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Cover illustration: Stereotomic helical staircase in Villa D'Este, Tivoli, Italy.

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A GENETIC ALGORITHM-BASED APPROACH FOR THE TIME, COST, AND QUALITY TRADE-OFF PROBLEM FOR CONSTRUCTION PROJECTS

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Abstract

Quality identifies the overall level of performance of the desired building facility or civil infrastructure. Quality can include safety and sustainability requirements, and planning the desired quality level is paramount in construction projects. Nevertheless, two other significant project management Key Performance Indicators (KPIs) must be considered in construction project management: time and cost. Project Managers always perform a trade-off between these three KPIs, but it is known that the relationship between these three indicators can be difficult to understand. Therefore, a multi-objective Genetic Algorithm (GA) has been proposed to develop a comprehensive approach to optimize project performance in construction. The proposed multi-objective GA can be used as a decision support system for the detailed design stage of a construction project to detect better and alternative detailed design and construction solutions. A GA is an Artificial Intelligence application (AI) that develops an evolutionary learning optimization process that discards worse solutions and re-introduces better solutions with an iterative process. Therefore, the most suitable solution can be found by performing a trade-off between the three indicators. The research aims to demonstrate the availability of AI applications to understand and perform the Time-Cost-Quality trade-off for construction projects. The developed procedure has been tested on a simple pilot study of a building renovation project, and the best-found optimized results have been detected with Solver® and discussed. Future research work will be aimed at improving the procedure's efficiency so that it can be implemented in larger projects.

Keywords

Construction, Project management, Genetic Algorithm, Detailed design, Time-Cost-Quality Trade-off.

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1. INTRODUCTION

Quality identifies the overall level of performance of the desired building facility or civil infrastructure, therefore, quality includes all design and technical requirements to be fulfilled by a construction project. Nevertheless, traditional project control techniques focus on time and cost constraints, meaning that the project baseline is built upon the project time schedule, which indicates the total project duration and the timing of work packages, along with the schedule of rates and the bill of quantities that compute the cost of work packages and the total cost of the project. The Earned Value Method generally addresses the integrated project control of time and cost. Nevertheless, time, quality, and cost create the well-known *Iron Triangle* of Project management [1], meaning that a Project Manager must balance these three constraints to reach the project's objective. Therefore, construction project managers are used to selecting a combination of construction technologies and resource usage that minimizes cost and time while maximizing quality. This project management process is termed the Time-Cost-Quality Trade-off problem (TCQT) [2]. In construction projects, quality is complex and meaningful. Quality can be defined as the level of accomplishment of a product or a process to a set of performance requirements [3]. ISO standards define quality as the degree to which a set of inherent characteristics fulfil requirements. Quality assessment in construction can be divided into three main components: quality of products, quality of design, and quality of processes. The quality of products can be understood primarily as a technical quality, whereas the quality of design is about meeting the needs of clients and end users successfully. The quality of processes refers to all activities throughout the construction project's life cycle.

Artificial Intelligence is playing a core role in the Fourth Industrial Revolution, providing significant productivity improvements via analyzing large datasets quickly and accurately, and the optimization of construction management problems via Genetic Algorithms (GA) has been largely addressed by literature. GA methods have been used by many researchers in literature as an optimization technology to address Architecture, Engineering, and Construction (AEC) optimization goals, as for instance construction scheduling and cost optimization. Most of the Artificial Intelligence techniques used in the AEC sector are GAs [4].

Construction Engineering and Management benefits from GAs because of intelligent optimization, meaning searching for the optimal solution to minimize or maximize an objective function subject to a set of constraints. This problem can be divided into two versions. The simple version is the single objective optimization to identify a single optimal alternative. At the same time, the complex one is multi-objective optimization, which simultaneously optimizes more than one objective function with a set of feasible solutions [5].

A GA can be used for project-controlling purposes, assisting decision-makers in identifying optimal or near-optimal solutions concerning project implementation and management processes addressing a project's planning, scheduling, and controlling functions. A GA is an AI application that can be used to optimize construction management problems. GA, indeed, creates a learning-based optimization process because better solutions are re-introduced in the iterative optimization process while worse solutions are discarded. Therefore, an optimized solution can be found in a reasonable amount of time, i.e., the algorithm converges to better solutions, even if sub-optimal [4].

Since in construction projects, the relationship between quality, cost, and time is usually unknown, and a dependence function between these factors can be challenging to detect, an AI application has been proposed to demonstrate that AI applications can help project managers perform project management processes concerning trade-off between time, cost and quality objectives.

The paper is structured as follows. The research background section presents an analysis of the state-of-the-art concerning TCQT and the related use of GA. The proposed method section presents a GA-based procedure to solve the TCQT problem, and an application to a pilot study follows. Then, the discussion and conclusion sections close the paper.

2. RESEARCH BACKGROUND

Few researchers focused on the problem of evaluating the global quality of a project or system using a quality indicator, and developing a time-cost-quality trade-off procedure is seldom the objective of research papers. The use of AI for construction management has been, instead, the aim of many research works. This section offers background on two different topics relevant to the current paper: the time-cost-quality trade-off and the related GA application. Construction project managers must deal with clients' objectives, and clients' general requirements concerning time, cost, and quality can be evaluated and weighted with a value management approach. Rwelamila and Hall [6] argued that despite time, cost, and quality being the most important issues for the clients of the construction industry, the vast majority of projects are procured by competitive bidding with the lowest cost or lowest cost plus project duration criteria. This traditional approach can lead to extensive delays, cost overruns, and serious problems in quality. Critical system thinking and the total systems intervention approach are proposed to balance these project management factors via a "problem-solving" approach. Quality is defined as the value for money from the client's point of view.

Babu and Suresh [7] suggested that project quality may be affected by project crashing for minimal cost search. Time-cost trade-offs can affect quality; therefore, a TCQT is needed. Linear assumptions are used to develop a simple methodology that links each project schedule activity's time, cost, and quality attributes. Time is considered the independent variable, and quality can be computed with cost constraints. Khang and Myint [8] tested the Babu and Suresh approach with a case study of the construction of a cement factory in Thailand, highlighting key problems and difficulties faced. A significant limitation of the method is that only a very small portion of the overall quality of a work package has a direct relationship with time and cost performances. Only labor-dependent quality is affected by time and cost constraints in the execution process.

