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Integrating a constraint-based optimization approach into the design of oil & gas structures

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Abstract

Currently, design optimization is widely applied in civil and mechanical engineering. Optimization strategies are used to enhance the product performance and reduce the cost, lead time and environmental impacts related to the product lifecycle. In this context, evolutionary algorithms are used for determining the optimum solution in engineering problems. The design of complex products, such as those that are engineered to order, often requires the study of subproblems. Modularization is a common practice to reduce the complexity; however, the configuration practices are difficult to be applied in engineered to order products. As a solution, the integration of the optimization tools and model-based simulations is proposed to manage the complexity. However, even when a commercial software is available to support the parameter optimization, there may exist a lack of design tools that can be integrated with the product structure of an engineered to order product. This paper describes a design optimization approach that integrates a Constraint Satisfaction Problem (CSP) tool with model-based simulations in a collaborative design context. A platform tool is developed using the .NET and MiniZinc languages. The case study is focused on the design optimization of a 700-ton steel structure. In particular, the optimization analysis considers the mechanical behavior, weight, and cost reduction.

Keywords: Constraint Satisfaction Problem, Design Optimization, Steel Structures, Engineer-To-Order, oil & gas

1 Introduction

Engineer-to-order (ETO) products are expensive and customized solutions that satisfy the client requirements with a high level of diversity. Moreover, ETO means that an engineering activity must be performed to achieve a solution. A business strategy based on ETO products often requires design tools for an efficient generation of the product variants [1]. The development of ETO products is characterized by a quotation process, which involves the customer and consists of four phases: *request for quotation* (RFQ), *quotation preparation*, *quotation evaluation*, and *order preparation* (Figure 1). The product delivery process requires the design tools to support the decision making during the stage of the quotation preparation because an ETO company is often involved in many quotation processes [1]. In this context, when the design targets are not achieved, numerous time-consuming iteration loops are necessary to optimize the initial solution [2].

The reuse of past solutions occurs widely in companies that produce customized and modularized products [3]. The sales-delivery process of ETO products presents a considerable potential for design reuse [4]. As analyzed by Sabin and Wiegel, 20 years ago, the design of ETO variants was seen as a Case-Based Reasoning (CBR) process, in which each new configuration problem was an adaptation solution of a product family model [5]. As a second step, modularity was applied in this context to reuse predesigned modules [6].

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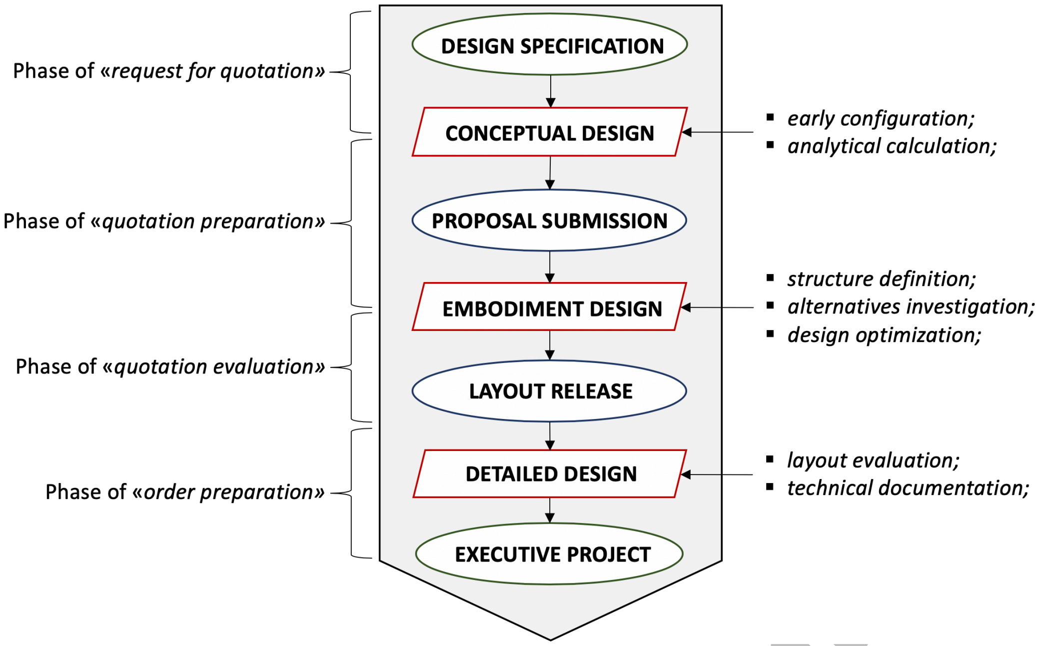


Figure 1 Typical Design Approach for ETO products.

Due to the market competition, solutions based on design automation, product configuration, and design optimization have been increasing in the field of ETO products. The product configuration is an essential approach for selecting various components to constitute a customized product with the aim of meeting the specific requirements of a customer [7]. However, the ETO products differ from configuration products due to the necessity of the engineering and detailed design phases. Johansson studied a method that could help manufacturing companies manage and reuse the engineering knowledge related to the ETO products [8]. Algorithms were implemented to retrieve the engineering knowledge from CAD models and spreadsheets used in the design of the ETO projects. Camba et al. [9] developed methods to retrieve knowledge from CAD models by analyzing the dependencies between each component. A knowledge eliciting approach was also investigated to support the configurations of the virtual prototypes [10]. These approaches can be considered valid to support a connectivism in the context of the Knowledge Based Engineering (KBE); however, these approaches do not consider the relation between the geometrical configuration and results of the simulations. Even if the KBE tools are widely applied in this context, they are used to only manage the product configuration as a reuse system of the design knowledge. Therefore, such approaches work well with light level ETO products, where the term "light" means that the ETO product corresponds to a standard configuration with minor customizations [11]. As already highlighted by André and Elgh [12], the future reuse of models in the ETO approach needs to involve problem solving methods. Additionally, the design of the ETO systems should simultaneously involve the development of a transdisciplinary environment, which requires a cooperation between the design and analysis [12].

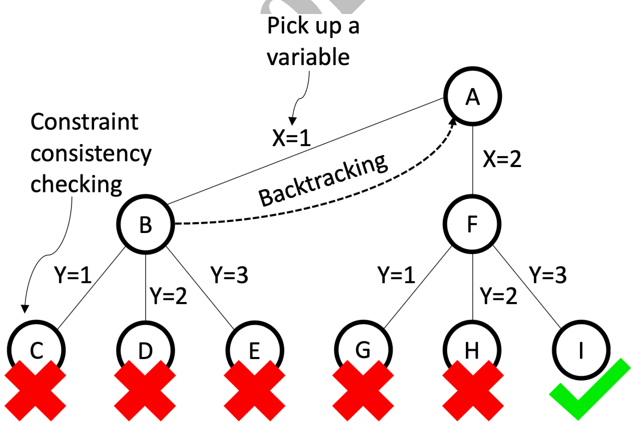
All these studies highlight that the tools to integrate the configurations and optimizations into the same design workflow for products with a high level of customization are lacking. A reason is that a high level of customization cannot be managed using standard interfaces. The recent improvements in computational analysis have continuously enhanced the development of the design optimization practices. However, ETO structures require a design platform that can optimize the product at different levels, integrating several design tools to reduce the time and cost.

Several ontological methods have been described in the literature to support the systematic design space exploration in the context of the model-based engineering. However, effective tools to capture, reuse, and represent the implicit knowledge in the exploration process of the design space are lacking. These tools could be a response to the ability to learn from previous cases and developing knowledge based methods for guided assistance in decision making [13]. Gadeyne et al. described a graphical approach based on the SysML modeling language with the object constraints language for representing the model of the design space for a gearbox [14]. Their research aimed to support the design synthesis during the early embodiment design [15] to define and fix the product topology, components, architecture and connections. The definitions of these parameters at the early design stage exert a considerable influence on the final product cost [16].

Designers apply design rules, tables, formulas, and relations during the engineering design process. Artificial intelligence technologies such as rule based reasoning [17], constraint satisfaction problems (CSPs) [11], case-based reasoning (CBR) [18] are mainly adopted as the problem solving mechanisms for obtaining the configuration solutions. The CSPs are mathematical problems in which each solution must satisfy a set of constraints. Each constraint is the synthesis of a knowledge formalization process through mathematical equations. CSP methods are also applied in engineering optimization problems [19]. In particular, Yvars introduced a deterministic CSP approach to solve a Pareto bicriterion optimization to reduce the size and complexity of the design phase [20]. Pitiot et al. used a CSP approach to support the concurrent product configuration of assemble to order products [21]. These authors considered a constraint filtering process in evolutionary algorithms, obtaining satisfactory results in terms of the time and convergence.

In general, in the literature, many design problems have been analyzed by using a CSP approach with design synthesis. For example, a multidisciplinary design optimization advisor system [22] and the implementation of an ICAD generative model [23] was proposed in the design of aircraft applications. Yang and Dong proposed a CSP approach to address the problems related to the configuration conflicts involving structural restrictions, configuration rules, and repair rules [7]. Some scholars also applied the CSP tools in configuration and planning problems [24]. In this case, the configuration and planning could be considered as two constraint satisfaction problems [25].

The solving processes of CSP problems can be described using a tree graph [26]. Backtracking, branch and bound, and depth first search are the common algorithms to solve these types of problems. Backtracking is a technique that consists of enumerating all the possible solutions and pruning the solutions that do not satisfy certain constraints [27]. This approach employs a graph tree remembering all the nodes already analyzed; in this case, if a path is to be pruned, the algorithm can return to the node that has not been visited yet without risking moving in a path already explored. The backtracking algorithm has an exponential complexity and thus it is not efficient for the not NP complete problems. Nevertheless, the algorithm integrates certain heuristic techniques that allow reducing the complexity.



