640,00	11
20	A.09.02	assistenze impianto elettrico	100%	€ 880,00	15
	A.10	opere da pittore			
21	A.10.01	tinteggiatura interna con idropittura traspirante			
A		tinteggiatura interna idropittura traspirante	95%	€ 3.648,20	55
B		tinteggiatura interna idropittura traspir. Lavabile	100%	€ 4.077,40	60
C		rivestimento effetto spatolato a base di resine	110%	€ 20.839,40	309

Table 1a - Time, cost and quality data for Pilot study
Table 1b - Time, cost and quality data for Pilot study

red dots) and the average score of the population improve through generations and asymptotically tend to the fittest score. Identified solutions are consistent through different runs and, if sometimes the fittest genotypes can show slight differences, in most cases the GA solver leads to the same solution. The found results can be displayed with the time-cost-quality chart in Figure 4
As expected, the parametrization of the fitness function strongly affects the solutions offered by the GA tool. In particular, when weighting parameters are set equally for costs, quality and time, the solution presented by the GA shows to be slightly biased towards cost and time, having quality as its worst score (Figure 4 – blue triangle).
On the other hand, forcing the GA to identify the best quality solutions, setting to 1 the quality parameter, 0 the costs, and 0.1 the time parameter, we obtain a quality biased fitness, in which costs and time score worse than in the previous solution (Figure 4 – yellow triangle).
Finally, if the largest weight is given to costs, time and costs are highly maximized (Figure 4 – dark green triangle), while quality score decreases dramatically. The best found optimized result in the case of balanced weights is the following: Total project duration = 1078 (h); Total cost = € 109.711.17; Total quality index = 104%. Further testing of the developed model will be needed to assess its effectiveness in case of more complex projects with multiple environmental constraints.

CONCLUSION

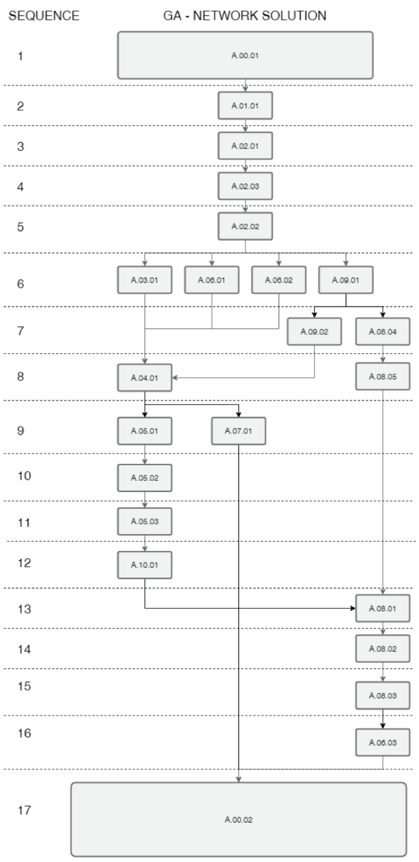
The well – known iron triangle of main project objectives, namely time, cost and quality, is still of capital importance for project managers in construction, but balancing these three parameters for actual and complex projects can be difficult because of the unknown or complex function linking all of these three parameters. With the aim of proposing an innovative approach for the time, cost and quality trade-offs, a GA optimization has been developed and implemented with Matlab®. Actual data concerning the expected duration of each work package, its quality index and its costs are gathered and three possible performing alternatives are detected from an official public works price list.

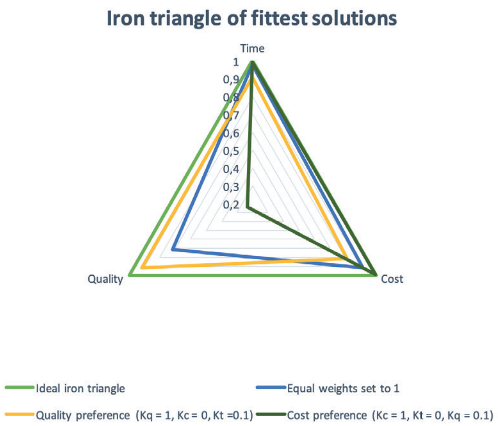
Therefore, the overall performance of the whole construction project, composed by all the work packages, can be simulated taking into account the different alternatives of activity duration, cost and quality. The overall time estimate can be developed by a CPM- based activity network, the overall cost is the sum of the cost of all work packages, and the overall project quality index can be estimated as the normalized sum of all work package indexes. The aim of the optimization is to find automatically or semi-automatically a balance between these three project indicators by a Genetic Algorithm.

Project modelling for Genetic Algorithm implementation needs a new approach because of Matlab® programming language and coding rules. When developed and implemented, the Genetic Algorithm extracts randomly one work package alternative for all the activities, thus creating a chromosome for each species (i.e. path) of the project for each generation, and compute its suitability by fitness equations. Then, a new generations are created and the found solution in terms of total project duration, total cost and total project quality are compared with the previous one by fitness function computation. The fittest generations are maintained and developed and the others are set aside from the evolutionary process.

The implementation of a Genetic Algorithm needs a new and complex approach in project modelling to reach the final results in terms of fitness of the final generation. Therefore, the creation of the fitness function plays a major role in selecting the developed new generations. Actual data for a pilot study simulation of a building renovation project of two residential apartments has been used to demonstrate the possibility of implementing a GA-based optimization of project objectives, and the found results are consistent with the initial assumptions in terms of ranges of time, cost and quality values. Future research work will be aimed at testing further the developed model with the imposed constraints and with more complex projects.

Total project values	*Maximum limit*	*Minimum limit*
Total project duration	1078 (h)	723 (h)
Total project cost	€ 128.547,49	€ 80.014,53
Total project quality index	109%	95%





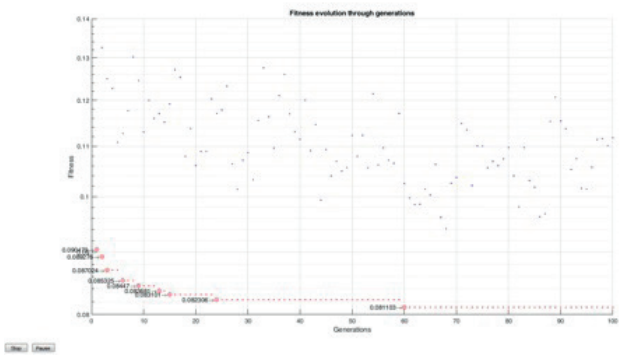


Figure 2 - Network diagramming of the pilot study project.
Table 2 - limit values of total project alternatives
Figure 3 - Fitness evolution through generations. Blue dots represent the average fitness of the population in each generation Red dots represent the fittest individual found across generations. In this specific case, the fittest individual have been found at 60th generation
Figure 4 - Time – cost – quality iron triangle represented with normalized scores. In blue the optimal solution with time, cost and quality parameters equally weighted and set to 1. In yellow, the optimal solution having quality as a preference (quality parameter Kq was set to 1, time parameter Kt to 0.1 and cost Kc to 0). In dark green a solution that strongly optimize costs. In this case, Kc has been set to 1, Kt to 0 and Kq to 0.1

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