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A multi-objective sequential method for manufacturing cost and structural optimization of modular steel towers

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Engineering with Computers

A multi-objective sequential method for manufacturing cost and structural optimization of modular steel towers

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Abstract:	This paper proposes a methodological approach for the multi-objective optimization of steel towers made from prefabricated cylindrical stacks that are typically used in the oil and gas sector. The goal is to support engineers in designing economical products while meeting structural requirements. The multi-objective optimization approach involves the minimization of the weights and costs related to the manufacturing and assembly phases. The method is based on three optimization levels. The first is used in the preliminary design phase when a company receives a request for proposal. Here, minimal information on the order is available, and the time available to formulate an offer is limited. Thus, parametric cost models and simplified 1-D geometries are used in the optimization loop performed by genetic algorithms. The second phase, the embodiment design phase, starts when an offer becomes an order based on the results of the first stage. Simplified shell geometries and advanced parametric cost models are used in the optimization loop, which present a restricted problem domain. In the last phase involving detailed design, a full 3-D computer-aided design (CAD) model is generated, and specific finite element method (FEM) simulations are performed. The cost estimations, given the high levels of detail considered, are analytic and are performed using dedicated software.
Response to Reviewers:	Authors would like to thank all the referees for their valuable reviews. Reviewer #1 The paper is a very interesting one which addresses a problem of practical value and investigates it properly. It is also generally well-written, well-structured, and graphically pleasant. Addressing the following issues can make the paper ready for publication: -Thank you for appreciating the manuscript. The title of the paper is somewhat uncommon and should be altered to something like

"A multi-objective sequential method for manufacturing cost and structural optimization of modular steel towers". The title should also suggest that "tubular shells" are considered.

-Thank you for this comment, the Title was changed. The topic “tubular shells” was included by the keyword “tubular steel towers” (this is a new keyword).

I suggest that the authors compare the results of their proposed method with a one stage optimization procedure to further signify the capabilities of their method.

-Thank you for pointing out this clarification, which was not presented in the manuscript you revised. We included a new paragraph in section 5.4 that explains the configuration used for evaluating the benefits of the structure obtained adopting the MOO approach presented in this paper. “The first configuration is a past project analyzed and optimized using a traditional one-stage process. In particular, the one-stage optimization was based on the CAD-model of the chimney elaborated during the embodiment design. The limits related to a one-stage approach concern the employment of a pre-defined structure with a fix number of items. In fact, without a first analytical MOO level, the number of the duct items must be defined by the designer using his/her know how. Even if further model changes are possible, a similar iterative process requires a lot of time for repeating design, setting, and optimization running. Moreover, the first MOO level can be used during the order definition to improve the answer to the RFP phase in terms of results and efficiency. Therefore, a multi-step optimization can be more suitable to support the design workflow for typical ETO products.”

I suggest that the authors compare their results with those of more recently developed optimization methods. Most probably these methods (even more recent variations of GA) will improve the quality of the results.

-Many thanks for this suggestion. Authors included a new chapter (6. Discussion) which aims to present the advantages of the presented MOO approach. This chapter presents future research about the optimization algorithms to be furtherly explored for the presented MOO method. Hereunder an extract of chapter 6. “Regarding the optimization methods, this paper is focused on genetic algorithms. In particular, MOGA-II has been tested and proposed for the highlighted test case. As a future research, this optimization method could be compared with other approaches such as Constraint Satisfaction Problem (CSP) and Particle Swarm Optimization (PSO). While the use of a PSO algorithm is still a heuristic approach, the CSP solution regards the mathematical representation of a set of engineering constraints to be evaluated inside a domain of solutions. In this paper a MOGA-II algorithm and a tool have been chosen to reduce effort and time in the definition of the optimization problem.”

What is the logic behind the list of acronyms? For example, why exactly PSO is mentioned in the list but ES and DE are not? (None of these methods are utilized).

-The Nomenclature was deleted because all the acronyms were presented in the text.

It can be interesting if the authors comment on more general regularity as introduced in:
A. Kaveh. Optimal Analysis of Structures by Concepts of Symmetry and Regularity, Springer, 2013.

-The reference to the suggested paper was included and commented. Authors have also included another interesting publication of the same author concerning multi-objective optimization.

The English of the paper should be improved. There are some grammatical error, nonstandard word usages and typos that should be eliminated. For example: "This paper proposes a methodological approach to supporting the multi-objective…" should read "This paper proposes a methodological approach for supporting the multi-objective…" Also the verb "support" does not seem to fit properly here and in the title. "… models are used in the optimization loop, which presents…" should read "….models are used in the optimization loop, which present…" The problems with the

	English of the paper are not limited to the abovementioned examples. -This paper was previously revised by an English Editing Service. After this comment, we sent back this paper for a new language revision. Thank you for this important comment. Reviewer #2 In this paper, authors proposed a sequential and multi-objective optimization method for supporting the design of engineer-toorder products. The method supports engineers in the development of products and in reducing manufacturing and installation costs. The paper specially focused on the design of tall modular steel towers in oil and gas power plants. Authors should explain Figure 13,14 and 15 more. -Thank you for this comment. Figure 13 and 14 were revised to increase the readability of the data. The cost breakdown originally included on these figures were moved in two separate graphs (Figures 14 and 16 of the revised manuscript version). Furthermore, authors included explained better graphs reported in the mentioned figures. Authors should explain some differences between design. -Many thanks for this suggestion. Authors included a new chapter (6. Discussion), which aims to present the advantages of the presented MOO approach, and a new subsection (5.4 Optimal configuration), which present technical details of the reference and optimized design Authors may explain whether the proposed method will use for designing wind turbine towers. -Authors explained the applicability of using the proposed method also for wind turbine towers made of fabricated circular tubes. Reference to this possibility was included in the new chapter (6. Discussion) and in the conclusions. “Even if the test case is focused on oil & gas chimneys, the approach can be extended and use for the design optimization of similar structures such as wind turbine towers” (from Discussion). There is some english mistakes in Figure 5. -This paper was previously revised by an English Editing Service. After these comments, we sent back this paper for a new language revision. Thank you for this important comment. I recommend this paper for publication with minor changes. -Many thanks for appreciating the manuscript.