Step	Variable	Assignment	Constraint checking
1	Pick X	X=1	
2	Pick Y	Y=1	X+Y=2>?4 NO -> fail
3		Y=2	X+Y=3>?4 NO -> fail
4		Y=3	X+Y=4>?4 NO -> fail
5	Backtrack to X, pick X	X=2	
6	Pick Y	Y=1	X+Y=3>?4 NO -> fail
7		Y=2	X+Y=4>?4 NO -> fail
8		Y=3	X+Y=5>?4 YES -> OK

Figure 2 Example of CSP solving processes in a tree graph and table.

Figure 2 describes the backtracking search process, known as depth traversal. This backtracking search begins with the selection of variable x (see node A) and the assignment of 1 to x (see node B). Next, the algorithm selects variable y and assigns values of 1, 2 and 3 to y (see nodes C, D, and E). For every such node, the constraints are checked to satisfy the following sample problem: $x + y > 4$. The relative consistency checking fails at nodes C, D and E. Because all the values in the domain of y have been attempted, the algorithm backtracks to the previous variable x (see node A). Consequently, the algorithm selects another value 2 from the domain of x and assigns this value to x. This selection allows node G to satisfy the problem domain.

As described, several tools and methods have been applied in the literature to support the design and optimization of the ETO products or similar configurations. Even if the design complexity can be managed using a KBE tool, CSP methods, and optimization algorithms, a lack of tools still exists in the development of a flexible and agile design method to support the optimization workflow [28]. The product configuration allows the past design solutions to be reused; however, the delivery of the ETO products requires an engineering analysis before closing the order with the customer. Therefore, the configuration tools can only support a predesign phase in the ETO context. Furthermore, the traditional commercial tools cannot support the designer from the early configuration phase to the product optimization phase including simulations and CAD automation.

Since the integration of the configurations and design optimization tools requires the development of a dedicated design platform, the scope of the proposed research is to study a methodology for improving the design of the ETO products. The paper describes the approach and introduces a test case based on the design of large steel constructions for oil and gas applications. A collaborative design platform is described to support such a design. The objective of the paper is to demonstrate how the reduction in the weight and cost is related to the design of the ETO products during the early design phase, which is the phase in which most of the project layout is defined. The paper also describes the use of the CSPs in the collaborative design platform. The CSP model is proposed as a tool to support the integration between the knowledge base and the design optimization with the simulations.

The remainder of this paper is organized as follows. Section 2 describes the approach, which is used to illustrate the methodology throughout the remainder of this text. Section 3 illustrates the product structure with the constraints and variables related to the proposed test case. Section 4 shows the results. Finally, Section 5 presents the conclusions and discussions.

2 Materials and methods

A collaborative design platform is proposed to support the design of ETO products by integrating a constraint-based optimization approach (Figure 3). The design of ETO structures requires the development of several engineering subsystems related to the structural layout, machineries, accessories, etc. Therefore, a collaborative design is proposed. In this context, a constraint-based optimization aims to fill the gap between the collaborative design, knowledge base, simulations and optimization during the early design phase of the ETO products. The approach is defined for the design of generic ETO products with the problem of the structural analysis. In particular, the methodology is applied in the context of large steel constructions.

Analyzing the design platform, as shown in Figure 3, the *Collaborative Design* domain concerns the study and coordination of each design subproblem within the design team. Focusing on modular steel structures, the design of a structure can include the study of a set of structures related to different conditions. In the context of the oil and gas constructions, if a steel construction is built and then shipped as a plug and play unit, the same structure will have three configurations related to the operation condition, sea transport and land transport. Furthermore, these three structures will have a common module related to the *Base Structure*, which consists of a primary structure (main frame or supporting structure) and a secondary structure. Therefore, the collaborative approach aims at defining the optimal base structure to be used in the highlighted conditions of the operation, sea transport and land transport. The collaborative approach also aims at searching the common and specific parameters to be involved into the constraint-based optimization of each configuration.

The *Knowledge Base* domain concerns the collection and sharing of rules, formulas, and constraints related to the engineering design of the ETO product to be analyzed. The constraints related to the engineering design of a steel structure are mainly focused on the normative checks and conditions, such as the structural limits to be applied. The other constraints are related to the validation rules based on the expert knowledge, and these constraints can refer to the formalization of the implicit and tacit knowledge. An example can be the rules of validation such as the check of the weight balance for the assemblies inside a steel structure. Another example can be the rules to evaluate and limit the number of different types of components such as beams into an assembly. The *Design Constraints* enhance the design synthesis, avoiding infeasible solutions. The level of the *Design Constraints* concerns the validation rules focused mainly on the domain of the technical expertise. Therefore, these constraints refer to the formalization of the explicit and implicit knowledge. This aspect ensures that the generated set of solutions is consistent using the knowledge and rules formalized in each constraint. Here, the *CSP tool* can be seen as a bridge between the three domains: *Collaborative Design*, *Knowledge Base*, and *Simulations* (Figure 3).

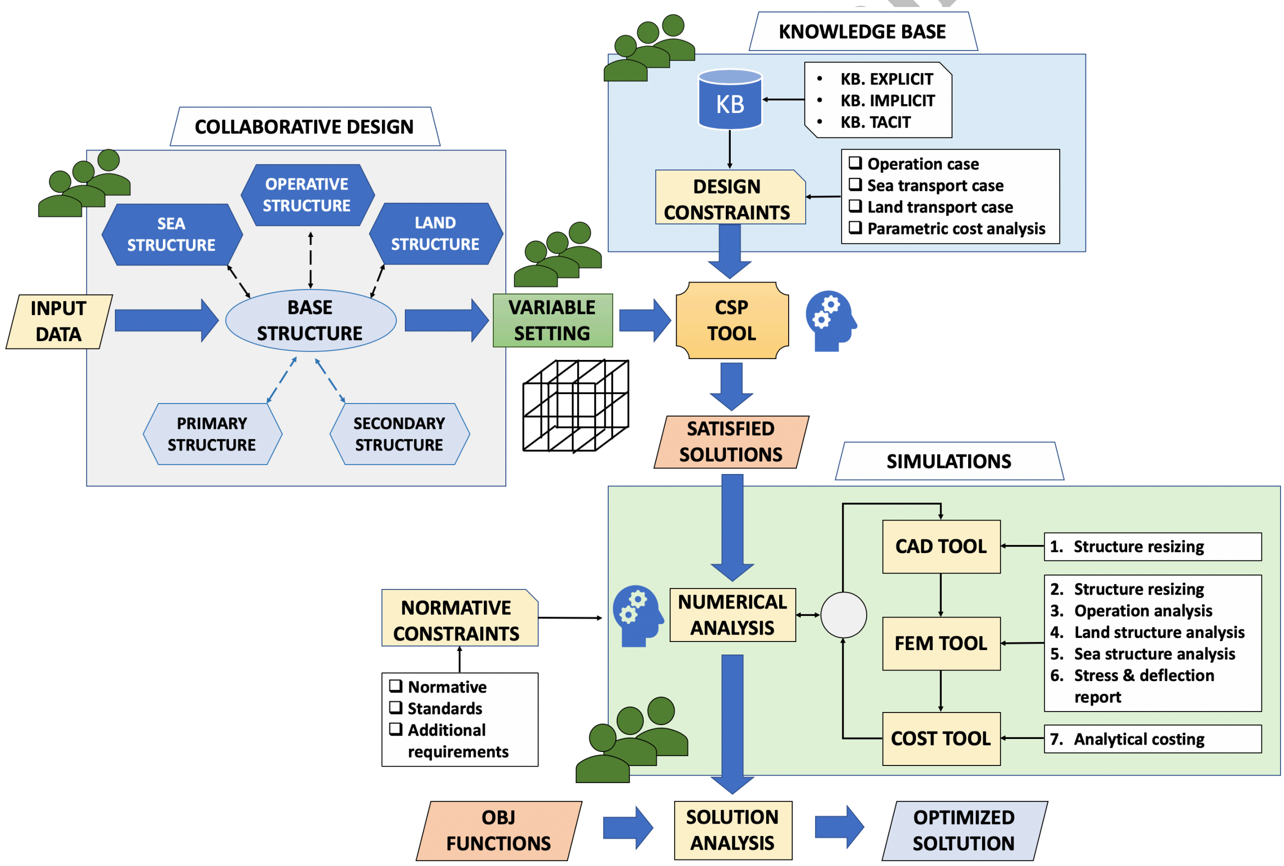


Figure 3 Proposed design methodology for the optimization of ETO structures.

The *Simulations* domain corresponds to the employment of a virtual prototyping approach to evaluate the structural feasibility and behavior. The definition of the boundary conditions and the evaluation of the results are shared along the entire collaborative design team. In particular, this phase corresponds to the detailed design. The *Simulations* level also involves the definition of a set of *Normative Constraints*, which are focused on the normative checks and loading conditions as check conditions to be applied into the simulation loop.

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The CSP model implements a set of variables, values, and constraints. The variables are defined during the *Collaborative Design* level, and each variable can take a range of values. The constraints are described using the mathematical functions. The definition of each constraint is related to the formalized knowledge base. In this context, the *CSP tool* implements the rules to solve the *Design Constraints* before launching any simulation loop. This approach can reduce the number of solutions to be evaluated in a further simulation phase, which involves a time consuming analysis.

Figure 4 describes the optimization workflow, which includes the *CSP tool* and *Simulations*. Considering the design of steel constructions, the simulation activities correspond to analyses such as FEM simulations and cost estimation. The *CSP tool* is employed to reduce the space of the solutions, and the *Simulations* node is applied to perform a deeper investigation of each resulting solution and searching for the optimum solution in terms of the cost, weight, and structural behavior. The *Simulations* level also involves the use of a parametric CAD model to allow an FEM model and a cost analysis to be solved.