Atkinson [1] introduced the project manager's iron triangle concept, meaning the need to integrate time, cost, and scope, or quality project objectives. These are also the most critical criteria available to measure project performance. It is suggested that a more realistic and balanced indication of project success should consider the project output, namely the technical strength of the resultant system and the benefits to the resultant organizations and the stakeholders. The "Quality–Based Performance Rating System" for contractors' qualification of the American National Cooperative Highway Research Program (NCHRP) [9] introduces the concept of Quality Breakdown Structure (QBS) of the project. Quality can be measured through a global quality Key Performance Indicator (KPI), termed Quality Index, based on the project's QBS. QBS aims to evaluate the final quality of the products for the construction process with a performance-based approach. Therefore, quality indicators are detected to assess the final product quality.

Many researchers tackled the resource-constrained project scheduling problem with AI applications, mostly with GAs. Ono, Yamamura, and Kobashi [10] proposed a procedure for Job-Shop-Scheduling Problems with GAs. The proposed approach used a job sequence matrix and introduced crossover and mutation operators. The proposed procedure seems very effective, though the method is not construction-oriented. A neural dynamic model for schedule and cost optimization was proposed by Adeli and Karim [11] for construction projects composed of repetitive and non-repetitive tasks. As network-based schedules have proven to present several shortcomings, linear planning charts are proposed for construction project scheduling. In addition, a robust neural dynamics model was developed to optimize the cost-duration relationship of the project.

Marki, Fischer, Kunz, and Haymaker [12] focused on the optimization of 4D building process planning using GA and developed an interactive 4D-modeling toolbox for the 4D modelling of buildings. The model consists of the following four tools: a 4D model builder that supports the identification of building components and the definition of structural dependencies between them; a discrete event simulator for the automated sequencing of activities into a network plan; a genetic algorithm process optimization (GAPO) that enhances project schedules in terms of time, cost and resource management; a 4D player for the visualization of the building processes. Later, Dong et al. [13] proposed a new GA-based method that automates look-ahead schedule generation in the finishing phase of complex construction projects to minimize project duration or cost. Intending to improve construction quality, El Rayes and Kandil [14–15] presented a multi-objective optimization model that supports decision-makers in creating an optimal resource optimization plan that minimizes construction cost and time while maximizing its quality. The *MACROS* automated optimization system for construction resources was implemented [14–15], and GA developed the TCQT algorithm. Following this research line, El Razek et al. [16] addressed the TCQT problem by implementing a Java programming code, AMTCROS, based upon a GA. Long and Ohsato [17] developed a project scheduling method for repetitive construction projects with several objectives, such as project duration minimization, project cost minimization, or both. A GA is used to find a set of suitable durations, and the method also considers resource work continuity and different relationships between direct costs and durations of activities. San Cristobal [18] proposed an Integer Programming model to meet quality output standards and time and cost objectives. Even in this case, the research aims to develop a method to search for an optimal/near-optimal resource utilization plan that minimizes construction cost and time while maximizing quality. The need to develop a trade-off algorithm arises because governmental agencies want to increase long-term returns on public-investments by using new types of contracting methods.

Zhang and Xing [2] addressed AI applications and presented a fuzzy-multi-objective particle swarm optimization to solve the TCQT problem. Solving a TCQT problem involves determining an optimal combination of construction methods for all activities in a project to achieve an optimal balance of time, cost, and quality. Zhang and Xing argue that the project performances, such as time, cost, and quality of construction activity, are measured with no precise numbers, i.e., they are uncertain, especially the quality. Therefore, uncertainty, vagueness, imprecision, and subjectivity are present in the performance measures of each project activity. A fuzzy multiple attribute utility method where fuzzy numbers describe time, cost, and quality is proposed to solve the TCQT problem about uncertainty.

Magalhaes-Mendes [19], instead, proposed a two-level GA for the multi-mode resource-constrained project scheduling problem for construction that minimizes project completion time and evaluates the quality of the schedule. The quality of the schedule is assessed by comparison with the best-known solution. Kim [20] proposed a GA-based decision support model that provides decision-makers with a quantitative basis for multi-criteria decisions related to the construction schedule. A multi-objective construction schedule optimization using a modified niched Pareto GA is presented [21] to minimize construction duration, construction cost, and variations in resource utilization during construction. Dong et al. [13] proposed a new GA-based method that automates construction schedule generation, intending to minimize time or cost, considering engineering and space constraints. Later, Faghihi et al. [22] developed a computer application that can automatically derive a statically stable construction schedule by data extraction from a BIM model using the concept of GAs.

In Information Technologies, Mishra and Mahanty [23] indicated that optimizing project cost, schedule, and quality for a software development project in an outsourcing environment can be studied with a system dynamics simulation approach. Kyriklidis and Dounias [24] addressed the resource levelling optimization problem with an evolutionary algorithm (GA) in the project management field, while in the specific construction sector, Monghasemi et al. [25] proposed a Multi-criterion decision-making approach that identifies all global Pareto optimal solutions by a multi-objective GA. Sorrentino [26] applied GAs to a time, cost, and quality optimization problem for project scheduling of road construction. Tiene et al. [27] investigated a similar application to select design alternatives for a building envelope. Liu et al. [28] presented a GA–based optimization for the Resource-Constrained Project Scheduling problem that enhances the evolution strategy by proposing modified operators for selection, crossover, and mutation. Hyun et al. [29] developed a multi-objective optimization tool for modular unit production lines based on GAs that assumes that the duration of activities on a production line in modular construction depends on the number of workers, and reducing construction duration and labour cost will be the optimization objectives. Soman and Molina-Solana [30] presented a novel Look-Ahead Schedule generation method that uses reinforcement learning algorithms and linked data-based constraint checking to help construction planners as a decision support system. The output schedule is compared with the manually generated one, with the critical path method, and with the modified GA by Liu et al. [28]. Therefore, a multi-objective GA can perform TCQTs that evaluate the effectiveness of various combinations, computing better solutions with an iterative process. At the end of the process, the most suitable balance between the three project targets can be selected between the outputs by project managers.