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A multi-objective sequential method for manufacturing cost and structural optimization of modular steel towers

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Highlights

1. A sequential optimization approach for the design of ETO products
2. A multi-objective design optimization (MOO) method for tower-type tubular shells
3. MOO is based on manufacturing costs and structural strength
4. Manufacturing cost estimations made throughout the product design phase are given
5. The test case is focused on stacked steel towers used in oil and gas chimneys

Abstract

This paper proposes a methodological approach for the multi-objective optimization of steel towers made from prefabricated cylindrical stacks that are typically used in the oil and gas sector. The goal is to support engineers in designing economical products while meeting structural requirements. The multi-objective optimization approach involves the minimization of the weights and costs related to the manufacturing and assembly phases. The method is based on three optimization levels. The first is used in the preliminary design phase when a company receives a request for proposal. Here, minimal information on the order is available, and the time available to formulate an offer is limited. Thus, parametric cost models and simplified 1-D geometries are used in the optimization loop performed by genetic algorithms. The second phase, the embodiment design phase, starts when an offer becomes an order based on the results of the first stage. Simplified shell geometries and advanced parametric cost models are used in the optimization loop, which present a restricted problem domain. In the last phase involving detailed design, a full 3-D computer-aided design (CAD) model is generated, and specific finite element method (FEM) simulations are performed. The cost estimations, given the high levels of detail considered, are analytic and are performed using dedicated software.

Keywords: sequential optimization, multi-objective optimization, engineering-to-order (ETO), manufacturing cost estimation, numerical simulation, tubular steel towers.

1 Introduction

The field of product customization has grown over the past years, and it will continue to expand in the future [1]. This trend has been common to a wide variety of industrial sectors, though some differences can be observed. For instance, while the Build-To-Order (BTO) business model is commonly used as a product practice in the automotive industry [2], the Engineering-To-Order (ETO) model is widely applied in different sectors such as the oil and gas sector [1]. BTO and ETO products differ with respect to the presence of preconfigured and prescheduled production activities. While ETO products are engineered and built after an order is made [3], BTO products are already developed before a customer's order is made. ETO situations are very common when customer requirements cannot be fulfilled through standard offers. Sylla *et al*. [4] have classified ETO solutions as "light" when standard solutions almost fully cover requirements through minor customizations or as "heavy" when the related solution must be completely adapted and defined.

ETO products are complex "*one of a kind*" systems and involve highly variable products [5] designed to satisfy client specifications. The ETO scheme is used as an optimal means to compete in modern industry, whereby the responsiveness of a company to customers' demands plays a key role in enhancing its attractiveness [6]. However, it involves designing new parts to cater to customer needs [1]. In the bidding preparation and order fulfillment processes, meaningful project-based efforts may be warranted. This approach typically involves engineering calculations and decision-making processes [7]. Growing levels of customization introduce more design complexity [8], which in turn creates different problems: incorrect quotations, late deliveries, missed financial targets, etc. André *et al*. [5] have highlighted that an ETO business could benefit from the introduction of design platforms that support the development of highly customized products. Krisanto *et al*. have noted that a lack of modularization lengthens the duration of engineering change orders [3].

Cost estimations and quotations present considerable challenges for ETO manufacturers [9]. The development of an accurate cost model is a serious issue that a company must face. Often, detailed designs and specific knowledge about different products and manufacturing aspects (e.g., materials, machines, work-center times, custom tools, labor costs and times, etc.) are needed for accurate costs estimations [10].

Quote response times present another major challenge for ETO companies [11], which must be able to prepare a competitive bid as soon as possible without taking on unacceptable levels of financial risk. Speed and accuracy almost always work against each other. Moreover, long engineering lead-times significantly affect the development of ETO products. Time-related problems are mainly attributable to the customizations required to develop a product, typically without the use of systematic approaches or specific tools, and this often results in a need for more complex design efforts than were expected, causing considerable delays in project development [12].

In accordance with Pahl *et al.* [13], the *product design process* (PDP) of complex ETO products can be divided into three main phases. The first one (*preliminary design*) begins when a company's commercial division receives a *request for proposal* (RFP) for a new product/system/plant. To complete this task, a preliminary design must be developed. The time period required to obtain a technical and economic proposal that can be accepted by the customer is generally very short. The errors made at this stage and especially in terms of cost estimations can lead to a severe reductions in company profits.

The second phase (*embodiment design*) starts when an offer becomes an order and when a design must be developed. Engineers determine the definitive product layout and ensure that the functional, strength, dimensional, and cost requirements are met. The time allotted to this phase depends on the complexity of the design concerned and can generally vary from a few weeks to several months.

In the third phase (*detail design*), an executive project must be completed. For typical oil and gas structures, all accessory parts (e.g., flanges, bolts, catwalks, etc.) must be designed, and final drawings must be produced to define manufacturing and assembly processes. Typically, less time is allotted to this phase than the embodiment design phase.

Multi-objective optimization (MOO) methods and tools coupled with numerical solvers, automatic cost estimation tools, product configurators and design automation systems allow companies to secure new market shares [14] and to beat competitors during the preliminary design stage when an RFP must be prepared [4]. As noted in the following section, MOO is a common practice used to reduce product costs and to enhance performance in line with project requirements and standards. This approach is used to deliver a competitive offer, especially in the sector of complex ETO products [15] [16]. Enhanced MOO achieved during the preliminary design phase can drastically enhance the competitiveness of a product and company’s profits. However, this is not a trivial task due to the presence of time constraints and limited product knowledge. Optimization must also be stressed in the design stages that follow. In fact, once a sale price has been determined in the first phase (order received), the optimization process directly influences the product profit margins.

The aim of the present study is to formulate a mean to optimize the design of modular steel towers consisting of cylindrical or conical shell items of stepwise varying thicknesses, heights and materials for each shell element. For this reason, a sequential and multi-objective optimization method for the design of ETO steel towers has been developed. The towers examined are subject to forces (weight, winds, earthquakes, etc.) and moments, typical of conditions prevailing at the related installation site. The most suitable load-carrying structure for a steel tower is a welded [17] and stacked steel shell [18]. During the RFP phase, an analytical-based MOO is used to support an early evaluation of the cost and product performance through a structural analysis. This optimization phase is performed using simplified simulation models (i.e., 1-D-product models solved using lumped parameter models) opportunely automated to explore several solutions without the use of manual inputs. Subsequently, during the embodiment design phase, a simplified 3-D shell model is optimized from the results of the first stage. This carryover approach restricts the optimization problem domain at the second stage (when the product is more detailed) by reducing the number of variables considered and/or their variation ranges. Finally, for detailed design, based on the results of the previous phase, comprehensive optimization is performed. In turn, from analytical cost estimations and broad analyses of the structural behaviors of a full 3-D model, an optimal solution can be identified. This method allows for a complete exploration of the problem domain for quickly developing a semi-optimized product design useful for the bidding phase and then a robustly optimized product design for the maximization of a company's profits during the engineering design phase of ETO solutions.

