Integrating a multi-objective optimization framework into a structural design software

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ABSTRACT

In this paper, we present a tool combining two software applications aimed at optimizing structural design problems of the civil engineering domain. Our approach lies in integrating an application for designing 2D and 3D bar structures, called Ebes, with the jMetal multi-objective optimization framework. The result is a software package that helps civil engineers to create bar structures which can be optimized further with multi-objective metaheuristics according to different goals, such as minimizing the structure weight and minimizing the deformation. The main features of both Ebes and jMetal are described and how they are combined together in one single tool is explained. Finally a case study to illustrate how the application works is presented.

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1. Introduction

Civil Engineering encompasses different phases in the process of building bridges, roads, and many other built environments. Some of these phases are the design, construction and maintenance of these environments. In this field, as in many other disciplines such as economics or biology, complex optimization problems continuously arise, making the tasks that civil engineers must face daily much harder. In such a situation, an expert on structural design but with a lack of knowledge about optimization techniques may be confronted with a complex optimization problem that needs to be addressed properly.

To complicate matters even further, most of the time these problems need to be optimized taking into account two or more conflicting criteria. If we focus on the design of a particular structure, this means that if we are looking to minimize the structure's weight and minimize the stiffness, improving one optimization criterion implies worsening at least another criterion. These kinds of problems are usually referred to as Multi-Objective Optimization Problems (MOP) in the literature [6]. Their main intrinsic feature is that usually, there is no a unique solution which optimizes all

the criteria at the same time. The solution to these problems therefore consists of a set of trade-off solutions between the different optimization criteria. In the field of multi-objective optimization, these solutions are said to be *non-dominated*, and the entire set of solutions that cannot be further improved in any criterion is referred to as the *Pareto optimal set*. This set, when it is plotted in terms of the optimization criteria being considered, is referred to as the *Pareto front*. If the MOP to be optimized is the design of a structure, the Pareto front represents an useful tool for civil engineers as it allows the trade-off between the different criteria to be graphically displayed, therefore enabling the designer to select the solution which better suits his/her interests at any given moment.

Most MOPs arising in real world scenarios, like civil engineering, can have NP-Hard complexity, present non-linear formulations, epistasis, and many other features that make the application of exact techniques infeasible. Therefore, approximation techniques, aimed at computing an accurate approximation of the Pareto front in polynomial time, are considered. *Metaheuristics* are an example of non-exact techniques which have been successfully applied to solving MOPs [6,7]. A metaheuristic is usually defined as a high-level strategy that governs a set of underlaying simpler operations (usually heuristics); an accurate coordination of these underlaying operations is what makes metaheuristics such a powerful search method [5]. The most well-known metaheuristics are evolutionary algorithms, but other techniques are also

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being used (e.g., Particle Swarm Optimization, Artificial Immune Systems, etc.). Some examples applied to structural design are [13,16,17]. Interested readers can refer to [14,22] for surveys of metaheuristics applied, respectively, to single- and multi-objective problems related to the design of civil structures.

In order to produce an optimized design of the structure of a building, different tasks must be completed. First, provide a sketch of the structure; second, define the MOP associated with that structure (i.e., the optimization criteria for the structure); third, apply an optimization technique (usually a metaheuristic); fourth, visualize the Pareto front of possible alternatives; and fifth, select a solution from the Pareto front. These tasks require knowledge in many different fields; furthermore, some of them are not specific to a particular design and can be applied to different structures; for example, the same optimization technique can be applied to optimizing many different types of structures. In this context, there is a lack of tools that (1) free civil engineers from having to have a deep knowledge on optimization, and at the same time and (2) allows them to apply different kinds of metaheuristics to optimize the same design or to apply the same metaheuristic to different problems with minimum effort.