Though all the previous approaches seem complete and effective, the quality dimension of project outcomes is still missing in pertinent literature concerning the construction sector. The TCQT problem is difficult to solve in the construction sector because of the variability of the relationship between quality, time, and costs. In general, less expensive resources or technologies would lead to a longer duration to complete an activity, but with some exceptions. On the other hand, even time reduction can produce low-quality products and project outputs. In addition, increasing project costs because of more efficient workers or equipment, because of the increase in the number of workers or machinery, or because of overtime work shifts may lead to time reductions but with a non-balanced time-cost-quality output. With this background knowledge and context, the paper aims to contribute to understanding the TCQT problem in construction and to propose the application of GAs for its solution.

3. PROPOSED METHOD: A GA-BASED APPROACH

The construction industry is going through constant innovations via digitalization and Artificial Intelligence [5]. Artificial Intelligence is a branch of computer science that drives computers to understand and learn inputs like humans and implement processes that include perception, knowledge representation, and problem-solving. There are many applications of AI in specific sub-areas of the construction industry, such as structural engineering and construction management. These applications can be categorized into four major groups: expert systems, fuzzy logic, machine learning, and optimization algorithms. Optimization algorithms aim to search locally or globally for optimal results from a set of available alternatives. The use of GAs was introduced by J.H. Holland [31] as a research method based on the mechanics of natural selection and natural genetics of Darwin's Evolutionary Theory. Later, Goldberg [32] developed further the GA approach in the field of automation engineering. GAs have been implemented in many engineering, operations research, and optimization problems, such as the Travelling Salesman Problem [33] and Construction Project Scheduling [5]. A GA is a global and stochastic operational research method termed "genetic" because of the implementation of an evolutionary and iterative computational process that creates a set of possible solutions for each step, termed generation, using the terminology from genetics, a branch of biology. It is a probabilistic search procedure designed to work on large spaces involving states that can be represented by mathematical strings, i.e., genes or individuals. A GA is an evolutionary computation technique that automatically solves problems without a deep understanding of what needs to be done, i.e., without specifying the form of the solution.

GAs usually start by generating an initial population of possible solutions called "individuals". This generation of individuals is based upon a random approach, i.e., stochastic. Every individual in the population is coded as a string called a "chromosome". Then, each chromosome is assessed by calculating its fitness value by the objective function, and chromosomes are sorted depending on their fitness values. The best individuals are selected as parents, and therefore, a set of new individuals is created, and a sequence of new populations, termed "generations", is produced to be assessed again. It is an iterative process [31] [32]. Generation by generation, GA develops populations of better solutions, hopefully. This process is random, and it can never guarantee results.

Therefore, the basic structure of a GA involves cyclic operations that simulate the evolutionary process of a population. Each loop represents one generation, and better and better individuals form each new population generated. Four steps are considered in a GA: setting GA parameters, developing the initial population, evaluating against fitness function, and breeding a new generation [15] (Fig. 1).

A GA-based optimization problem has the task of detecting the optimal solution related to a specific objective function termed "fitness" under a set of constraints. There are two types of optimization problems: single-objective optimization, which identifies a single optimal alternative, and multi-objective optimization, which simultaneously optimizes more than one objective function and gives a set of feasible solutions as an output [5]. As identified by many researchers [5] [34], optimization-based scheduling can maximize project quality while minimizing project

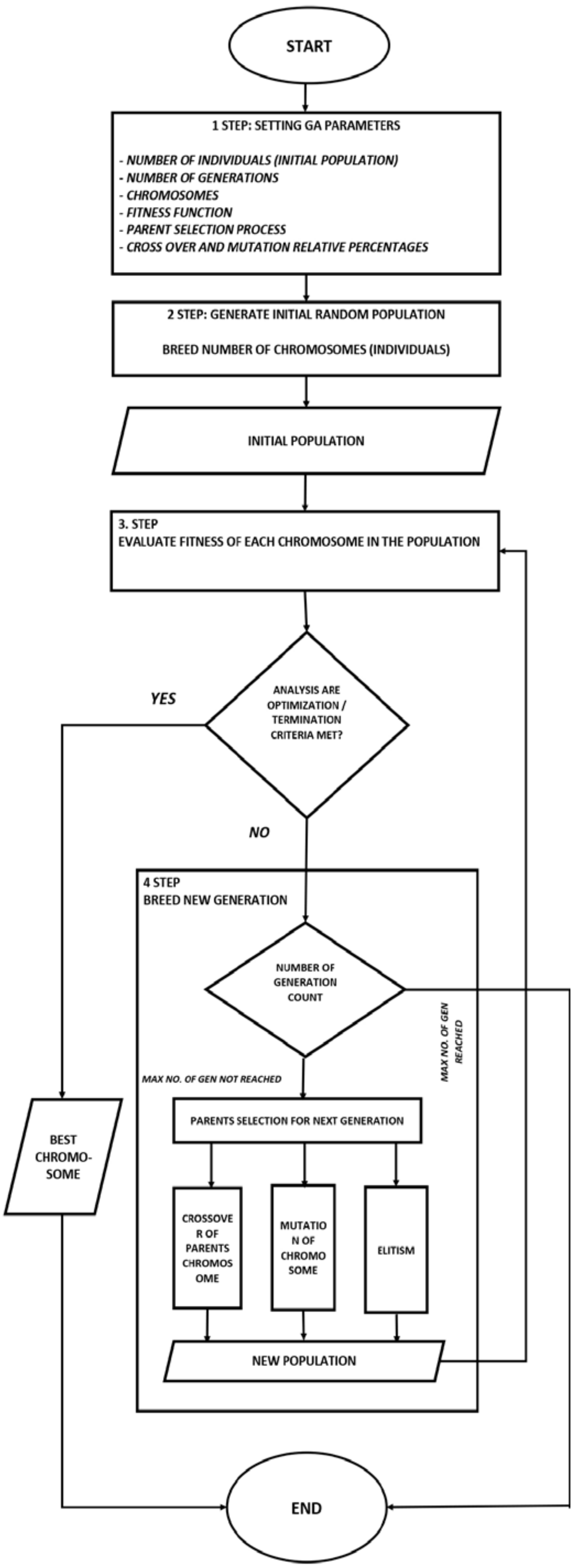

Fig. 1. *Steps of a GA.*

total cost and duration. In other words, the TCQT can be developed. The research work aims to optimize only one objective function to simplify decision-making.