2 Literature review

2.1 Cost analysis and numerical simulations

During the design of modular steel towers, engineers must complete three main tasks: cost estimations, performance simulations and multi-objective optimizations.

Manufacturing cost estimations have been widely examined in research studies and characterized by numerous methods. In this context, Duverlie *et al*. [19] classified such methods as follows:

- Intuitive: method based on the tacit knowledge of the estimator. This method does not involve the use of a detailed product model, and the results are strongly dependent on the knowledge of the technician;
- Analogical: method based on group technologies according to the principle that similar products should have similar costs. This method involves making high initial investments in classifying products;
- Parametric: method based on product parameters (e.g., weight, dimensions, or materials). This method involves using specific formulas perceived as black boxes that combine such parameters to estimate costs;
- Analytical: method based on elementary tasks required to manufacture a product. This is the most detailed approach and involves the full definition of a product model.

Each method presents advantages and disadvantages that indicate the best fields of application. The adoption of such methods depends on the levels of product model maturity determined by the phases of the PDP. For instance, the analytical method requires the use of a detailed product model with almost all information defined that is generally available during and after the embodiment design phase. The parametric cost estimation approach is more suitable for use in preliminary design phases during which a 3-D computer-aided design (CAD) model is missing and when designers know only the most important functional features of a product (e.g., meaningful dimensions, overall shapes, and types of materials). Hence, within an industrial context, a combination of parametric and analytical methods is required to facilitate the entire product development process. With regard to the cost estimation of steel towers, *Papavasileiou et al*. [20] developed a model that takes into account the unitary cost of steel and concrete to predict the manufacturing costs of complex civil structures. *Lagaros and Karlaftis* [21] proposed a lifecycle costing approach for comparing different shapes of steel wind turbines and their installation scenarios.

2.2 Multi-objective optimization of mechanical products and steel towers

In the ETO sector, one of the main priorities is the identification of an optimal solution, which is the solution that allows one to achieve the best measurable performance (objective function/s) under given constraints. Therefore, MOO has become very popular in this sector [16]. When performing MOO, several methods (*genetic algorithms* (GAs), *evolution strategies* (ES), *differential evolution* (DE), *particle swarm optimization* (PSO), *neural network* (NN), etc.) can be employed to find a solution [22]. The use of such expensive computational methods has been facilitated by recent progress made in the development of computing technologies [23]. In this context, research on this topic has become even more popular. As an example, *Castorani et al* [24] developed an automated optimization procedure for achieving the right trade-off between conflicting objectives in developing mechanical products by using surrogate models and the multi-objective genetic algorithm (MOGA). *Cicconi et al*. [16] developed a tool for optimizing steel structures for the oil and gas sector during the preliminary design phase. *K. Martini* [25] described MOO based on a "VESPO" method that supports decision making in the conceptual design phase. The authors highlighted that *"relative to the needs of final design, conceptual design may be better served by optimization methods which can sacrifice some precision to achieve higher speed and maintain acceptable consistency." S. Arnout et al.* [26] used commercial *finite element method* (FEM) software to analyze the structural behavior of a barrel vault with large dimensions early in the design phase. *P. Hao et al*. [27] developed a method based on the use of surrogate models to achieve weight reduction using CAE simulations. *Brown et al.* [28] proposed MOO (based on FEM and energy simulations) to be applied early in the design of long-lifespan buildings to reduce their environmental impacts. This study was conducted using one of the most widely known GAs: the nondominated sorting genetic algorithm II (NSGA-II). *Tort et al*. [29] presented a tool for the automated design of steel lattice transmission line towers that integrates the *simulated annealing* (SA) optimization algorithm into a commercial *finite element analysis* (FEA) tool. *Zou et al.* [30] used an optimization process based on the ε-constraint method to find an optimal design solution that minimizes the lifecycle cost of a reinforced concrete frame. Kaveh *et al*. [31] presented a framework to find the best solution for large steel structures subjected to seismic loads in terms of the manufacturing and lifecycle costs. *Shin and Singh* [32] discussed the optimal design of yielding metallic devices that minimize the expected lifecycle costs. The authors carried out MOO driven by the NSGA-II algorithm. Liang *et al*. [33] compared four different optimality algorithms commonly used in the MOO of steel structures. Their results show that the multi-objective heuristic particle swarm optimizer (MOHPSO) generates a more stable and universal Pareto front relative to the NSGA-II, MOPSO and MGSO. Uys *et al*. [17] proposed an approach for the cost optimization of a 45-m steel tower modeled by three welded and stacked cylindrical shell modules. The authors used an FEM tool to optimize the thickness of each shell; however, they did not consider the height of each item as a design variable to be analyzed. Many studies have focused on wind towers. The simplified method proposed by Negm and Maalawi [34], which does not involve the use of FEM solvers, serves as an example. This method offers benefits in terms of the computing time.

Moreover, this optimization approach considers the height of each shell item as a main design variable for design optimization. In fact, even though other studies [17] do not consider the module height as a key variable similar to the cross-sectional parameters, Negm and Maalawi highlight that the module height is an important parameter for the structural optimization of steel shell towers. Other research papers stress that the seismic response is often significantly less critical than the response resulting from wind loading for steel towers [35,36]. Regarding optimization methods, evolutionary algorithms such as GAs and PSO methods are widely applied for steel tower design [35] and to other engineering applications [26]. In fact, they offer superior global search capacities compared with conventional optimization algorithms [35].