The aim of this paper is to fill this gap and to describe the tool that covers all these issues. Specifically, our tool, called Ebes + jMetal, is intended to aid civil engineers from the very first design step of the structure to the last phase in which a solution from the approximated Pareto front is chosen. Ebes + jMetal integrates two existing open-source software applications: Ebes,[1] which incorporates a graphical tool for defining the components a structure is composed of a structure, and jMetal [10], which is a powerful optimization framework containing the implementation of many advanced metaheuristics for multi-objective optimization. There are a number of structural design software packages (e.g., Frame3DD,[2] PowerFrame,[3] RISA-3D,[4] etc.) but, to the best of our knowledge, none of them have an integrated multi-objective metaheuristics optimization framework.

Our goal is for Ebes + jMetal to become a useful tool in the field of civil engineering, enabling the application of unexplored optimization methods in the field. In this context, the survey [22] revealed that the vast majority of existing approaches only explore the application of NSGA-II [8] and SPEA2 [23], two algorithms that were developed more than ten years ago. The use of jMetal can facilitate the application of state-of-the-art optimizers to structural design problems.

The benefit of using our Ebes + jMetal software is therefore two-fold. First, civil engineers are endowed with a software package covering the full process of developing bar structures including a powerful optimization module that can be used with a minimum knowledge of the metaheuristic internals. Second, the problems defined within Ebes can be used as benchmark problems by researchers working on the design of new optimization techniques, which can lead to new algorithmic advances that can be applied to improve the design of 2D and 3D bar structures.

Our tool can be used according to the work flow presented below:

1. The bar structure is designed using Ebes. Once this step has finished, an output file with the description of the design is generated.
2. The parameters of the metaheuristics intended to be used as optimizers are set.

3. The selected jMetal algorithm is chosen from Ebes, which launches the jMetal solver. The algorithm takes the file previously created in Step 1 as an input; the output of the jMetal algorithm consists of two files containing the Pareto optimal set approximation and its corresponding Pareto front.
4. The resulting files of the solver are loaded back into Ebes, so that the generated structural designs can be analyzed. The user of the tool can then decide which of the optimized designs fits more closely within the context.

We would like to remark that our software has a Web site[5] containing support information, such as tutorials, examples of use and a set of ready-defined structures.

The rest of the paper is structured as follows. Section 2 describes the main features of Ebes and jMetal. The process of combining both tools is detailed in Section 3. A case study illustrating how the Ebes + jMetal software works is included in Section 4. Finally, Section 5 presents the conclusions of the paper and suggests further lines of research.

2. Description of the tools

In this section, we describe the main features of Ebes and jMetal.

2.1. Ebes: design of bar structures

Ebes is a software application aimed at the design, calculus, and analysis of bar structures including trusses, frames, and a combination of the two, supporting flat (2D) and spatial (3D) structures. It is written in Visual Basic.Net and is intended for students and professionals of disciplines such as civil engineering, mechanical engineering, and architecture.

The numerical model incorporated in Ebes for calculus is the direct stiffness method also known as the matrix stiffness method [21], based on the first-order conventional linear elastic stiffness matrix, so forces and deformations are linearly related [1]. Second order effects include the geometric stiffness matrix [18,12], which considers the effects of axial load on the bending stiffness of a member. The effect of buckling can also be considered in the calculus.

Ebes provides pre- and post-processing modules, which allow the users, respectively, to design the overall design of the structure and to analyze the results both numerically and graphically.

The main features of Ebes are:

- The maximum number of nodes and bars which compose an structure is unlimited and it is only bound by the main memory of the computer.
- Automatic grouping of bars that present similar behavior according to a set of acceptable parameters, thus simplifying the input of the data into the application.
- Self deduced bars weight according to the type of material and the bar cross-section, static excess of loads in the node, and static excess of load distributed over the bars.
- Up to seven combinations of hypotheses using different weight vectors.
- Computation of the variable efforts along bars as part of the post-processing component.
- Verification of the bar stress according to the shape and measurements of the bar's cross section.
- Capability to import files with DXF v12 architectures generated with third party CAD/CAM software. This feature is

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[1] Ebes: http://ebes.sourceforge.net.

[2] Frame3DD: http://frame3dd.sourceforge.net/.

[3] PowerFrame: http://www.buildsoft.eu/en/product/powerframe.

[4] RISA-3D: http://www.risatech.com/p_risa3d.html.

[5] http://ebesjmetal.sourceforge.net.