3.1. PROPOSED GA COMPUTATION PROCEDURE

The proposed GA-based computation procedure aims to detect an optimized solution of the TCQT for a construction project. The proposed approach follows two stages: construction project identification and iterative population generation (Fig. 2).

3.1.1. STAGE 1: CONSTRUCTION PROJECT IDENTIFICATION

The construction project must be identified in terms of time, cost, and quality. Therefore, the database is the set of construction activities of the project and the Work Breakdown Structure (WBS) that identifies Work Packages (WP), their durations, their cost, and related quality indexes. Following these datasets, a network-based project schedule, a bill of quantities, and a QBS can be created [14]. Anyway, in the project's detailed design stage, some alternatives for WP and activity execution concerning activity description, building products, construction methods, and the number and type of resources (crew, equipment, production systems) can be evaluated. These WP alternatives produce different outputs regarding duration, quality estimate, price, and direct cost. Duration is the time needed to build, install the building component, or perform the activity. Quality is an intrinsic feature characterized by a relative concept because it consists of an objective and subjective part. Direct costs are related to the cost of materials or building products, labour, and equipment rental needed to perform the activity. If an official price list estimates the cost indicator, the cost index can also include markup and overhead costs. Therefore, it is much more challenging to quantify the quality performance of an activity than time and cost performances [26] [27]. Three possible activity alternatives have been considered (Tab. 1 and Fig. 2).

The project dataset is summarized by a table that lists for each WP the possible alternatives of duration, cost, and quality (Tab. 1). The following three KPIs have been defined for each (i) activity and WP: Quality indicator, Time indicator, and cost indicator.

Quality indicator Qi

A quality index Qi is identified for each (i) activity of the WBS. The quality index indicates a quality estimate developed by the designer, taking into account the complex set of performance requirements needed to perform the specific activity based on design and physical or functional requirements (for instance, thermal transmittance) [14].

Time indicator Di

The time indicator of each (i) project's activity is its duration. The duration of the activity can be computed based on labour hours and crew members of each activity [27].

$$Di = MHi / nm \quad [1]$$

where Di = duration of the activity (i) in hours; MHi = total labor estimate of the activity (i) in man-hours; nm = the number of members of the working crew of the activity (i).

Cost indicator Ci

The cost indicator Ci for each (i) activity is the work package rate as detected from an official price list for public works or its direct cost, depending on the study perspective (i.e., from owner or contractor standing points). Each activity's design alternatives entail different initial products and building procedures, as indicated by the official price list. All design alternatives are suitable solutions for the final building products, meaning that the product alternatives generate activity alternatives consistent with building design and processes. The sum of the cost of each activity gives the total cost of the j project, TCj.

The following three KPIs have been defined for each (j) project alternative, depending on the chosen performing option of each activity and its different contribution to project execution: Total Quality indicator, Total Project Duration, and Total Cost indicator.

Total Quality indicator TQj

TQj can be found by the following equation:

$$TQj = \frac{\Sigma\, Qi}{n} \quad [2]$$

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

Total Project Duration TDj

TDj is the total project duration found by network diagramming and critical path computation for project j. TDj is the maximum duration found by critical path analysis comparing each total duration TDjk of a single path k of the project j composed of the work packages ik belonging to the k network path. Therefore, k species can be found in the project network, meaning each species is a single dataset for time-based network computation.

$$TDj = \max TDjk \quad [3]$$

Total Cost indicator TCj

TCj is the total cost of the j project defined by the sum of the costs of the i work packages of the project:

$$TCj = \Sigma Ci \quad [4]$$

where ΣCi is the total cost of each j project, found by adding the cost Ci of all the n work packages of the project (i = 1, 2, 3, ….n).

3.1.12. STAGE 2: ITERATIVE POPULATION GENERATION

Each project activity includes three possible alternatives. Each has its own different time, cost, and quality indicators; thus, a search space of thousands of possible solutions is created. An initial random selection of options for each activity is performed, a population of individuals – chromosomes are generated, and the corresponding objective function – fitness – is computed. Next, GA uses genetic operators to create a new population, or generation, in an iterative manner. The genetic operators are three: crossover, mutation, and elitism. “Crossover” divides two initial solutions, exchanging their chromosomes to generate new solutions, “mutation” simulates the effect of random errors, and “elitism” maintains the best individual in the next generation or substitutes the son with the parent if it gives better performance. The new solution is a set of new chromosomes, a new generation. The new generation is computed again, and the objective function results are compared with the previous ones. The best solutions are selected to improve the fitness function. Each solution has a fitness value different from the others, and the best solutions are chosen for future generations while worse solutions are set aside (Fig. 2).

The goal of the proposed procedure is to develop a chromosome or a set of them that will minimize construction total cost and construction entire duration while maximizing project quality, thus performing the TCQT problem automatically. The proposed GA procedure can use both direct costs or prices, including overhead costs and markup. Generally speaking, other lowest pricing strategies and bid-related considerations are not addressed in this paper.