2.3 Sequential optimization

MOO is a computationally demanding task, especially when it is conducted solely in the detailed design phase. To address this problem, researchers have developed new means to solve optimization problems faster. Kaveh [37] collected and described the most used algorithms in handling large-scale optimization problems in an efficient way, i.e. lowering the computational cost of the analysis. Most of the research has focused on "*sequential optimization.*" Such approaches enable designers to find solutions appropriate for different design phases. In this manner, rough results derived from the preliminary design optimization stage can be exploited to drive subsequent optimizations in the identification of a more accurate optimal solution. For instance, *Zou's* [38] study is based on two sequential optimizations with the aim of reducing the lifecycle costs of a building while respecting seismic performance criteria. The first optimization stage does not consider costs, and it is focused on nonlinear structural analysis only. Then, from previous results, a lifecycle cost model is defined, and MOO is performed. *Ozturk et al*. [39] divided the cost optimization of a cold-forged product into two stages. In the first stage, the design of a part is optimized, while in the second stage, both the product design and forging process are optimized. In this way, the second optimization stage can be completed within a restricted design domain (identified during the first optimization stage). *D. Bruno et al*. [40] developed an iterative optimization approach for network arch bridges based on three stages involving phases considering increasing levels of detail in terms of loads and constraints. *I. Steponavičе et al*. [41] provided a three-phase solution approach to the optimization of conflicting multiple objectives employing the MOEA/D, a generic algorithm based on decomposition. They started with the use of a computationally expensive method employing parallel computing and then, based on the generated solutions, applied an approximation method to create a computationally inexpensive surrogate problem. In the third stage, the solution best matching that of the second stage is identified for the original problem.

All related studies on steel tower optimization describe a lack of tools and methods that support the design of an ETO product from the bidding stage to detailed design. In fact, while some researchers describe an optimization approach based on FEM analysis used for embodiment and detailed design, others describe simplified methods suitable for the early stages of conceptual design. Design issues related to ETO projects concern the need to perform different levels of analysis with increasing degrees of detail throughout the design process until a product is developed.

3 Materials and methods

3.1 Steel tower configuration

The product parameterization approach is widely applied in the design of oil and gas systems, as it enhances the reuse and adaptation of previously developed solutions while saving time and costs. In this paper, a steel tower for GT chimneys is taken as an example. The stacked tower consists of different shell elements, each of which is composed of a fabricated circular tube (Figure 1). The configuration of each related circular stack consists of four main components:

- *Casing*: this is the main component of a circular stack and is generally created by calendering and welding sheet metal;
- *Casing stiffeners*: these are used to stiffen the casing and are welded to the outside of the casing. They are composed of a calendered and welded angular beam;
- *Flanges*: these are used to connect adjacent stacks and are generally made from a calendered, welded and drilled angular beam;
- *Flange stiffeners*: these are used to stiffen flanges by connecting them with a casing. They are triangular and created from sheet metal.

The characteristic features (dimensions, shapes and materials) of each component of a circular stack are determined according to configuration rules based on the fundamental dimensions defined by a designer (Table 1). Such dimensions apply to the following: casing diameters, casing lengths, casing thicknesses, casing materials, diameters and quantities of holes in flanges, and flange widths. Such dimensions are respectively discrete or continuous when they assume only a set of predetermined values (e.g., material) or change continuously within a specific range of values (e.g., casing length). According to the fundamental dimensions, configuration rules allow one to determine all other dimensions.

