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Sequencing algorithm with multiple-input genetic operators: Application to disaster resilience

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ABSTRACT

A novel evolutionary optimization methodology called "*Algorithm with Multiple-Input Genetic Operators*" (*AMIGO*) for scheduling independent tasks considering resource and time constraints is presented. *AMIGO* is characterized by new genetic operators enriched with complementary information, including auxiliary variables computed by the fitness function, as well as the global parameters of the problem. The application of *AMIGO* to multi-phase optimal resilience restoration scheduling of highway bridges is presented and discussed. To this purpose, enhancements have been made also to the bridge network resilience analysis (a new performance metric and restoration model). The quality of the solution and efficiency of *AMIGO* are demonstrated through the application to a large transportation network subjected to earthquake.

1. Introduction

This paper presents a new multiple-objective optimization methodology, consisting in an evolutionary solution technique for scheduling of independent tasks, considering time and logistic constraints. The optimization solution methodology called *Algorithm with Multiple-Input Genetic Operators* (*AMIGO*) includes novel genetic operators, which take advantage of auxiliary variables computed during the fitness evaluation process, as well as some global problem parameters, to enhance the search procedure. Fig. 1 highlights this feature compared to common genetic algorithms. The versatility of the proposed methodology makes it applicable to a variety of scheduling problems common in different fields, such as construction management, production and manufacturing industry, and emergency planning. There has been an extensive research in the field of project scheduling optimization. Alternative approaches and their foundations have been discussed in [1–4]. Also, extensive review of different techniques and formulations of project scheduling problems can be found in [5–8]. In many classical forms of project management and scheduling, the objective of the problem can be formulated in closed-form, such as project duration, time lag, lateness, and resource consumption [1–4]. However, in the majority of real-world applications, the objective functions of scheduling optimization problems cannot be presented by an algebraic model due to the complexity involved in the computation of the objectives. Focusing on such cases, the heuristic nature of *AMIGO*, eliminates the constraints on the form of the objective, and therefore can be used for any type of function. An effort has been made to make the technique appealing for practical applications, in terms of simplicity, efficiency, and applicability to large real-word problems.

To showcase the proposed algorithm, its application to resilient disaster recovery is presented. In particular, the prompt recovery of infrastructure systems is pursued. In fact, the life of the modern society is highly reliant on its critical lifelines and infrastructures, such as healthcare facilities, water and electric supplies, and transportation networks. In the case of an extreme event (such as earthquake or hurricane), the long lasting loss of functionality of these vital elements contributes considerably to the reduction of habitability of the impacted regions. The consequent gradual (large-scale) migration of the population is one of the major threats to the community's recovery process and its social and economic integrity [9,10]. Therefore, it is imperative for the communities located in disaster prone regions to have a comprehensive pre-disaster mitigation and post-event restoration plan, which allows to retrofit the most vulnerable components, and to recover efficiently from the unavoidable damage. This encouraged researchers from several academic fields, as well as disaster

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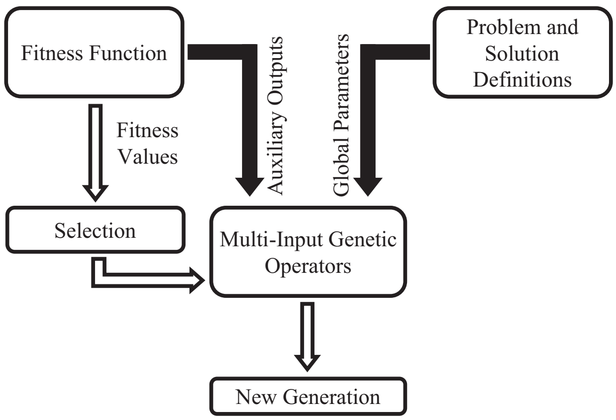

Fig. 1. Schematic view of *AMIGO*. The highlighted arrows indicate the novel elements of the framework. The use of additional information in the genetic operators enables a much faster convergence to the optimal solution.

officials, to pay a paramount attention to the topics of disaster mitigation, emergency management, and restoration planning. As a result, several planning and scheduling computational models and optimization methodologies have been proposed and developed for a variety of applications. Along this line of research, *AMIGO* is a major improvement in the ability to consider very complex objectives, while maintaining the computational cost acceptable for realistic applications.

