4.3 A MATHEMATICAL OPTIMIZATION AND MACHINE LEARNING APPROACH FOR PIPELINE ROUTING

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ABSTRACT

In shipbuilding, pipeline routing is a difficult problem as space is rather limited. This constraint and others related to obstacles, costs, legislation, or operability are considered to set the pipeline layout by means of a mathematical model. The problem is solved in an exact or heuristic way when the complexity increases when dealing with real instances, using Artificial Intelligence tools. In this work, we outline some issues and solution proposals which have been applied to a case study that shows the usefulness of mathematical tools in design engineering.

INTRODUCTION

Shipbuilding consists of a conceptual design phase, when engineers determine all the necessary construction requirements, and a basic design phase, when the equipment are adequately selected and connected by pipes or electrical circuits. Due to the limited space, more pronounced in the shipping industry than in other industrial plants, the later phase is crucial. Some constraints must be satisfied by the optimal routes such as avoiding obstacles or passing through initial and end points. Others are more flexible, such as preference zones, elbows, and material and maintenance costs and can be determined with the appropriate mathematical tools.

GHENOVA is an engineering company which delivers consulting in marine services and requires design tools based on Artificial Intelligence and Machine Learning. These tools must incorporate particular features or restrictions for ships which are not currently considered by commercial software. Among them is the so-called scheme problem. The scheme encompasses a set of design specifications regarding the number of branches that must be connected to a trunk line, valves on the branches, and some other related aspects to be considered. Once the initial design has been determined, given by the scheme conditions, the pipeline routing problem will be solved following the technical specifications.

STATE OF THE ART

The first approach to the scheme problem proposed by GHENOVA company has been addressed by mixed-integer programming (Cuervas et al., 2017). In this paper, we will focus on pipeline routing, including main lines and branches.

The pipeline routing problem was previously solved by means of three-dimensional routing algorithms. We refer the reader to Park and Storch (2002) and the references therein to see some particularities of the pipeline design in a shipbuilding domain. In that paper, the proposed algorithm combines a cell-generation method to consider the geometric aspects and the correct assignment of costs, in order to take into account the non-geometric ones. Subsequently, the path for each pipeline is chosen from a tree of combinations.

Pipeline routing has been studied in other spheres beyond ships. For instance, the problem has been addressed to design chemical plants (Guirardello & Swaney, 2005). Here, the developed procedure is based on the construction of a partial graph where node positions determine where pipes can be routed, provided that the safety restrictions and minimum distances from components are satisfied.

Traditionally, pipe routing has been studied as a shortest path problem solved using A* or Dijkstra algorithms, among others. When the problem is designed in three dimensions, it becomes more complicated. To face the problem, Min, Ruy, and Park (2020) have recently designed an ad hoc Jump Point Search algorithm. This method is performed in a three-dimensional space and provides pipe paths which are parallel to the axes.

Building information modeling (BIM) software is used during the design pipeline process. However, still there is room for improvement for those automatic tools and experienced people have to intervene in choosing the final pipe system layout (Singh & Cheng, 2021). To ease the task, many heuristics and optimization methods have been studied and developed in the field in recent years.

CONTRIBUTION

There are many aspects to consider as part of solving the pipeline routing problem by means of Artificial Intelligence techniques. These issues are, among others, the adequate definition of the solution space, the correct pipe layout satisfying a given scheme design, or the definition of an appropriate function to compare the quality of different routing solutions. Our first contributions to the field were reported in Cuervas et al. (2017). In this research, several of these technical aspects were solved following the instructions of GHENOVA, a company with which we are collaborating since 2015.

Some of the contributions arising from previous and current transfer collaborations with that company are (1) the development of a procedure that discretizes the solution space by means of nonuniform meshes considering the present physical barriers, (2) an approximation of the scheme design problem by means of a mixed-integer programming model capturing the main theoretical characteristics of the problem, and (3) a cost function to take into account the singularities in naval design, such as length, number of elbows, and zone priorities. They have been included in the objective function as both bonuses and penalties.

From this starting point, we have improved the graph-based discretization solution space. Along with the nodes contained in the primitive mesh, the new graph structure adds virtual nodes to incorporate changes of directions (elbows) in a number considerably smaller than the original one and, therefore, the size of the problems has decreased. Given the graph that defines the solution space, the adequate objective function, and the known initial and end points of the pipelines which were defined by the scheme specifications, the pipeline routing problem has to be solved. Our contributions concerning this stage focus on modeling the pipeline routing problem in an efficient way, so that the problem can be solved exactly. On the other hand, for large-sized instances, we have tested Machine Learning heuristics which provide feasible good-quality solutions sought by naval engineering.

In this respect, we have developed three Matheuristics that share a common idea: the decomposition of the general problem in subproblems which can be independently solved by flow algorithms or by shortest path algorithms. It should be noted that depending on the pipe's dimensions and shapes, the pipeline routings must keep a security distance between them and, therefore, they "compete" for common space. Thus, the decomposition of the general problem on subproblems might lead to incompatibilities that can be solved by an iterated scheme. The different Matheuristics differ in the choice of the set of subproblems, in how to solve the incompatibilities, and in how to carry out the iterated scheme.

Another important issue is the minimum required distance between consecutive elbows belonging to the same route. Accordingly, we propose a recursive algorithm to obtain the shortest paths that meet the threshold between consecutive elbows that extends the classical shortest path algorithms. Nevertheless, the complexity of this new algorithm is greater than the classical ones, so we have also defined a heuristic algorithm to be integrated into the above described Matheuristics.

At the same time, we have developed a model to exactly solve the pipeline routing problem. The problem is seen as a multicommodity flow problem which extends classical models by means of adding constraints to ensure that the pipeline routes of different services keep a security distance between them. Additionally, constraints to keep the above-mentioned distance between elbows are defined. At this moment, we are working on algorithms which are able to reduce the solution space, in order to solve the problem in this reduced solution space using branch-and-cut methods.

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