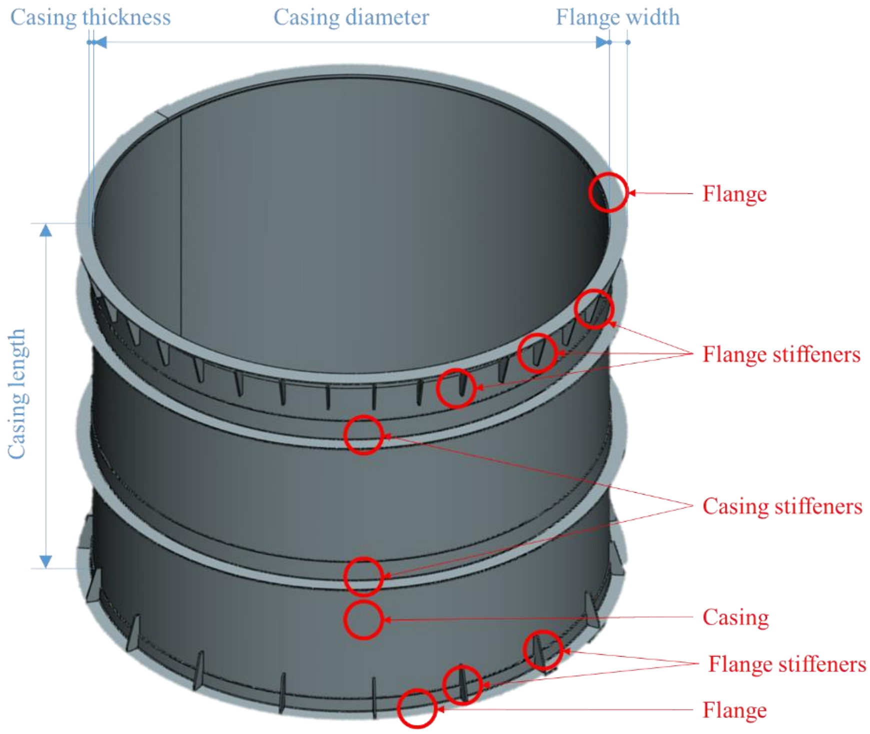


Figure 1: 3-D CAD model of a circular stack

Table 1: Characteristic features of a circular stack

Parameter	Description	Unit of measure	Configuration rule
CasingDiameter	Diameter of the external casing	mm	Input (continuous variable)
CasingLength	Axial length of the external casing	mm	Input (continuous variable)
CasingThickness	Thickness of the external casing	mm	Input (discrete variable: 1, 1.2, 1.5, 2, 2.5, 3, etc.)
CasingMaterial	Material of the external casing	-	Input (discrete variable: Fe360, Fe430, Fe510, etc.)
CasingStiffenerWidth	Width of a casing stiffener	mm	=FlangeWidth
CasingStiffenerHeight	Height of a casing stiffener	mm	=CasingStiffenerWidth
CasingStiffenerThickness	Thickness of a casing stiffener	mm	=CasingThickness
CasingStiffenerQuantity	Number of axial stiffeners	-	=Integer (CasingLength/CasingStiffenersOffset)-1
CasingStiffenerOffset	Offset between two consecutive axial stiffeners	mm	Database (Constant)
CasingStiffenerMaterial	Material of the casing stiffeners	-	=Casing Material
FlangeHoleDiameter	Diameter of each hole in the flange	mm	Input (discrete variable: 10, 12, 14, 16, 18, 20, 22, 24, etc.)
FlangeHolesQuantity	Number of holes in a flange	-	Input (discrete variable: 16, 18, 20, 22, 24, 26, etc.)
FlangeWidth	Flange width	mm	Input (discrete variable: 50, 60, 70, 80, 80, 90, 100, 120, 140, 160, etc.)
FlangeHeight	Flange height	mm	=FlangeWidth
FlangeThickness	Flange thickness	mm	=CasingThickness
FlangeMaterial	Flange material	-	=CasingMaterial
FlangeStiffenerWidth	Flange stiffener width	mm	=FlangeWidth
FlangeStiffenerHeight	Flange stiffener height	mm	=1.5·FlangeStiffenerWidth
FlangeStiffenerThickness	Flange stiffener thickness	mm	=FlangeThickness
FlangeStiffenerMaterial	Flange stiffener material	-	=CasingMaterial
CasingQuantity	Number of casings	-	=1
CasingStiffenersQuantity	Number of casing stiffeners	-	=Integer (CasingLength/CasingStiffenerOffset)-1
FlangeQuantity	Number of flanges	-	=2
FlangeStiffenersQuantity	Number of flange stiffeners	-	=(Integer (pi.greco·CasingDiameter/FlangeStiffenerOffset)-1)·2

3.2 The sequential optimization approach

The methodological approach is designed to support the design of modular steel towers from the early design phase to the detailed design stage. Even though studies have focused on chimneys for oil and gas systems, the approach is also applicable to different types of steel towers composed of prefabricated cylindrical or conical items. Such stacked steel towers are ETO products; therefore, they are designed and engineered based on a customer’s order.

As discussed above, the design of ETO products begins with the RFP phase. In this stage, engineers develop a project draft for proposing a reliable quotation to the customer. Therefore, an efficient and agile design methodology must be used to execute a reliable draft project during the RFP phase. The proposed method highlights three different levels of design for ETO products: i) conceptual design, ii) embodiment design and iii) detail design (engineering).

Objective functions focus on weight and cost reduction. Weight reduction is an important issue because it impacts material costs, transport, and handling [42]. Cost reduction is another important issue related to the design of oil and gas systems, as it directly increments the competitiveness and profits of an ETO producer [43]. Regarding the proposed design approach, MOO analysis is common to each design level; however, the methods and tools used vary and are described in the following sections, as highlighted in Figure **2**.

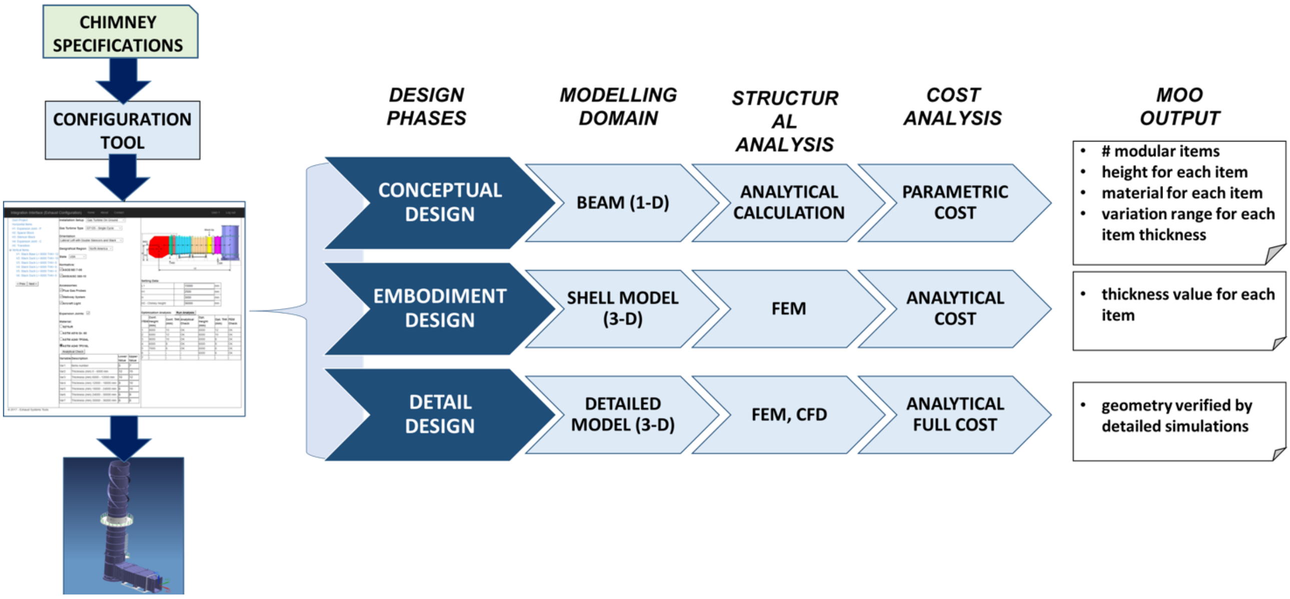


Figure 2 The proposed design methodology

While Figure **2** describes the design optimization approach, which is applied at each design level, the workflow illustrated in Figure 3 and Figure **5** shows the interactions occurring between each optimization level during the design phases. The input of the proposed workflow includes the specifications of the ETO product to be engineered. Therefore, input data are related to the geometrical dimensions, constraints, boundary conditions, and standards and regulations to be applied. Generally, the total height of a steel tower to be built is fixed because this is specified as a customer requirement. The boundary conditions and applied loading forces are the same for each level of the proposed design optimization. The design loads are described in more detail in the following sections. Generally, the loading conditions include the following: the dead load, live load, wind load, seismic load, and operative pressure level.

As stated above, the proposed approach is focused on a MOO analysis for the design of modularized steel towers such as oil and gas chimneys. Such ETO products require the use of configuration tools to perform design activities [3,4,18], for limiting the efforts and costs involved in the early design phases. The design methodology analyzed in this paper considers a configuration process as highlighted in Figure **2**. The configuration process is designed to develop CAD models with a related *bill of materials* (BOM) used during the three stages of design optimization. Parametric CAD models generated from predefined templates may be configured with varying levels of detail depending on the design stage in which they are used (i.e., 1-D and 3-D shells and detailed 3-D solids for the conceptual, embodiment and detailed design phases, respectively).