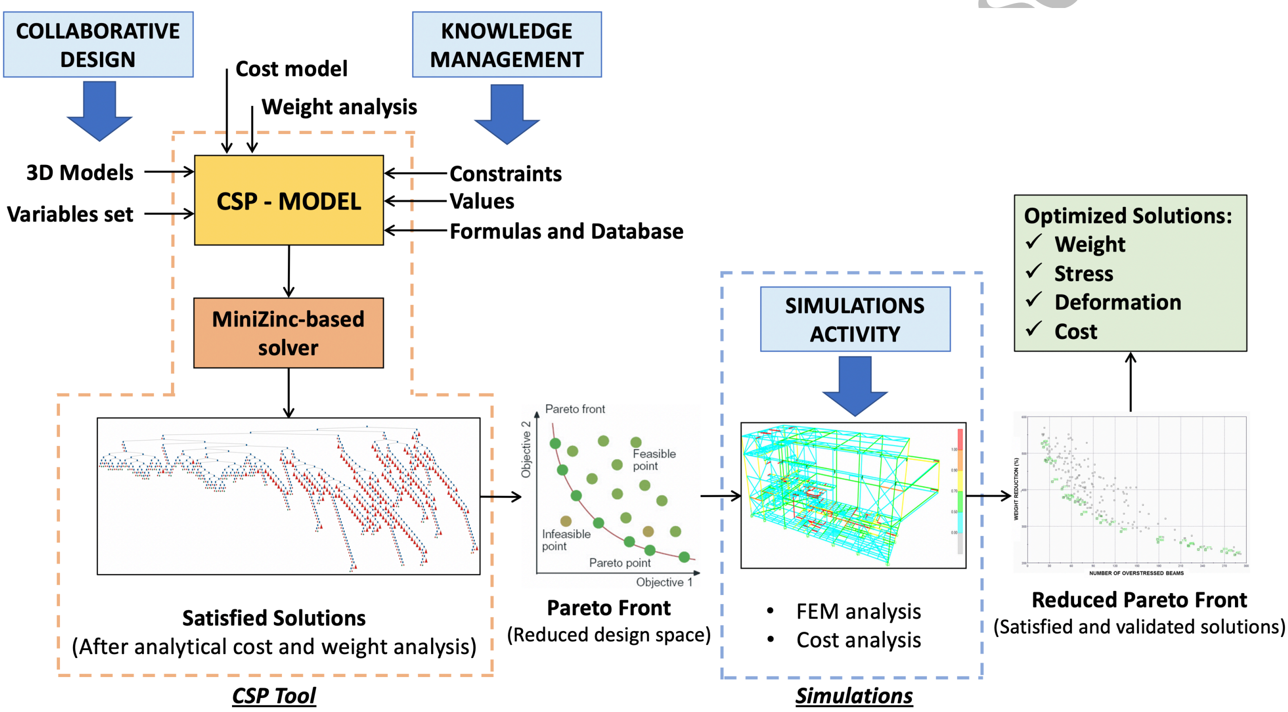

Figure 4 Description of the optimization workflow, which integrates the CSP tool and Simulations with the FEM solver.

2.1 Design tools

The proposed methodology was implemented into a platform tool to support the multi objective optimization of a steel structure for oil and gas applications. To solve the constraint-based problem, the *CSP tool* has been implemented in Visual Basic.NET using MiniZinc, which is a Gecode platform toolkit. The resulting tool consists of a *CSP Solver* and *GUI Interface*. The *CSP Solver* uses the Gecode code for running the problem solution, and it works in the background. Furthermore, the *GUI Interface* shows the visual commands for the management and definition of the parameters, constraints, and values (Figure 5).
Figure 5 describes the software architecture to solve the CSP problems. The user interacts with the GUI interface after the phase of the problem modeling (Figure 5), which concerns the definition of the CSP model. This task is challenging because it pertains to the formalization of the technical and practical knowledge in the constraints, which means translating an aspect that is often only in the mind of the designer into a computational representation involving variables and functions. In this context, while the explicit knowledge

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is easy to translate into mathematical constraints, the implicit and tacit knowledge are difficult to be elicited and later formalized.

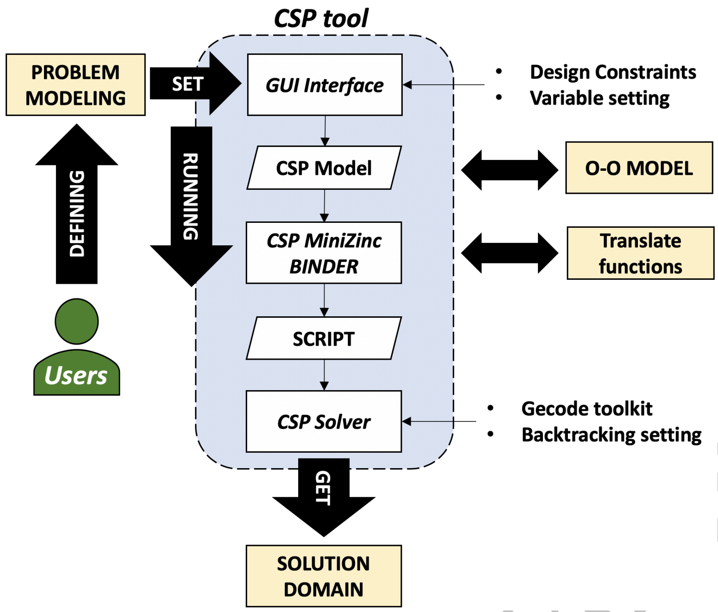


Figure 5 The software architecture related to CSP tool.

The *CSP model* is defined into the *GUI Interface* using the MiniZinc language. Figure 6 shows the form of the software for the definition of the variables and constraints. In particular, each constraint is edited using a mathematical representation of formulas and rules. Behind this definition is an object-oriented (O-O) representation of the product structure. The generic classes are defined in Visual Basic.NET for supporting the O-O representation of a product structure. In particular, a generic set of must inherit classes is implemented. These classes provide the parent-child relationship between each component of the product structure. This O-O representation includes the definitions of the properties, methods, variables, and constraints.

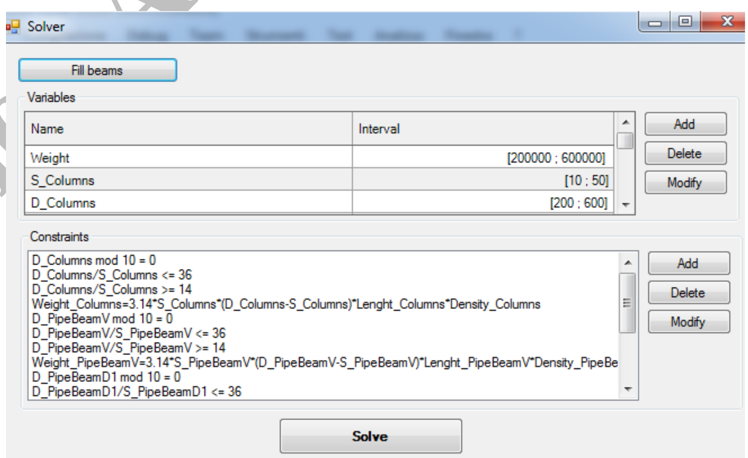


Figure 6 GUI Interface for the setting of variables and constraints.

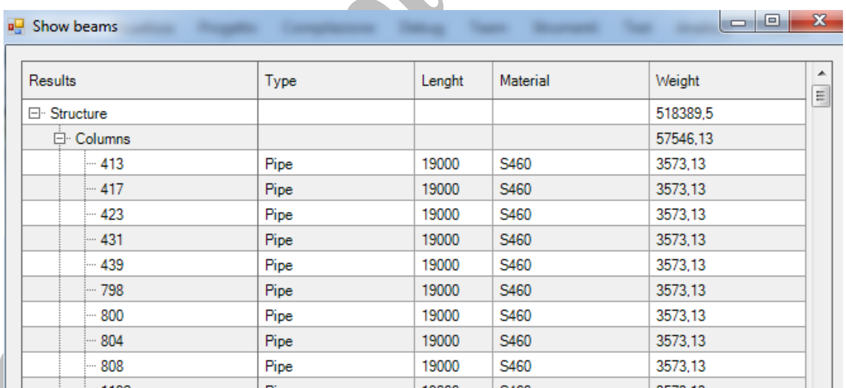
In this paper, the set of classes to describe the product structure was termed as the *Beam Module*. This project inherits the generic classes defined in the *CSP model* to represent the specific design problem related to the steel structures. The classes related to the *Beam Module* classify the definitions of the standard beams, pipes, and built-up shapes. These classes also include the variables related to the shape geometry of each beam. The procedures to calculate the cost and weight of such a steel construction were implemented in each element.

The *CSP MiniZinc Binder* is a tool that was developed to translate the input data into a MiniZinc structure before running the CSP solution using Gecode. While a user can add/edit constraints and variables using the *GUI Interface* without using any specific programming language, the *CSP MiniZinc Binder* implements the methods to write constraints as a MiniZinc script for solving the CSP problem. Figure 7 shows an example of a MiniZinc code for the description of certain design constraints. When the user launches the CSP solution, the *CSP Solver* invokes Gecode using the MiniZinc script.

```
constraint D_PipeBeamD2/S_PipeBeamD2 <= 36;
constraint D_PipeBeamD2/S_PipeBeamD2 >= 14;
constraint 3.14*S_Columns*(D_Columns-S_Columns)*Lenght_Columns*Density_Columns+3.14*S_PipeBeamV*(D_PipeBeamV-
S_PipeBeamV)*Lenght_PipeBeamV*Density_PipeBeamV
+Area_BeamD0MBT500*Lenght_BeamD0MBT500*Density_BeamD0MBT500+Area_BeamD0MBL400*Lenght_BeamD0MBL400*Density_BeamD0MBL400+Area_BeamD1MBT400*Lenght_B
eamD1MBT400*Density_BeamD1MBT400+3.14*S_PipeBeamD1*(D_PipeBeamD1-
S_PipeBeamD1)*Lenght_PipeBeamD1*Density_PipeBeamD1+Area_BeamD0SB300*Lenght_BeamD0SB300*Density_BeamD0SB300+Area_CrossBeam*Lenght_CrossBeam*Densit
y_CrossBeam+Area_CrossBeamDeck*Lenght_CrossBeamDeck*Density_CrossBeamDeck
+Area_BeamD2MBL500*Lenght_BeamD2MBL500*Density_BeamD2MBL500+Area_BeamD2MBT500*Lenght_BeamD2MBT500*Density_BeamD2MBT500+Area_BeamI*Lenght_BeamI*De
nsity_BeamI+Area_Supports*Lenght_Supports*Density_Supports+3.14*S_PipeBeamD2*(D_PipeBeamD2-S_PipeBeamD2)*Lenght_PipeBeamD2*Density_PipeBeamD2<=
600000;
```

Figure 7 Example of constraints in the MiniZinc language.