In particular, in this paper *AMIGO* is applied to the post-disaster repair and restoration prioritization of damaged highway networks. Among various infrastructure systems, transportation networks require particular attention, as the performance and quality of services provided by many other physical and socio-economic units (e.g., businesses) are highly dependent on the functionality of transportation networks, both in ordinary and emergency situations. The functionality of transportation networks is threatened by different factors (e.g., closure of roads due to collapse-induced debris or landslides), among which damage to the bridges is the most common and critical. To this respect, *AMIGO* was tailored to find the optimal restoration sequence of the damaged bridges in the context of a highway network. Among several infrastructure system performance criteria, resilience has been selected as the objective of the optimization problem. Resilience assessment requires several sophisticated, iterative, and computationally expensive procedures. Moreover, these procedures can be formulated only algorithmically, thus the objective function cannot be coded in closed-form. These challenges make resilience assessment a perfect benchmark to test *AMIGO* and showcase its characteristics.

The notion of resilience was first propounded by ecologists to describe the reorganizing capability of ecological systems after a disruption, to a new stable state [11,12]. In the engineering world, resilience has been generally defined as the ability of social units to absorb, withstand, and efficiently recover from a perturbation [13]. Bruneau et al. [14] have first presented a conceptual framework for quantitative assessment of seismic resilience and highlighted the need for communities to focus on different aspects of this concept. Following this work, many researchers have presented procedures and metrics to quantify and enhance disaster resilience such as in [15–22]. Moreover, extensive studies have been performed on formulating and quantifying resilience for particular infrastructures and lifelines, such as healthcare facilities and hospitals [23], power grids [24], telecommunication systems [25], water supplies [26], and maritime transportation systems [27]. Regarding the recovery and resilience of transportation networks, Bocchini and Frangopol [28,29] presented a framework for quantifying the performance of highway networks considering the influence of the damaged bridges and optimizing the bridge restoration in terms of resilience and intervention cost. The impact of different retrofit techniques on seismic resilience of highway bridges has been presented in [30].

While the focus of this paper is the presentation and application of *AMIGO*, refinements have been performed also on the formulation of post-disaster resilience analysis of bridges and highway networks compared to the previous model presented in [31]. These are (1) a new bridge recovery model, and (2) the consideration of different phases of disaster management by introducing a new network connectivity-based resilience metric.

The performance of *AMIGO* is demonstrated through a large-scale numerical example. The highway network serving the port of San Diego has been chosen for this purpose, which contains 238 highway bridges. The proposed methodology has been utilized to find the best restoration strategies for the bridges of the network damaged by an earthquake scenario, selected based on the seismicity of the region. In addition, the efficiency of the proposed formulation has been examined through comparison of the results with previous methodologies using smaller test networks.

2. Proposed optimization technique: *AMIGO*

In this section, the framework and solution strategy of the proposed scheduling optimization problem are presented in general terms. Several project scheduling problems have been addressed by the research community, considering different objectives (e.g., project duration, maximum activity lateness, net percent value), and constraints (e.g., precedence, resources, time lag). An extensive review of different problem definitions, formulations, and solution methodologies can be found in [5–8]. The optimization problem framework propounded in this study is a version of resource-constrained project scheduling with one renewable resource type, considering a maximum project duration and generic objectives. The problem is formulated as a combinatorial optimization characterized by a triple $(\mathbf{A}, NSA_{max}, T)$. Activities (the words "activity" and "task" will be used interchangeably throughout this paper) of the project are collected in set $\mathbf{A} = \{A_1, A_2, \ldots, A_n\}$. To take into account logistic constraints (such as man-power, equipments, contractors) typically involved in planning, the number of simultaneous activities at each time step t is limited to NSA_{max}. T is the investigated time span of the project. A schedule $\mathbf{S} = \{S_1, S_2, \ldots, S_n\}$ is defined as a vector in $\mathbb{R}^n$ such that S_i is the start time of activity A_i. Finally, the quality of each schedule is determined by its associated fitness, which is a function of the sequence of tasks.

In many cases, the essential components (e.g., fitness functions and constraints) of the problem cannot be formulated in closed-form due to their complexity. This in fact, limits the application of standard optimization methodologies. For such cases, the advancement of heuristic optimization techniques, and evolutionary algorithms in particular, has resulted in high-quality near-optimal solutions for several challenging real-world optimization problems involving industrial, transportation, structural, and infrastructure engineering, among other fields.

AMIGO belongs to this class of optimization solvers, which are powerful heuristic optimization techniques inspired by the process of natural selection and offer several advantages, such as applicability to almost any type of optimization problem (discrete and continuous), objective functions (differentiable and non-differentiable), and constraints (constrained and unconstrained domains). Moreover, they are particularly convenient for solving multi-objective optimization problems by Pareto-based approaches. Discussion about the fundamentals of evolutionary