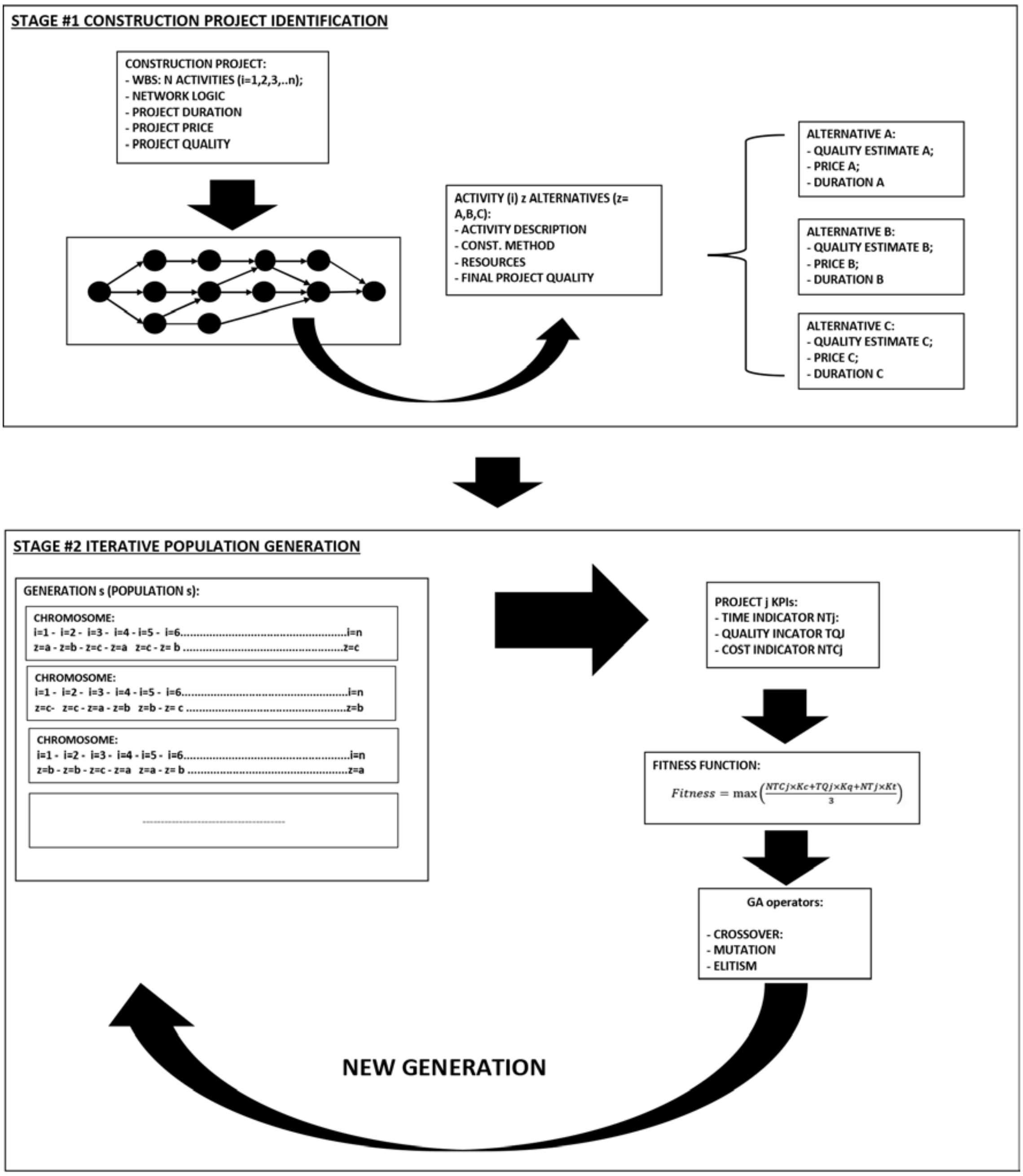

Fig. 2. *Stages of the proposed GA procedure.*

Therefore, the proposed fitness function depends on the three total project indicators – TQj, NTCj, and NTj – weighted (please note that j indicators refer to the whole project while i indicators to single activities). The following equation (4) is proposed:

$$Fitness = \max\left(\frac{NTCj \times Kc + TQj \times Kq + NTj \times Kt}{3}\right) \quad [5]$$

where NTCj is defined by the following:

$$NTCj = 1 - \frac{TCj - TCmin}{TCmax - TCmin} \quad [6]$$

in which TCj is the total cost of the project (j = 1, 2, 3, ….n). TCmin and TCmax are the project's minimum and maximum possible total cost values.

TQj is the total quality indicator of project j found with equation (1). TQmin and TQmax are the project's minimum and maximum possible total quality values.

NTj is the time parameter found for the j project, defined by the following:

$$NTj = 1 - Tj \quad [7]$$

where Tj is the normalized total duration:

$$Tj = \frac{TDj - TDmin}{TDmax - TDmin} \quad [8]$$

in which TDj is the total project duration found by network diagramming and critical path computation for the j project. TDmin and TDmax are the minimum and maximum possible values for the whole duration of the project.

The weighting parameters k_c, k_q, and k_t can range from 0 to 1 for cost, quality, and time, respectively. In order to balance the three parameters, the following values have been set: k_c=1; k_q=1; k_t=1. The final evaluation of the found solutions can be performed by comparison

WORK AND QUALITY BREAKDOWN STRUCTURE (1)

No. / WP alternatives	WBS	Work Package description	Quality Index Qi (%)	Cost Ci (€)	Duration (h) Di
1	**A.01**	**demolition and removal**			
A		demolition and removal works A	90%	€ 15.174,00	177
B		demolition and removal works B	100%	€ 15.345,85	177
C		demolition and removal works C	110%	€ 15.409,35	179
	A.02	**Brickwork**			
2	A.02.01	sew-unstich brickwork (indent repairs to masonry)			
A		solid bricks	100%	€ 18.225,22	248
B		old-style solid bricks semi-crafted	110%	€ 30.846,14	307
C		old-style hand-crafted solid bricks	90%	€ 35.972,56	308
3	A.02.02	partition walls perforated bricks cm 8 thickness			
A		six hole perforated bricks 8 x 14 x 28	100%	€ 592,08	8
B		ten hole hollow blocks 8 x 25 x 25	90%	€ 572,64	7
C		gypsum panels partition wall thickness 8 cm	120%	€ 738,24	8
4	A.02.03	partition walls perforated bricks cm 10 thickness			
A		six hole perforated bricks 10 x 14 x 28	100%	€ 1.540,59	19
B		gypsum panels partition wall thickness 10 cm	110%	€ 1.839,02	20
C		gypsum-clay panels partition wall thickness 10 cm	120%	€ 2.304,46	21
	A.03	**Concrete screed**			
5	A.03.01	lightened insulating screed			
A		lightened insulating screed with expanded clay quick	105%	€ 3.379,20	34
B		lightened insulating screed with natural cork	110%	€ 4.878,40	34
C		lightened insulating screed with expanded vermiculite	90%	€ 5.156,80	33
	A.04	**Plaster finish**			
6	A.04.01	Premixed plaster for interior wall coatings			
A		Interior plaster with lime - cement mortar	100%	€ 4.994,08	83
B		Interior plaster with lime mortar	110%	€ 4.877,60	82
C		Interior plaster with cement mortar	90%	€ 4.994,08	82
	A.05	**Floorings and sheathing/walls**			
7	A.05.01	ceramic floor blasted tiles			
A		ceramic floor blasted tiles 40 x 40	100%	€ 2.837,97	18
B		ceramic floor blasted tiles 60 x 60	110%	€ 4.874,85	14
C		ceramic floor blasted tiles 20 x 20	90%	€ 2.497,11	18
8	A.05.02	Ceramic wall cladding			
A		ceramic wall tiles 20x20 mono-coloured	90%	€ 6.261,71	49
B		ceramic wall tiles 20x20 marble-effect	100%	€ 3.632,72	49
C		ceramic wall tiles 10x10 stone-effect	110%	€ 7.433,79	60
9	A.05.03	Skirting board			
A		Stoneware skirting board 10x20	110%	€ 2.504,80	21
B		Clinker skirting board 8x24 glazed	100%	€ 1.700,00	17
C		Wooden skirting board - cherry 75x10mm	80%	€ 1.201,60	9