The test case, as described in Section 3, proposes the modeling and optimization of a steel structure, which consists of different groups of beams; each group is characterized by its type and structural function. A tool is developed using Visual Basic.NET to directly interact with the CAD model during the optimization analysis. A function called *Fill Beams* reads the data and automatically gathers all the information necessary to solve a minimization problem for the weight and cost of the structure (Figure 8). After the data import, the designer can use the *GUI Interface* to implement the constraints, variables, value domains, etc.



Results	Type	Lenght	Material	Weight
Structure				518389,5
Columns				57546,13
413	Pipe	19000	S460	3573,13
417	Pipe	19000	S460	3573,13
423	Pipe	19000	S460	3573,13
431	Pipe	19000	S460	3573,13
439	Pipe	19000	S460	3573,13
798	Pipe	19000	S460	3573,13
800	Pipe	19000	S460	3573,13
804	Pipe	19000	S460	3573,13
808	Pipe	19000	S460	3573,13

Figure 8 Module structure imported from SAP2000 and exported in the .XML format (lengths are expressed in meters and weights in kilograms).

This paper considers an analytical calculation phase to estimate the early product cost and weight. The cost and weight models are implemented into the *CSP model*. The cost analysis is performed using an analytical solver, which analyzes the model related to the *Base Structure* to recognize the information from the CAD model. The weight evaluation, which corresponds to the multi objective function, refers to the weight of the *operative structure*, including the *primary* and *secondary structures*. In particular, the weight value is analyzed using the CAD model. The configurations related to the sea and land transports have different weights related to a different set of specific accessories used for the corresponding transportation. However, this additional equipment is not evaluated in this research.

The interaction between the CSP solver and the simulation software is realized using the code developed in Visual Basic.NET. For the structural analysis, SAP2000® is employed as the FEM solver. This tool provides an application programming interface (API) to develop a background control of the geometry, boundary conditions, loading combinations, calculation settings, checks and results. Therefore, using Visual Basic.Net and these API utilities, a plugin application is developed to open a SAP2000® document, load/edit the CAD model, upload the parameters and geometry, and simulate the current model configuration. As reported, an .XML structure is delivered for each FEM simulation. Tekla® is used as the CAD system for the representation of the steel structures. A simplified geometry of the structure is generated by the CAD assembly model. This simplified geometry is then uploaded inside the FEM solver for the structural simulation.

The output of the *CSP tool* is a reduced space of solutions, which is the domain in which the optimal set of parameters is searched. The CSP analysis represents the generation of the domain of the satisfied solutions to be evaluated within the simulation activity (Figure 9). Each satisfied solution can be considered as a set of values that solve the constraint satisfaction problem. Next, each set of data is imported into the *Model-Based Simulation* module to launch the numerical analysis for checking the structural behavior. This task is automated using Visual Basic.NET and the API library provided by SAP2000®.

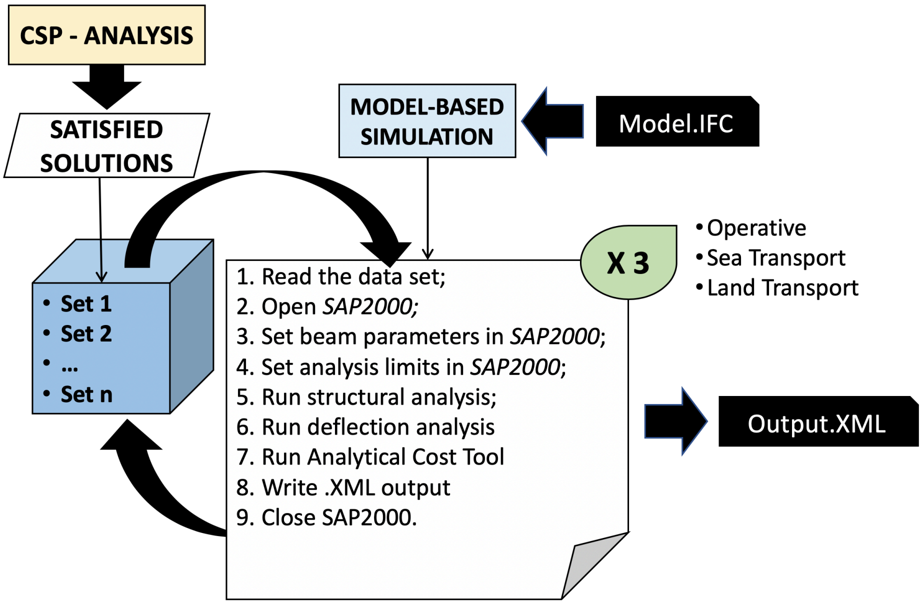


Figure 9 Simulation workflow with FEM and cost analysis.

A tool is developed to read the data set related to each CSP solution and write this information into a .XLS file. This format is chosen for the management of the structured data, which contains the information related to each group of the beams, such as the geometrical section, height, material type, structural limits, and deflection limits. Next, all this information is used to set the solution parameters inside the SAP2000® model and run the relative analysis. All these steps are highlighted in Figure 9. In particular, these steps are repeated three times, one for each condition (operation, sea transport and land transport). Each condition has a specific configuration of loading conditions to be applied. For each analysis, an output file is exported in the .XML format. This file contains the information related to the product structure with the results of the FEM analysis for each simulation. The .XML file (output) contains a general section, which includes the information pertaining to the number of beams with an overstressed status or an overdeflection set (Table 1). These data are related to each structure and each simulation. A second set of data contains the information pertaining to the stress and overstressed values achieved for each beam, including the information regarding the deflection state.

Table 1 Scheme of the output values for each FEM simulation.

Output Value	Structure	Simulation type

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Total number of overstressed beams	Primary; Secondary;	Operation; Sea transport; Land transport;
Total number of overstressed beams over 120%	Primary; Secondary;	Operation; Sea transport; Land transport;
Total number of overdeflected beams	Primary; Secondary;	Operation; Sea transport; Land transport;

The assembly of the structure is analyzed as a collection of groups. Each beam can be included in only one group of beams. A group of beams has items with the same cross-section. Moreover, the limits for the overstress and deflection conditions are defined for each group of beams. In particular, the deflection limit indicates the maximum value of the deflection allowed in the middle of the beam. For example, a L/100 limit describes the value to be considered for the maximum deflection, where L is the longitudinal length of the beam. This information is added by the designer using the *GUI interface*.

3 Test case

The test case is focused on the design optimization of a large steel construction weighing approximately 700 t. The objective of the analysis is to reduce the weight and cost during the early design phases. This steel structure is used in oil and gas systems called *modules*. A *module* is the smallest functional unit of a larger plant, which consists of a set of *modules*. A module includes its equipment (piping, battery, etc.), machineries (turbine, compressor, etc.) and the steel structure. These *modules* are prefabricated and later shipped to be erected in a place that is different from the construction site.

The steel structure that supports each *module* is analyzed in this test case. The overall structure can be divided into the *primary* frame (also known as the supporting frame) and the *secondary* frame (Figure 10). The secondary level of the structure provides the support for minor equipment. In general, the secondary frame includes braces to increase the stiffness of the construction. The oil and gas module proposed in this test case is an example of a 700 t construction with three stories.

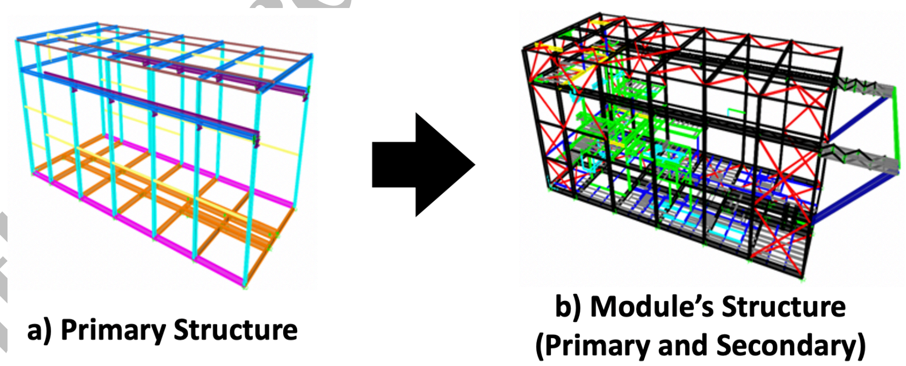

Figure 10 Representation of the primary structure (a) and the full module structure (b), which includes the primary and secondary structures.

The classification of the primary and secondary structures is described in Figure 10. The *Primary Structure* is more important because it is composed of the elements that provide the structural resistance (Figure 10). If a failure affects one of these elements, the construction can collapse. In contrast, the *Secondary Structure* is composed by elements that cannot cause the collapse of the construction. A third category also exists, called the *Tertiary Structure*; however, it is not considered in the proposed design optimization workflow. This category includes the stairs, ladders, handrails, floor, roof, wall plates, and maintenance/access platforms, and the design of such elements is usually considered in the engineering design phase.

Table 2 Classification of Primary and Secondary Structures.