The optimization process is designed to define the optimum configuration of design variables (e.g., the height and thickness of each duct item) based on three different levels of geometrical detail. While the first optimization level is based on a 1-D model, the second one is based on a 3-D shell model. Finally, the third level involves detail design where simulations and analyses are based on 3-D solid models. The first step aims to define the quantity of duct items that optimizes manufacturing costs. The optimal combination of the height and thickness configurations for each shell item also affects the structural behavior of the resulting stacked tower. This result is further optimized in the second stage based on the thickness of each cross-section. During the second MOO stage, the number of duct items and their height values are fixed based on the first stage. Therefore, the second stage of the MOO refines the optimization defining the thickness of each duct. The third stage is focused on detailed simulations and calculations used to release the engineered design. Further information is available in Table 2. Moreover, the following section describes the design approach used in each MOO stage.

Table 2: Summary of the optimization

	CAD Model	**Configuration parameters**	**Optimized variables**	**Boundary conditions**	**Structural simulation approach**	**Cost estimation approach**
Conceptual	1-D	**Stack**: *diameter*, *thickness*, *material*, *length* **Steel tower**: *height*, *stack quantity*	All configuration parameters apart from design constraints, stack quantities, and stack thicknesses	Loads and constraints applied to a 1-D geometry	De Saint Venant beam solved with Excel or MATLAB	Simplified parametric cost models not considering the manufacturing process.
Embodiment	3-D shell (simplified model)	**Standard stack**: diameter, thickness, material, length, flange width, flange hole diameter, flange hole quantity, casing stiffeners width, casing stiffener height, … **Special stack**: custom parameters, accessory components, custom parameters **Steel tower**: height, sequence of stacks, accessory components	All configuration parameters excluding: • design constraints • those not influencing objectives • domain limitations …	Loads and constraints applied to a 3-D geometry	3-D shell model solved with FEM software tools	Detailed parametric cost models considering the manufacturing process.
Detailed	3-D solid (detailed model)			Loads and constraints applied to a 3-D geometry	3-D solid model solved with FEM software tools	Analytical cost models

3.3 MOO steps

The first design stage is concurrent with the RFP phase (Figure **3**), as a simplified CAD model is developed and optimized.

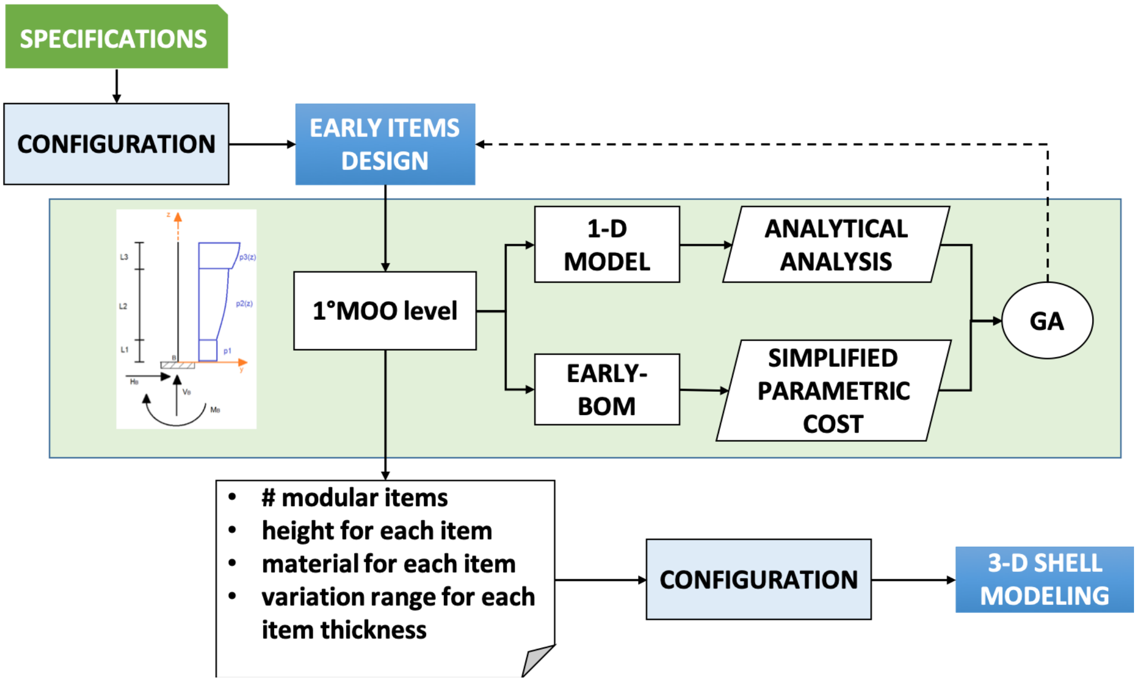


Figure 3 Description of the first MOO stage of the proposed design workflow

The proposed preliminary design method employs a 1-D model in which the steel tower of the chimney to be studied is described by a beam model (Figure **3**) that is divided into a variable number of segments. Each segment represents a duct item with its cross-section (thickness and inner diameter). The length of each segment is the height of the related duct item. While the thickness and height are geometrical variables of each duct item, the inner diameter is a constant parameter, as it is an input value related to the product configuration. This first optimization phase is focused on the analytical analysis of a 1-D model, which can be solved by applying equations of a pole fixed in the ground. This simplified approach considers the product mass and inertia and guarantees efficient calculation (faster than a 3-D analysis). A MATLAB® calculation tool has been developed to solve the stress state of the simplified 1-D model. This tool performs a structural analysis based on an analytical approach (lumped parameter model). The cost analysis approach related to this 1-D model is based on a simplified parametric approach that considers the number of items involved, duct dimensions and weights. At this level, a simplified parametric cost is calculated based only on the product BOM. The proposed optimization analysis approach is performed using a GA-based tool that describes the geometrical parameters of each duct item to achieve a configuration with a reduced cost and weight. The objective function is evaluated using the analytical model for structural analysis and the parametric model for cost evaluation. In a preliminary phase, the output is a simplified layout of the chimney specifying the number of modular items to be involved and the thickness of each item. The quantity of items and their thicknesses are the most important design variables in relation to weights and manufacturing costs. This is why these must be optimized during the first

MOO stage. While the item height is defined in this phase, the thickness of each item is optimized in the second stage. However, the first MOO stage reduces the range of variations to be investigated in the second MOO stage for each duct thickness. This is important in limiting the computational time needed to simulate the design solutions generated during the embodiment design stage.