WORK AND QUALITY BREAKDOWN STRUCTURE (2)

No. / WP alternatives	WBS	Work Package description	Quality estimate Qi (%)	Cost Ci (€)	Duration (h) Di
	A.06	**Windows and doors**			
10	A.06.01	counter frame for sliding doors			
A		metal sub-frame for sliding doors	100%	€ 511,28	3
11	A.06.02	counter frame for hinged doors max width 11 cm			
A		wooden counter frame fir depth 2,5 cm width 11 cm	100%	€ 93,60	1
12	A.06.03	wooden hinged solid door			
A		Hinged solid interior door - tanganika walnut wood	90%	€ 2.412,84	8
B		Hinged solid interior door - walnut wood	120%	€ 3.855,00	7
C		Hinged solid interior door - oak wood	100%	€ 3.209,88	8
	A.07	**Electric system**			
13	A.07.01	Electric system for one apartment			
A		Electric system for one apartment	100%	€ 2.200,00	21
	A.08	**Plumbing and sanitary system**			
14	A.08.01	Supply and installation of vitreous china toilet bowl			
A		Vitreus china toilet bowl	100%	€ 473,50	5
B		Vitreus china wall-hung toilet bowl	110%	€ 629,10	5
C		Vitreus china wall-hung chrome finish toilet bowl	120%	€ 1.034,08	6
15	A.08.02	Supply and installation of vitreous china bidet			
A		Vitreous china bidet	100%	€ 469,26	4
B		Vitreous china wall-hung bidet	110%	€ 625,10	5
C		Vitreous china wall-hung bidet with chrome finish	120%	€ 1.030,08	6
16	A.08.03	Supply and installation of vitreous china wash basin			
A		vitreous china wash basin 70x55	100%	€ 687,84	5
B		vitreous china wash basin 65x50	95%	€ 643,20	5
C		vitreous china washbasin 70x55 pedestal basin	105%	€ 842,06	6
17	A.08.04	Sanitary waste water system			
A		sanitary waste water system for one bathroom PVC	100%	€ 629,12	8
18	A.08.05	domestic hot/cold water system			
A		domestic hot/cold water system polybutylene	100%	€ 967,00	9
B		domestic hot/cold water system galvanized steel	95%	€ 1.156,64	18
C		domestic hot/cold water system cross-linked polyethlene	105%	€ 1.366,44	17
	A.09	**Building assistance**			
19	A.09.01	wal assistance plumbing	100%	€ 640,00	11
20	A.09.02	wal assistance electrical system	100%	€ 880,00	15
	A.10	**Painting**			
21	A.10.01	Indoor water-based paint			
A		Indoor water-based breathable paint	95%	€ 3.648,20	55
B		Indoor water-based breathable / washable paint	100%	€ 4.077,40	60
C		Indoor palette knife effect resin-based wall coating	110%	€ 20.839,40	309

Tab. 1. *Pilot study data set.*

with the maximum and minimum set limits of the three parameters, termed TC_{max}, TC_{min}, TD_{max}, TD_{min}, TQ_{max}, and TQ_{min} (Tab. 1) (and Fig. 3).

4. PILOT STUDY APPLICATION

A GA-based algorithm has been implemented with Solver®, an add-in of MS Excel® [35]. This application can quickly explore the solution space and identify a set of optimal solutions. The purpose of the pilot study is to test the proposed GA-based procedure. The pilot study consists of a small building renovation project that has also been used in previous research works by the authors but with different procedures and computer applications. This paper constitutes an evolution aimed at increasing the procedure's efficiency. The pilot study consists of a refurbishment project of two small residential apartments with a superstructure of load-bearing masonry walls. Most activities were aimed at renovating the architectural finishes and the mechanical, electrical, and plumbing services. For each work package of the pilot study, three different commercial product options have been considered, and the corresponding activity durations, costs, and quality performances have been detected from a public works price list. Quality indexes have been evaluated straightforwardly as product quality and its suitability for use (Tab. 1). Therefore, the proposed TCQT procedure has been implemented using Solver®-based GAs to find a set of optimal solutions for the building construction project. The data found for each work package are presented in the following text.

No alternative permutations are possible between different species because of the structure of chromosomes, i.e., the number of WPs in each network path. The chromosome of a species is created by time, cost, and quality data of each chosen WP alternative belonging to a network path. The limit values of total project alternatives can be found by time-based computation of the critical path method (Fig. 3 and Fig. 4) and the total sum of the cost and quality data of the project (Tab. 1). Minimum and maximum total values of the three project parameters, time, cost and quality, can be found by manual computation of the corresponding alternatives of each WP (Tab. 2). The minimum total value of TDj was computed