Primary Structure	Secondary Structure
• All main frames (columns, deck frames)	• Braces
• Gantry crane	• Beams supporting floor
• Monorail runway and supports for crane	• Pipe supports
• Stiffeners	• Miscellaneous structure

3.1 Product structure

The product structure is analyzed at the beginning of the research activity. For the representation of the product structure, the unified modeling language (UML) is used. Figure 11 shows the component structure for an operative structure, related to the analyzed steel construction. In particular, a composite structure diagram is applied for establishing the CSP model with an object-oriented representation of the components, variables, and constraints. In this representation, the constraints are added to the diagram using the object constraint language (OCL) formalism. Established using the Papyrus software, the highlighted diagram (Figure 11) also helps the designer understand the structure of the existing systems and formalize the blocks, variables, and constraints. This diagram describes the relationships among the different components in terms of the associations, dependences and references (Figure 11). Moreover, the composite structure diagram adds the internal structure of a classifier to the configuration and relationship of the parts. Therefore, each component is represented as a graphical class element.

As shown in the diagram in Figure 11, the main component is the *Operative Structure*, which is the configuration of the steel structure in the operation phase. The correlated structures, known as the *Sea Structure* and *Land Structure*, inherit both the *Primary Structure* and *Secondary Structure* from the *Operative Structure*. However, additional information is necessary for modeling the phases of the shipping and road transport. The shipping and road transport are described and simplified using two abstract interfaces. The multiplicity of each relationship involving a structure is 1. The multiplicity is 1 to N for the groups of beams and the collections of the types of beams.

The geometrical variables are related to the geometry of each beam section. As described in more detail in Section 3.2, two different types of beams are involved in this research: commercial beams and built-up beams. While commercial beams have hot rolled laminated profiles with fixed cross-sections, the built-up beams are customized welded metal plates to shape the I beams (also known as double T type beams) or pipe beams (such as cylindrical columns). This paper considers standard beams for the *Secondary Structure* and built-up beams for the design of the groups related to the *Primary Structure*. The reason pertains to the possibility of obtaining more degrees of freedom in the design optimization of the *Primary Structure*. In fact, while a built-up section can be described using up to 4 geometrical variables, a standard beam is described only by a designation label, which can be seen as one variable related to the main geometrical parameter.

The generic representation of a beam object is defined including the parameters related to its section and length (here termed as *height*). The O-O representation of the product structure of such ETO structures is a collection of beams and nodes. Considering the classification highlighted in Table 2, the specific steel structure is divided into functional groups such as the “Central Columns”, “Lateral Columns”, “Main Deck - Traversal”, “Main Deck - Longitudinal”, “First Deck”, “Second Deck - Traversal”, “Crane Supports”, “Piping Support”, “Braces – First Level”, and “Secondary Beam Deck”.

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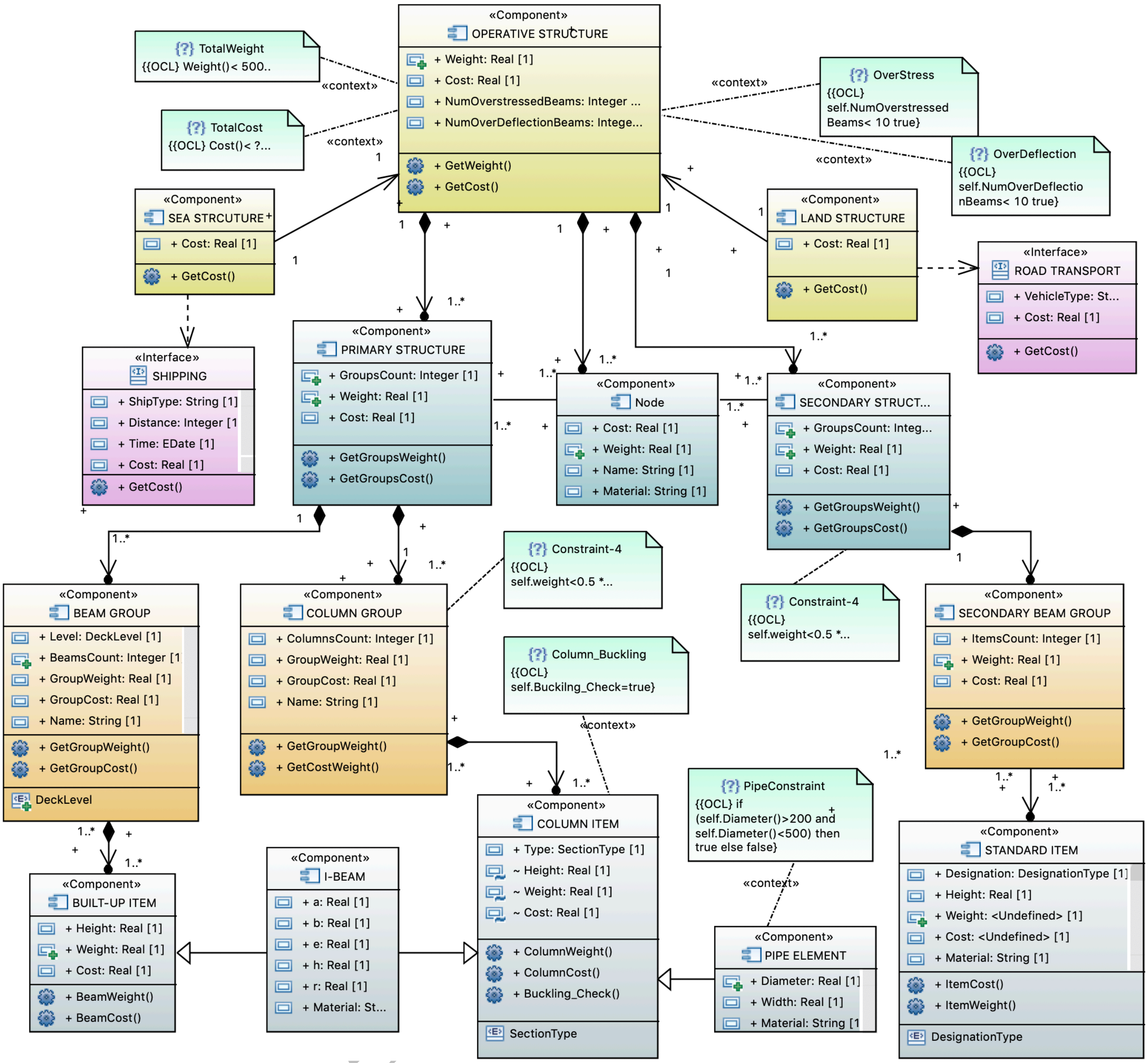

Figure 11 The composite structure diagram related to the analyzed product structure, including several examples of the constraints represented in the OCL.

3.2 Variables and constraints

An object-oriented model of the product structure is implemented inside the *CSP Tool*. This model involves the possibility of defining a set of variables (1) and constraints (2) for each component. The definition of such values and objects is an interactive process that commits the engineering team.

$$V = (V_1, V_2, \dots, V_n) \tag{1}$$

$$C = (C_1, C_2, \dots, C_n) \tag{2}$$

Continuous or discrete domains are defined for each variable. A set of *n* domains (3) is defined for solving the CSP problem (4). While a continuous domain concerns the values or intervals of ℝ, a discrete domain is an enumerative and finite set of values (which can be Boolean, string, etc.). Therefore, a mixed constraint domain is applied in this research due to the conjunction of the discrete and continuous constraints for the variables.

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$$C = (D_1, D_2, \dots, D_n) \quad (3)$$

$$P = \{V, C, D\} \quad (4)$$

In terms of the CSP model, this paper considers the arc-consistency approach [29] realized using the filtering process of the conjunction of the constraints. The arc-consistency is used to guarantee the local consistency of the problem. Since the arc-consistency is 2 consistent, the node consistency (1 consistency) is guaranteed according to the definition of the k consistency provided by Kumar [30]. This consistency is obtained through the filtering process of the conjunction of the constraints.

In this paper, the solution search engine uses a simple backtracking algorithm combined with the constraint propagation method due to the dimension of the space of the solutions to be investigated. The use of the backtracking algorithm is necessary due to the lack of the proof of the global consistency. In particular, this algorithm is already implemented into the Gecode framework used for solving the CSP problem. Generally, backtracking has been widely used in many research works [31].

The variables employed in the proposed test case correspond to the geometrical representation of the steel structure. In particular, these variables pertain to the sizing of each beam section. As aforementioned, two types of beams are involved in this study: standard and built-up beams. A subclassification corresponding to the built-up beams, which can be I section beams (double T) or cylindrical pipes, is established. The standard beams are described considering a list of different types. Therefore, the resulting variable for a standard beam is only one. However, the domain of the values related to each standard beam is defined by the designer on the basis of the type of the group of beams to be optimized inside the overall structure. The geometrical definition of a standard cross-section is collected in the database of the catalogues, while the dimensions of the built-up sections can be defined by the designer. Table 3 and Table 4 show an example of a list of standard beams involved in the design process of the *Secondary Structure*.

Table 3 I Shape: An example of a set of standard beams involved into the design process.

Description	Material	Section height (h)	Type
HE200A	S355	200 mm	I shape
HE260A	S355	260 mm	I shape
HE300A	S355	300 mm	I shape
HE400A	S355	400 mm	I shape
HE500A	S355	500 mm	I shape
HE700A	S355	700 mm	I shape

Table 4 Circular hollow section: An example of a set of standard beams involved in the design process.

Description	Material	Outside diameter	Thickness [mm]	Type
139.7X5CHS	S355	139.7 mm	5	Circular Hollow Sections
168.3X6.4CHS	S355	168.3 mm	6.4	Circular Hollow Sections
219.1X6.4CHS	S355	219.1 mm	6.4	Circular Hollow Sections
273.1X6.4CHS	S355	273.1 mm	6.4	Circular Hollow Sections
273.1X12.7CHS	S355	273.1 mm	12.7	Circular Hollow Sections

Figure 12 illustrates the geometrical parametrization related to each type of built-up section such as an I beam and a cylindrical pipe. On the left side (Figure 12), the I beam section is represented with 4 parameters: beam height (*h*), web thickness (*a*), flange thickness (*e*), and flange width (*b*). On the right side, the cylindrical section is represented with 2 parameters: main diameter (*d*) and pipe thickness (*s*).