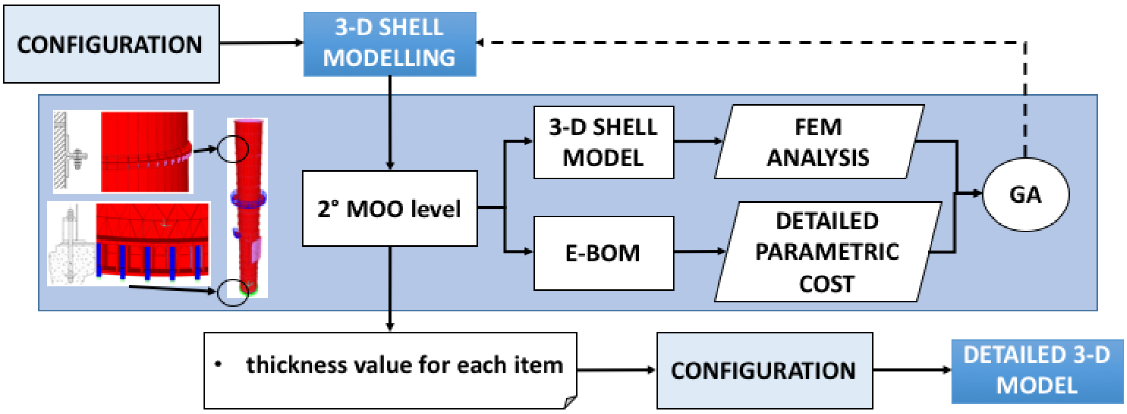


Figure 4 Description of the second stage of MOO within the proposed design workflow

The second stage of design focuses on the optimization of a 3-D model based on shell objects (Figure **4**). While a duct item is represented by a shell entity such as a cylindrical surface, reinforcements and flanges are modeled as planar surfaces. This second MOO stage occurs after the RFP phase and refers to a product's embodiment design. The structural analysis is based on a 3-D FEM solver that calculates the resulting stress behaviors of the simplified shell model. This second level considers each cylindrical and conical item involved in the chimney's structure with reinforcements and accessories such as catwalks. The presence of a 3-D geometry increases the level of detail of the optimization analysis. As described above, an engineer can use previously generated results to conduct a new optimization analysis. In fact, an investigation of variation ranges related to each duct thickness can be simplified from the first stage to the second stage. From the second MOO stage, an optimized value of thickness for each duct item is determined to reduce costs and enhance structural performance using a detailed parametric cost approach and FEM solver (Figure **4**).

Here manufacturing cost estimation follows a detailed parametric approach due to the availability of more detailed product-related information on stiffeners and flanges with related features. The values of design variables are defined by the product configurator. In this stage, costs can ben computed more specifically than before since the availability of the 3D CAD model and manufacturing process related information.

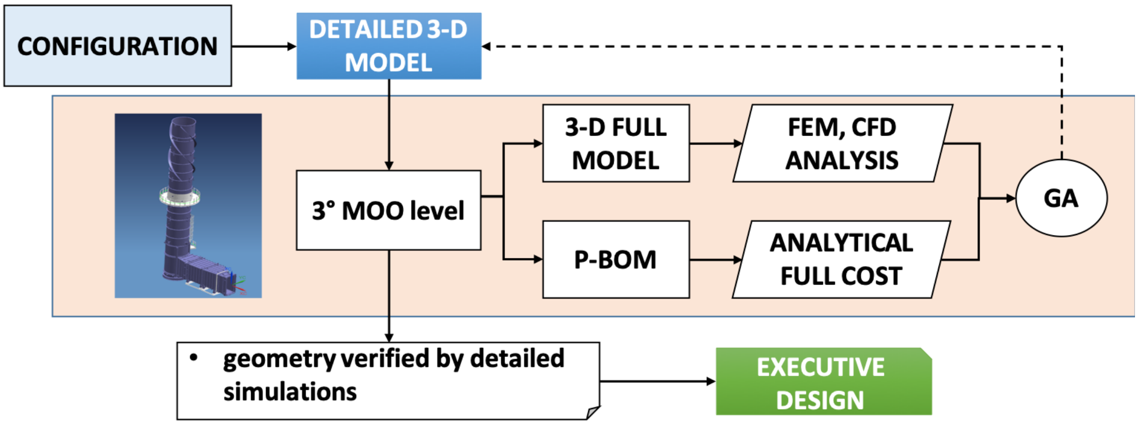


Figure 5 Description of the third MOO stage of the proposed design workflow

The third stage of the design of ETO steel towers involves detailed design where the output is the executive project (Figure **5**). This level is based on a full 3-D model generated by the configuration tool. Therefore, the full 3-D model has parametric dimensions that have been optimized through the first and second stages of the MOO. MOO focuses on specific features of the 3-D full model to determine the executive design. For example, design optimization can be used in studies of the temperature profiles and structural behaviors observed at a specific point of flange contact. Moreover, in this stage, engineers simulate the overall product via a FEM analysis. In this phase, the FEM simulation differs from that executed in the second MOO stage, as it is based on a full 3-D geometry with a solid tetrahedral mesh. Therefore, the costing phase of the detailed design is based on an analysis of a 3-D geometry related to the full assembly model of the stacked steel tower. The costing tool employed can read the geometrical parameters of the costs based on each model component. The engineer can perform a cost analysis by defining manufacturing parameters related to machine tools, setups, and raw materials. The employed costing tool can apply specific functions to predict the final manufacturing costs.

3.4 Optimization algorithms

All optimization levels are based on GA methods and on the MOGA-II in particular. This algorithm is widely used in the related literature [35] because it uses a smart multisearch elitism approach that preserves excellent solutions without spurring premature convergence to local-optimal frontiers [44].

The optimization approach is similar for each stage as discussed above. The main difference is rooted in the number of parameters involved and in the use of different tools to solve objective functions. In fact, while the first stage considers a small number of geometric parameters, the second stage focuses on a larger number of variables related to the 3-D geometries involved. An additional increase in parameters is related to the third stage of optimization, which involves detailed design. The last stage involves parameters related to the geometry, manufacturing, and assembly. Each optimization process starts with the definition of an initial population as a first set of values for the variable parameters. The evaluation process is based on the calculation of objectives, on the evaluation of the fitness, and on rankings to add solutions to the Pareto dominance value. The Pareto dominance value provides excellent solutions that are nondominated, meaning that no point is superior among the objectives considered in optimization functions. The Pareto analysis approach is one of the most widely applied in the field of mechanical engineering because it allows the evaluation of different optimal solutions. The generation of new populations of individuals is based on typical GA phases (e.g., selection, crossover, and mutation).