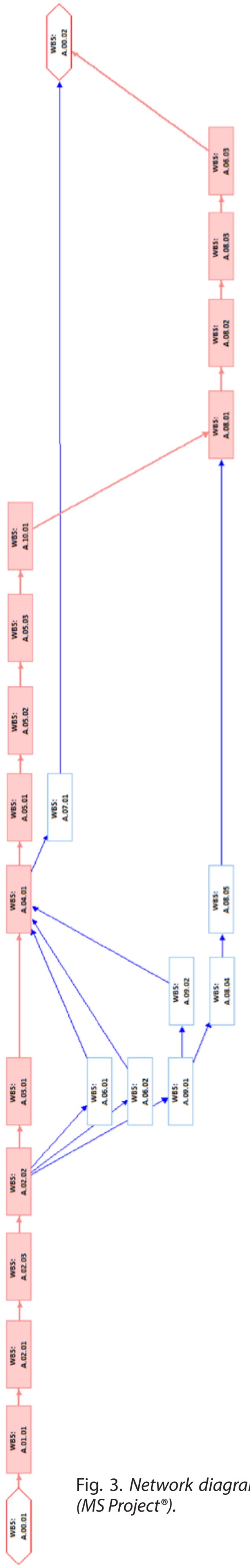

Fig. 3. *Network diagramming of the pilot study project (MS Project®).*

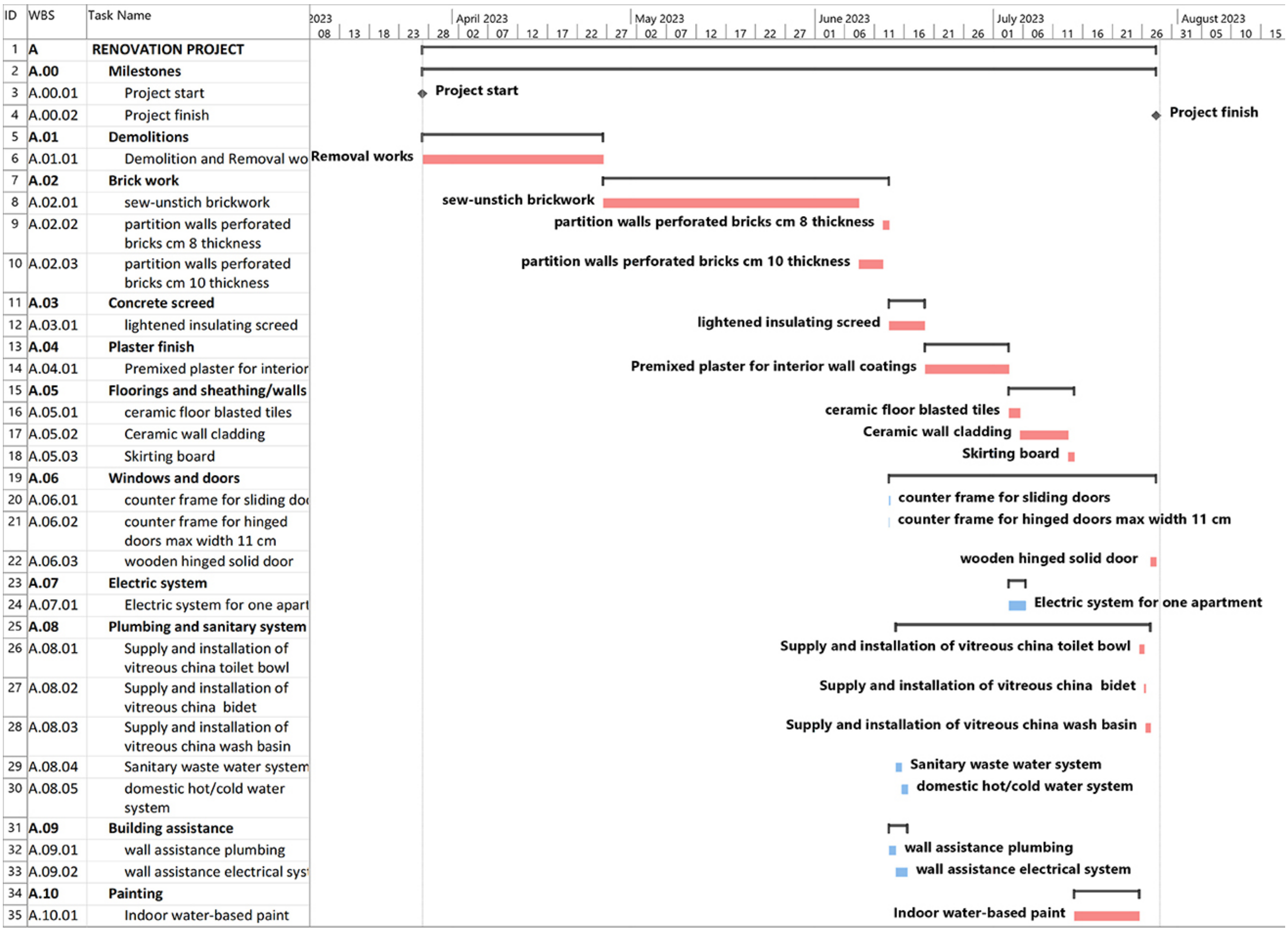

Fig. 4. *Gantt Chart of the pilot study project (MS Project®).*

selecting all the possible options of the dataset of table 1 with the minimum activity duration (Di), and then calculating the critical path. The minimum total values of TCj and TQj were found by adding all the possible alternatives in Tab. 1 with the minimum cost Ci and quality Qi. Maximum limits TDj, TQj, and TCj were computed similarly but using maximum values Di, Ci, and Qi of activities and WPs. Please note that the six limit values found in Tab. 2 belong to six different project alternatives. The aim of setting each indicator's min/max limits is to assess the boundaries that define the min/max performance of project alternatives indicated by the outputs computed by the GA-based procedure.

Therefore, using the evolutionary algorithm, the Solver® application has been set for the specific problem. The optimization engine has the following characteristics. Each WP has three alternatives, say A, B, and C, each with corresponding time, cost, and quality indicators. Each option is multiplied by a scalar coefficient ci that can be 0 or 1 depending on the value of the random variable xi given by the Solver and by the constraints of the spreadsheet (Fig. 5). The network diagram and the

Total project values	**Maximum limit**	**Minimum limit**
Total project duration TDj	TDmax = 1067 (h)	TDmin = 714 (h)
Total project cost TCj	TCmax = € 113.309,99	TCmin = € 64.668,68
Total project quality index TQj	TQmax = 109.1%	TQmin = 94.5%