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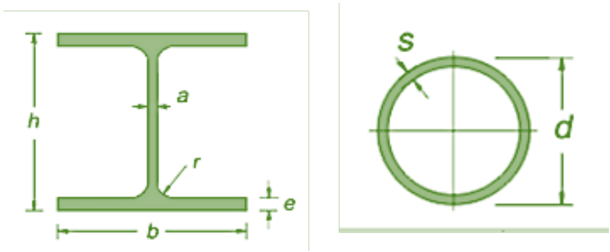

Figure 12 Example of parametrization for two different beam sections: I beam and cylindrical pipe.

In this paper, no parameter is assigned for the action related to the grouping of the beams. The design team defines the setting of each group of beams in terms of the items included. Therefore, the design optimization is focused on the geometrical dimensions of each beam section.

The *Design Constraints* were analyzed in an early phase and discussed with an expert team of designers. These constraints are focused on validation rules, which are mainly related to the domain of the technical expertise, and the constraints are described and formalized into the CSP problem using an analytical approach. These constraints can refer to the formalization of the explicit and implicit knowledge. An example can be the validation rules to check the weight balance of the assemblies in a steel structure. Another example can be the rules to evaluate and limit the number of different types of components, such as the types of beams into an assembly. Subsequently, the resulting list of constraints can be classified into three types:

- critical buckling;
- pipe sizing;
- weight ratio and balance;
- specification limits.

Next, the *Design Constraints* are described with several examples pertaining to the practical satisfaction rules, which depend on the engineer's expertise.

3.2.1 Critical buckling

The set of constraints related to the *critical buckling* pertain to the ratio between the section area of each column and its vertical height, which is the length of the beam item. These constraints aim to avoid any possible buckling problem during operation, including the relative instability problem of the steel structure. The buckling problem pertains to vertical structures such as steel columns when subjected to a compressive load. This condition is characterized by a sudden sideways deflection; therefore, the cross-section of each column must be optimized to avoid this effect. The use of built-up sections for each group of columns allows each double T section and pipe to be optimized for the customized application.

Since carbon steel and stainless steel are high resistance materials, the relative double T beams have a small cross-section area. Therefore, these beams can be affected by compression problems. The buckling constraints are related to the specification provided by AISC 360-05, which regulates the limit factors for the width and thickness of a built-up I shaped beam. In particular, Eq. (5) describes the limiting width-thickness ratio (b/e) for a compression I beam under the condition of flexural compression:

$$\lambda_r = 0,95\sqrt{\frac{k_c E}{F_L}} \qquad (5)$$

where K_C is the coefficient for slender unstiffened elements (6), E is the modulus of elasticity of steel (200.000 MPa), and F_L is the calculated stress used in the calculation of the nominal flexural strength. In particular, F_L is calculated as being 70% of the specified minimum yield stress (F_y) of the compression flange (for example,

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for steel S355, F_L = 0,7 x 355 Pa). The K_C term is also evaluated using Eq. (6), and its value must be lie the range expressed in (7).

$$k_c = \frac{4}{\sqrt{h/_{\mathrm{a}}}} \quad (6)$$

$$0{,}35 \leq k_c \leq 0{,}76 \quad (7)$$

The circular hollow sections (pipe beams) under uniform compression have a different limiting width-thickness ratio formula (8), which limits the *D*/*s* ratio. More constraints related to the pipe beams are analyzed in the following section.

$$\lambda_r = 0{,}11 \frac{E}{F_y} \quad (8)$$

These limits of slenderness are critical for I shape beams. This type of constraint ensures that the design solutions are free of the buckling problem before high computational cost FEM analysis is performed. In this manner, a slender beam with a possible buckling problem is eliminated during the CSP analysis. The limits highlighted in this section were modified by the experts to provide a more restrictive condition for the described constraint.

3.2.2 Pipe sizing

The rules related to the *pipe sizing* limit the employment of non-suitable pipes in terms of the stability and static resistance. A mathematical formulation is used to describe the ratio between the diameter and width (9). Moreover, a second limit is applied to the diameter range (10). The designer can reduce the range of possible values for each pipe section (for example, a possible diameter range can be between 400 mm and 600 mm).

$$14 \leq \frac{D}{s} \leq 36 \quad (9)$$

$$D_{min} < \mathrm{D} < D_{max} \quad (10)$$

3.2.3 Weight ratio and balance

This set of *Design Constraints* is related to the *weight ratio and balance* between each group of beams to avoid non suitable configurations. A list of such constraints is presented as an example in Table 5. The terms *C1*, *C2*, …, *C5* represent the numerical value for each constraint definition.

Table 5 A list of the constraints related to the t weight ratio and balance.

Example of constraint	Description
Constraint 1	the **weight** of the main deck (at zero level) **is greater than** that of the structure of the first deck, which Is greater than the weight of the second deck x *C1*;
Constraint 2	the **weight** of the main deck (at zero level) **is greater than** *C2* x the weight of the equipment and machineries;
Constraint 3	the **weight** of the main deck (at zero level) **is less than** *C3* x the total weight of the steel construction;
Constraint 4	the **weight ratio** between the *secondary* and *primary* structures **is less than** *C4*;
Constraint 5	the **weight ratio** between the groups of columns and *primary* structure **is greater than** *C5*;

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3.2.4 Specification limits

This set of design constraints pertains to the limits related to the maximum values of the weight, cost, number of different beam sections, etc. Therefore, in this paper, the maximum weight and maximum cost are the examples of two *specification limits*; however, similar relations can be considered in this context.

The CSP solver can analyze the sum of the costs and weights related to all the groups of beams. Additional cost and weight factors are considered for the assembly, nodes, and transportation. Therefore, using the proposed analytical approach, the constraints related to the *specification limits* can evaluate if a set of parameters can satisfy these general limits. These constraints can be evaluated because an O-O model is implemented into the *CSP Tool*.

3.3 Cost modeling

3.3.1 Parametric cost level

Two levels of cost analysis are considered in this paper: parametric and analytical. The parametric level is in the phase of the CSP analysis to evaluate the constraints related to the cost of the structure. As analyzed previously, the cost evaluation is a constraint classified as a *specification limit*. A parametric approach for costing means that a method involving an analysis using only simple formulas based on the product parameters such as weight, sizing, and material should be applied [32].

The CSP solver considers the cost related to the *Primary* and *Secondary* structures. This cost evaluation refers to the analysis of each group of beams. The total cost is the sum of the costs evaluated for each beam. In the first level, the approach is prompt because only a few parameters are considered: beam weight, material (*m*), section type (*st*). Eq. (11) describes the cost related to one beam, as implemented for the first level of the cost analysis.

$$Cost_{Beam-I} = W_B \cdot SC_{(m,st)} \tag{11}$$

The term W_B in (11) represents the weight of the element in kg, and the term $SC_{(m,st)}$ is the specific cost related to the selected beam. This specific cost is evaluated in €/kg; its value is not constant and depends on the type of section (*st*) and the type of material (*m*). Table 6 presents an example of the cost database used for the first cost evaluation implemented into the CSP model.

Table 6 Specific cost [€/kg] related to the section types and materials: an example of the evaluation in the parametric cost level.

Section Type	Material Type	Specific Cost [€/kg].
HE200A	S355	0,75
HE200A	S275	0,70
HE500A	S355	0,77
HE500A	S275	0,72
273.1X6.4CHS	S355	0,85
…	…	…
BUILT-UP: Circular Shape	S355	0,68
BUILT-UP: I Shape	S355	0,70

3.3.2 Analytical cost level

The analytical method considers the analysis of each elementary task related to the product fabrication [32]. Therefore, this approach considers tasks such as cutting, welding, and assembly. The level of detail is arbitrary and depends on the availability of the formulas and database for each test case.

Eq. (12) shows the total cost (evaluated in €) related to the steel construction described in this paper. This cost is the value analyzed after the FEM simulation. The term $Cost_{STR}$ is the cost related to the construction of the steel structure in the operation condition. Thus, this term includes the cost related to the *Primary* and *Secondary* structures with the relative set of nodes and beams. The term $Cost_{TRA}$ represents the cost of the transportation. This parameter includes the sea and land transport (13). Finally, $Cost_{ERE}$ is the cost related to the construction erection and installation on site. This cost pertains to only the steel structures, without considering any equipment or machinery, and it is correlated to the structure self weight (W_{STR}) and a specific cost per weight (SC_{ERE}), as highlighted in (14).

$$Cost_{TOT} = Cost_{STR} + Cost_{TRA} + Cost_{ERE} \quad (12)$$

$$Cost_{TRA} = Cost_{SEA} + Cost_{LAN} \quad (13)$$

$$Cost_{ERE} = W_{STR} + SC_{ERE} \quad (14)$$

For the transport cost ($Cost_{TRA}$), Eq. (15) and (16) describe the approach for the sea and land transport. In particular, the transportation cost includes a fixed cost ($Cost_{FIX}$), a variable cost related to the distance (d), a specific cost (SC_{SEA} and SC_{LAN}) related to the vehicle, and a cost related to the additional structures necessary for the transportation ($COST_{STR\text{-}SEA}$ and $COST_{STR\text{-}LAN}$). The fixed cost is related to the accessories and operators involved in the transportation phase. The cost related to the additional structures concerns objects such as braces that are added into the *Sea* and *Land Structures* to limit the deflection due to the transportation phases. The cost of such braces is an additional item because they are temporary objects not included into the CAD model that represents the *Operative Structure*. In particular, the braces are disassembled before the installation.

$$Cost_{SEA} = Cost_{FIX-SEA} + (SC_{SEA} \cdot d_{SEA}) + Cost_{STR-SEA} \quad (15)$$

$$Cost_{LAN} = Cost_{FIX-LAN} + (SC_{LAN} \cdot d_{LAN}) + Cost_{STR-LAN} \quad (16)$$

The cost related to the steel construction ($Cost_{STR}$) is analyzed as the sum of three parts:

- Raw material cost
- Fabrication cost
- Assembly cost

The *raw material cost* corresponds to the built-up beams, standard beams, and nodes (17). In particular, the built-up beams and nodes pertain to a set of sheet metal plates that compose the final shape after a welding process. The fabrication cost pertains to the manufacturing of the beams and steel nodes. The beam fabrication includes the cutting ($Cost_{CUT}$) and welding ($Cost_{WEL}$) costs for the built-up profiles; however, the fabrication of standard beams includes only the cutting cost because the shape of these beams is produced using a hot rolling process (18).

$$Cost_{MAT} = \begin{cases} \sum_i^N Cost_{PLA}, \; for\ nodes\ and\ builtup\ beams \\ \sum_i^N Cost_{STD}, \; for\ standard\ beam\ sections \end{cases} \quad (17)$$

$$Cost_{FAB} = \begin{cases} \sum_i^N Cost_{CUT}, \; for\ all\ items \\ \sum_i^N Cost_{WEL}, \; for\ nodes\ and\ builtup\ beams \end{cases} \quad (18)$$

Eq. (19) describes the formulation adopted to represent the cost related to the cutting process, which includes the preparation of the plates for the nodes, built-up beams, and standard beams.

$$Cost_{CUT} = (l_{EDG} \cdot \frac{1}{V_{CUT}} \cdot HC_{CUT})/3600 \quad (19)$$

The cutting process involves the cutting edge (l_{EDG}), which is related to the geometry of the part to be manufactured; the cutting velocity (V_{CUT}); and the hourly cost (HC_{CUT}) of the cutting process used. Using a similar approach, Eq. (20) introduces the calculation of each welding with the welding velocity (V_{WEL}) and the related hourly cost (HC_{WEL}).

$$Cost_{WEL} = (l_{EDG} \cdot \frac{1}{V_{WEL}} \cdot HC_{WEL})/3600 \quad (20)$$

While the geometrical data were acquired from the CAD model, the other costing parameters were previously defined into a database. The average values were selected for parameters such as the cutting and welding velocity, specific costs, and other parameters. Figure 13 describes an example of the I shaped beam with the welding edges highlighted.

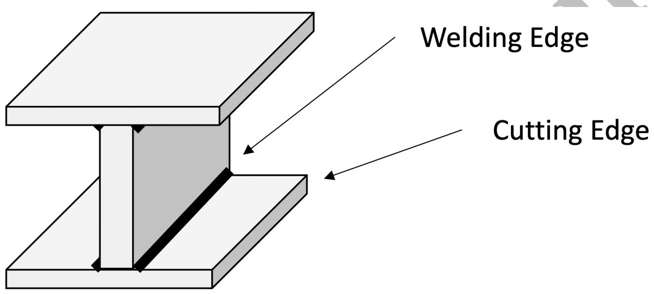

Figure 13 An example of an "I shaped" beam.

The *assembly cost* is considered as a function of the nodes and beams (21) by using empirical parameters analyzed from past projects. This cost depends on the number of nodes (n_{NOD}) and beams (n_{BEA}) per the specific assembling cost (€/kg) defined for each node (SC_{NOD}) and each beam (SC_{BEA}). All the data related to the number and weight of each element are retrieved from the CAD geometry.

$$Cost_{ASS} = (n_{NOD} \cdot SC_{NOD}) + (n_{BEA} \cdot SC_{BEA}) \quad (21)$$

3.4 Loading conditions

Due to its typical functionality, the steel structure of a *module* is subjected to static loads, dynamic loads, land transport loads, sea transport loads and fatigue loads. The modules are prefabricated in a construction site and later shipped by sea to the destination for the installation. Therefore, the weight optimization of such ETO constructions is a critical issue.

The simulation tools based on an FEM analysis are used in the design of the steel structures to allow the investigation of the behavior of the mechanical structures with virtual prototypes. Figure 14 shows the simplified FEM model, which reproduces the steel module with the primary and secondary structures. In the proposed research, the structure of the model is simulated using SAP2000®. The geometrical simplification considers 1D beams and does not include the tertiary structure, which includes the stairs, ladders, handrails, floor, roof, wall plates, maintenance/access platforms, etc.

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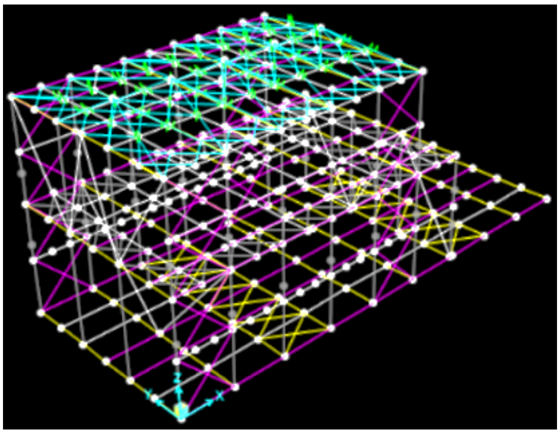

Figure 14 The structure of the module including the primary and secondary structures, as modeled using the FEM solver.

The specific load conditions to be considered during the design process are related to the installation case (geographical region, local conditions, normative rules and regulations, etc.). In this context, the resistance limits for a structure to be designed are defined and agreed with the customer on the basis of specific normative standards.

For example, the ASCE/SEI 7-05 [33] is a typical standard used for the definition of the design loads and cases to be applied in the structural analysis for the North American areas. The strength criteria for a structural analysis are defined by normative standards such as the ANSI/AISC 360-10 [34]. Generally, the design loads considered for a steel construction inside a national/international normative standard are as follows:

- **Dead loads**: the total weight of the structure with all the equipment, machineries, and accessories;
- **Live loads**: variable loads related to the use of the structure and their accessories such as a crane;
- **Wind load**: the action of the wind in each direction (+X, -X, +Y, -Y);
- **Seismic load**: the simulation of the dynamic load related to a possible earthquake. Response spectra are particularly useful tools for analyzing the performance of structures and equipment under earthquakes;
- **Operative pressure**: the nominal operative pressure inside the structure (if present);

Different normative standards propose a combination of loads to be evaluated in different design cases. Eq. (22) shows a typical load combination with a dead load (*Dead*), wind action in the +X direction ($Wind_{+x}$), live forces in the +x direction ($Live_{+x}$), and seismic load as the response spectra in the X direction. The coefficients (A, B, C, and D) are calculated on the basis of the related normative standards to be applied in the specific case. The design of a steel structure includes the analysis of different load combinations with different numbers of loads applied. Each combination provides different values for the highlighted coefficients. The combinations and coefficients are related to the specific normative standard.

$$A \cdot Dead + B \cdot Wind_{+x} + C \cdot Live_{+x} + D \cdot Seismic_{ResponseSpectra-x} \quad (22)$$

3.5 Multi Objective Function

A multi objective function is used to evaluate each simulation in terms of the four targets related to the weight, cost, and number of overstressed and overdeflected beams. This objective function is described in Eq. (23):

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$$f_W \cdot Cr_W + f_C \cdot Cr_C + f_{OS} \cdot Cr_{OS} + f_{OD} \cdot Cr_{OD} \quad (23)$$

where:

f_W = the weight factor assigned to the weight reduction (*first criterion*)
Cr_W = *first criterion* related to the weight reduction
f_C = the weight factor assigned to the cost reduction (*second criterion*)
Cr_C = *second criterion* related to the cost reduction
f_{OS} = the weight factor assigned to the overstressed beam reduction (*third criterion*)
Cr_{OS} = *third criterion* related to the overstressed beam reduction
f_{OD} = the weight factor assigned to the overdeflected beam reduction (*fourth criterion*)
Cr_{OD} = *fourth criterion* related to the overdeflected beam reduction

The described function (23) considers four criteria, each of which follows the quality characteristic small is better (SiB). The SiB characteristic means that a small value is better and achieves a greater score in the function calculation. The description of the SiB approach is described in Eq. (24), where $Value_{MAX}$ and $Value_{MIN}$ represent the maximum and minimum values allowed in the optimization analysis. These values are defined by the designing team. For example, the designer can define as a target a weight reduction of approximately 20% considering the maximum and minimum values. The terms such as f_W, f_C, f_{OS}, and f_{OD} are the factors that regulate the weight of each factor into the calculation of the objective function (23); the sum of these factors is 1.

$$\mathrm{Cr} = \frac{Value_{MAX} - Value_i}{Value_{MAX} - Value_{MIN}} \quad (24)$$

4 Results

This section presents the results related to the design optimization of the steel structure described in Section 3. The optimization is based on a 700 t construction that exhibits a weight reduction of approximately 10% with a cost reduction of approximately 12%. The reference structure and the loading conditions are generic and not related to an existing construction.

Table 7 lists the variables defined and analyzed in the constraint analysis using the *CSP tool*. A number of 18 parameters were selected to represent 9 groups of beams. More than 56 million combinations were analyzed and elaborated using the *CSP tool* in approximately 1 hour.

Table 7 Variables related to the analyzed test case for the CSP analysis.