Tab. 2. *Limit values of total project alternatives.*

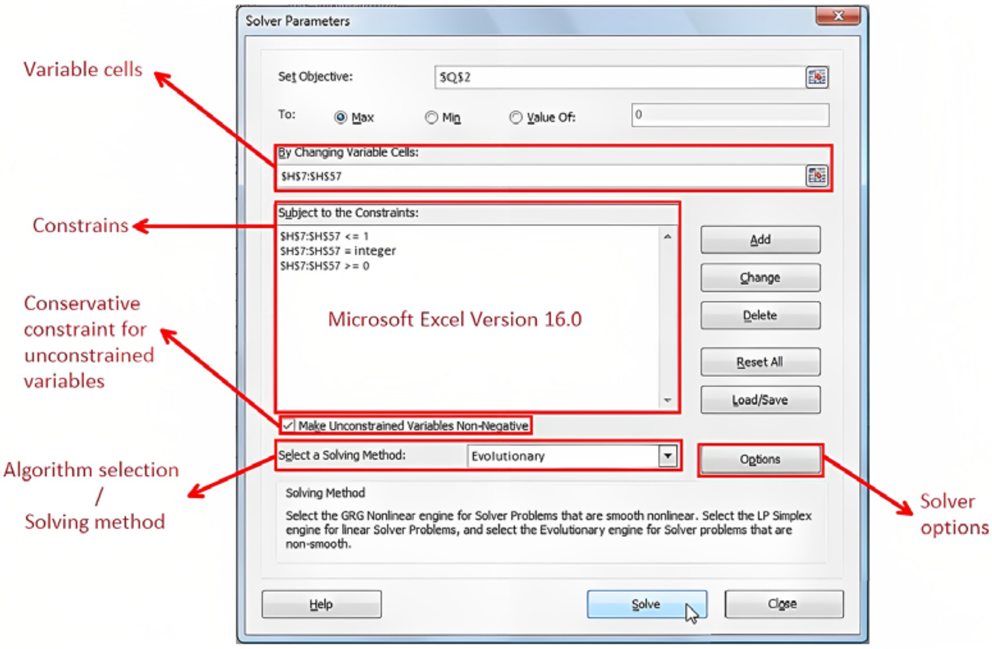

Fig. 5. *Setting of Solver® for the pilot study project (MS Excel®) (Pozzi, 2021).*

working options of the pilot study have been formalized in Microsoft Project (Fig. 3 and Fig. 4). The maximum number of generations has been set to 100 and the maximum time without improvements to 100 seconds. The best-found optimized result in the case of balanced weights (Kq=1, Kc=1, Kt=1) is the following: Fitness value=0.34853; Total project duration TDj=720 h; Total cost TCj=€ 64,668.68; Total quality index TQj=97.38%. The results are consistent with the limit values of total project alternatives in Tab. 2.

5. DISCUSSION

Solver® is an Excel add-in program that can be used for different optimization analyses of MS Excel®. It includes a GA, termed evolutionary Solver. The Solver guide [35] describes the following steps of the GA:

1. Start with a population of chromosomes randomly chosen that constitutes the first generation or first iteration;
2. Evaluate the fitness values of chromosomes;
3. Rank the chromosomes by their fitness;
4. Apply genetic operators: elitism, crossover, and mutation. All these operators are assigned a probability of occurrence;
5. Create a new generation from these chromosomes and evaluate their fitness;
6. Apply genetic operators again as before and iterate until the process is stopped;
7. End of the process when convergence is achieved or the maximum number of generations is reached.

The critical point of this process is setting constraints concerning the value of the variables and required path computation. The results are inside the possible maximum and minimum limit values of each project index representing TCQT, intending to find a solution that optimizes the time and cost with the lowest possible values and maximizes the quality of the project work packages. The time-related index addresses the total project duration TDj of the j project, found by critical path computation. The range of TDj values is from 714 h to 1067 h (Tab. 2). Solver found an optimized TD value of TD=720 h. The quality-related index addresses a designer's comprehensive score Qj of the project found as the mean value of the 21 Qi indexes of each "i" activity of the project. The range of Qj values is from 94.5% to 109.1% (Tab. 2). The optimized found TQj value is TQj=97.4%. The cost-related index is the total project cost TCj found by adding the cost Ci of each "i" activity of the project. The range of TCj values is from € 64,668.68 to €

113,309.99 (Tab. 2). Solver found as TCj value TC=€ 64,668.68, which is the minimum value. Actually, the proposed application found the project with the lowest cost value as the best result. This issue is of interest, as it could be the typical solution the owner's consultant found without any decision support system like the one described and implemented with Solver®. Also, the total project duration value is excellent, near the minimum value. The calculated quality value is 97.4% under all activities' 100% quality index target. However, as a compromise, a trade-off between the three values addressing time, cost, and quality can be considered a good result. This indicator can be enhanced by increasing the relative weight of Kq for quality. Limits of the proposed application is using a standard spreadsheet, which prevents the use of the procedure to large construction projects and small population sizes [36]. These limits will be tackled in future research work.

6. CONCLUSIONS

TCQT problem is of great importance in construction project management. Still, the complex relationship between these project KPIs varies from case to case, and no simple solutions are feasible in actual projects. In order to demonstrate that AI applications can address the TCQT problem, an innovative GA optimization has been developed and implemented with Solver®, a Microsoft Excel® add-in program. Actual data from a pilot study concerning each project activity's expected duration, quality index, and cost have been detected, and three possible performing alternatives of the WPs were developed. Therefore, the overall performance of the whole construction project, with the processing of all the WPs, was simulated, considering the possible alternatives of activity duration, cost, and quality. The time estimate was developed using a network-based activity network with Microsoft Project®, while the total cost estimate was the sum of the cost of all work packages, and the overall project quality index was estimated as the average quality index of all work packages. A GA-based procedure has been proposed, developed in two stages to find automatically (or semi-automatically) a balance between the time, cost, and quality project objectives via GA computation. In Stage 1 – Construction Project Identification, the WBS, QBS, BOQ, and project schedule logic are developed corresponding to the three possible activity alternatives. In Stage 2, the iterative population generation process is performed based on the fitness function evaluation and the selected GA operators (crossover, mutation, and elitism) after setting algorithm constraints. After 100 generations, the procedure is terminated, and the found results are evaluated. Actual data for a pilot study simulation of a building renovation project of a small residential building have 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. Limits of the proposed application are the use of a standard spreadsheet that prevents the application of the procedure to large actual construction projects and the small population size. Nevertheless, researchers and practitioners can easily implement this simple application addressing the desired TCQT problem solution, even if it is sub-optimal. Future research work will be aimed at improving the procedure's efficiency so that it can be implemented in larger projects.

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