Group Type	Group Name	Section Type	Variable list	Variable count
Primary Structure	Column 1	Circular Hollow	D, s	2
	Column 2	Circular Hollow	D, s	2
	Main Deck Traversal	I beam	b, h	2
	Main Deck Longitudinal	I beam	b, h	2
	First Deck Traversal	I beam	h	1
	First Deck Longitudinal	I beam	h	1
	Second Deck Traversal	I beam	h	1
	Second Deck Longitudinal	I beam	h	1
	Crane support	I beam	h	1

Secondary Structure	Piping support	Standard beam	h	1
	Braces First Level	Standard beam	h	1
	Braces Second Level	Standard beam	h	1
	Secondary Deck 1	Standard beam	h	1
	Secondary Deck 2	Standard beam	h	1

The result of the constraint-based analysis performed using the *CSP Tool* by employing the MiniZinc and Gecode toolkit is described by the tree view represented in Figure 15. Green elements represent the satisfying solutions, red elements represent a combination of variables pruned because they do not satisfy some constraints, the yellow element represents the optimal solution. A total of 50 satisfied solutions exist. These solutions are ordered by increasing weight. The domain of solutions is further analyzed into the optimization loop by using the numerical FEM tool and the described analytical cost tool.

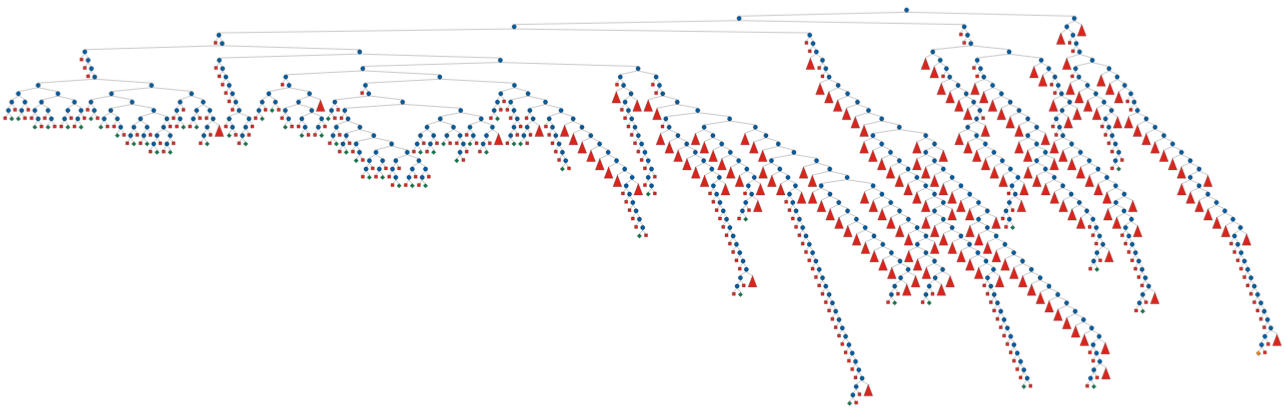

Figure 15 A graphical report of the CSP solution.

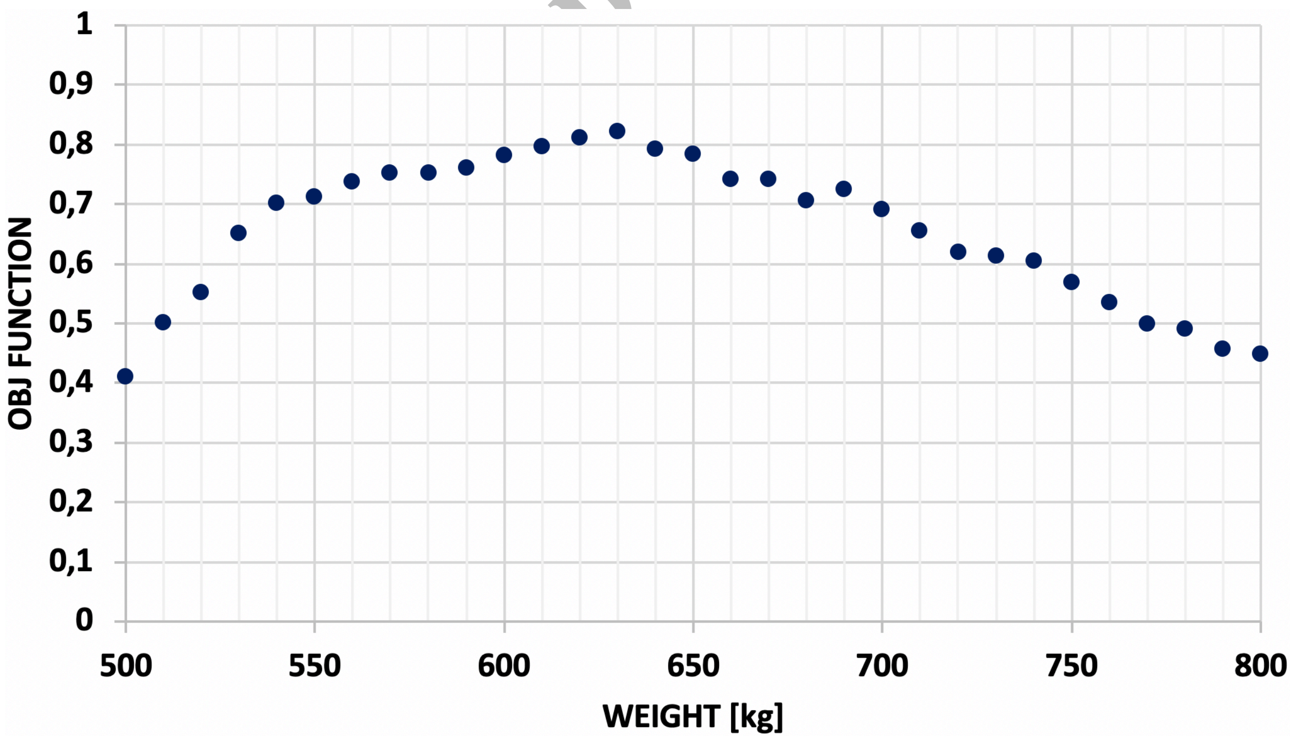

Figure 16 The relation between the OBJ function and the weight of the structure.

Figure 16 shows the result of the optimization after the simulation phase. The simulation phase lasted approximately 20 hours. Each possible solution is evaluated in the simulation loop (Section 2.1) by using the multi objective function defined in Section 3.5. The graph exhibits a parabolic behavior, which maximizes the solution with a better compromise among the cost, weight, and number of resulting overstressed and overdeflected beams. In this case study, the optimum solution is represented by a configuration that achieves a weight of approximately 630 t. This configuration provides a limited number of non-verified beams that must be reinforced during the engineering detail phase. Heavier solutions are not suitable because they increase the cost of the structure. However, lightweight solutions increase the number of non-verified beams with overstressed and overdeflection problems.

5 Conclusions

The paper proposes tools and methods to support the design optimization of ETO products. In this context, the integration between the traditional design workflow and optimization tools is necessary to participate in a worldwide competition. A constraint-based approach is introduced to reduce the space of the solutions in the optimization analysis.

The approach is defined for medium-large ETO companies that produce complex and expensive solutions that are not configuration products. The scientific context pertains to the research and application of the tools and methods in industrial engineering for enhancing the collaboration and optimization activities in the design. Even though the approach is generic, it is implemented for the design of steel constructions called *modules*, which are used in modular plants, for which the common multi objective analysis corresponds to the reduction of cost and weight. These steel constructions are prefabricated units, which consist of a main structure and a secondary structure. Since these modules are prefabricated, the engineering design also considers the loading conditions related to the transportation.

Modularization is a traditional design approach to reduce the cost in ETO products; however, this practice is not sufficient to achieve critical tasks in terms of the product optimization and cost. Focusing on oil and gas systems, the paper describes how to support the designer with tools in the early design phases for searching the optimum solutions to be submitted with the relative quotation after a request for proposal is generated.

Computer aided engineering (CAE) tools are generally applied to compare the mechanical behaviors of different ETO configurations, and therefore, such tools are often involved in the optimization loops for the design exploration. Here, the proposed design platform integrates these practices with the CSP analysis and analytical solvers. The CSP algorithms can search for the parameter combinations by exploring a new variable with consistency checking. Subsequently, the consistency checking is performed by checking whether the constraints among the variables are satisfied in terms of the new value combinations.

While a CSP model can be solved in a reasonable time, numerical simulations can take from a few seconds to several hours for the computation. Therefore, the simulation activity is proposed after the CSP exploration to overcome such computational limits. During the CSP analysis, the steel structure is redesigned for each set of parameters. The activity of the FEM simulation occurs after the CSP analysis, which resolves the domain of the solutions applying the required *Design Constraints*. In this context, a simulation loop is implemented to determine the structural behavior and realize the cost analysis. In the simulations, for each set of the parameters, the steel structure is redesigned in three different models related to three different configurations: operation, sea transport, and land transport. Each simulation is analyzed in terms of the maximum values of the deflection and stress state for each group of beams.

A Windows based application is developed to implement and solve the relative CSP model. This tool implements an O-O model, which represents the specific product structure. Since the designer can edit this

O-O model with its constraints, the approach is generic and allows different case studies to be analyzed. The analyzed design methodology demonstrates that it is possible to integrate the analytical and numerical solvers by using a CSP based optimization for mechanical and civil engineering problems. These analyses, applied for searching the optimum solutions, are executed in the background; therefore, they require a low effort by the user.

The paper also proposes the definition of a knowledge base with the design rules formalized after interviews and meetings with experts. In particular, the knowledge base focuses on past design experiences and provides a set of design constraints. The reduction in the design time is achieved because the time related to the optimization setup is reduced due to the employment of preconfigured design constraints to be used with an analytical approach.

The results indicate the possibility of achieving a prompt response and a short draft delivery to increase the competitiveness when a proposal is required. This outcome is suitable for ETO companies for ensuring the profitability due to a prompt process for the proposal submission and a cost optimization study from the early design phases. Using the proposed approach, the resulting lead time for the structural optimization is approximately 3 working days against an average period of 10 working days required for the past projects. Therefore, a time reduction of approximately 1 week can be achieved in the quotation process. As future work, the research could include a life cycle assessment to consider the environmental impacts on the optimization workflow.

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