3.5 Cost analysis

According to our literature review, four different cost estimation approaches are available. In reference to their characteristics, in the context of this paper the authors propose a simplified parametric method for the first optimization stage, in which the product is simplified with a 1-D CAD model and a detailed parametric method for the second optimization stage, in which a simplified 3-D CAD model of the product is made available (surface model). The third optimization stage uses an analytical cost estimation approach, as 3-D CAD solid models are available at this stage.

The integration of different approaches to estimate the cost throughout a PDP should allow engineers to monitor the cost progression. Indeed, a standard cost breakdown that remains the same during the different design stages is recommended for the monitoring of a product's cost history. Using this approach, engineers can control the cost progression from the preliminary design phase (first level) to the detailed design phase (third level) through the embodiment design phase (second level). Such a solution is also very useful for budgeting related activities. The cost items considered for the estimation of a fabricated tube are as follows:

- *Material items*: the costs of raw materials, including commercial items (e.g., screws, nuts, and pin) and customized parts (e.g., sheet metals, beams, supports, and flanges);
- *Manufacturing items*: costs to obtain a final product from the material (e.g., lasers, oxyacetylene and saw cutting, bending, calendering, drilling, and milling);
- *Logistical items*: the cost of moving parts between production departments of a construction site. This is an overhead cost based on the use of cranes, forklifts and other tools in handling raw materials and semifinished components;
- *Nondestructive testing (NDT)*: costs for controlling welding through the use of liquid penetrant technologies;
- *Assembly*: costs necessary to assemble each component based on the costs of positioning and welding parts together.

The simplified parametric cost models are based on configuration parameters used in the conceptual design phase (Table 1) (i.e., the diameter, thickness, material and length of each stack, the tower height and the number of stacks). This cost analysis generates a value for an entire stack divided into materials, manufacturing tasks, logistics, NDT values and assembly costs. At this stage it is not possible to calculate the cost of each component of a stack due to a lack of available information (e.g., number of stiffeners and flange dimensions). The simplified equations listed below are used to compute the total cost of a stack using a simplified parametric approach.

The raw material cost is mainly determined from the weights of the casings, scraps and other components such as stiffeners and flanges

$$\boldsymbol{MaterialCost} = \pi \cdot CasingDiameter \cdot CasingThickness \cdot CasingLength \cdot CasingMaterialDensity \cdot CasingMaterialUnitPrice \cdot \left(1 + \frac{CasingScrapeRate}{100} + \frac{StiffenersFlangesWeightImpact}{100}\right) \quad (1)$$

The manufacturing cost is determined from a reference table citing diameters, thicknesses, lengths and casing materials. Given the complexities of the manufacturing process, the number of influencing parameters involved and a lack of 3-D CAD models, this cost item can be determined by examining previous configurations and projects.

The assembly cost, which is mainly affected by welding operations, depends on the casing diameter and length considered. This cost item is measured using the same approach as applied to determine the manufacturing cost, as it is determined from a reference table.

The NDT cost is a percentage of the assembly cost, as it is mainly needed to test the welds.

$$\boldsymbol{NDTC}\mathbf{ost} = AssemblyCost \cdot NDTCostPercentage \quad (2)$$

The logistics costs are shaped by the overall weight because they refer to the movement of components across the shop floor.

$$\boldsymbol{LogisticsCost} = CasingWeight \cdot \left(1 + \frac{CasingScrapeRate}{100} + \frac{StiffenersFlangesWeightImpact}{100}\right) \cdot LogisticUnitCost \quad (3)$$

The parametric method used to determine cost items is based on the configuration features presented above, which are the independent variables used in the equations. *Material* and *manufacturing* cost items are relative to each component while *logistics*, *NDT tests* and *assembly* refer to the entire fabricated tube. The cost calculation equations also consider additional parameters related to the manufacturing processes required to realize the components of a stack. For each parameter, Table 3 reports descriptions, units of measurement, sources and influencing parameters. Each parameter listed in this table is shaped by one or more parameters. For instance, the *DrillingUnitTime* value (the time needed to drill a hole) is shaped by the hole diameter, depth and material used. For such an example, the drill time is obtained by collecting and analyzing drill times determined from workshops, from the literature or from analytical cost estimation software tools.

Table 3 Parameters used in cost calculation equations

Parameter	Description	Unit of measure	Source	Influencing parameters
CasingMaterialDensity	Density of the casing material	kg/m^3	Database(Function)	CasingMaterial
CasingStiffenerMaterialDensity	Density of the casing stiffener material	kg/m^3	Database(Function)	CasingStiffenerMaterial
FlangeMaterialDensity	Density of the flange material	kg/m^3	Database(Function)	FlangeMaterial
FlangeStiffenerMaterialDensity	Density of the flange stiffener material	kg/m^3	Database(Function)	FlangeStiffenerMaterial
CasingMaterialUnitPrice	Unit price of the casing material considering sheet metal cutting operations	€/kg	Database(Function)	CasingMaterial
CasingStiffenerUnitPrice	Unit price of the casing stiffener material considering sheet metal cutting operations	€/kg	Database(Function)	CasingStiffenerMaterial
FlangeMaterialUnitPrice	Unit price of the flange material considering saw cutting operations	€/kg	Database(Function)	FlangeMaterial
FlangeStiffenerMaterialUnitPrice	Unit price of the flange stiffener material considering sheet metal cutting operations	€/kg	Database(Function)	FlangeStiffenerMaterial
CasingScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	Database(Function)	Shape
CasingStiffenerScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	Database(Function)	Diameter
StiffenersFlangesWeightImpact	Weight of flanges and stiffeners as a percentage of the casing weight	%	Database(Function)	Shape
FlangeScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	Database(Function)	Shape
FlangeStiffenerScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	Database(Function)	Shape
SheetmetalCalenderingUnitTime	Time required to calendar sheet metal	Minutes	Database(Function)	Thickness Length Diameter
BeamCalenderingUnitTime	Time required to calendar a beam	Minutes	Database(Function)	Thickness Length Diameter
WeldingSpeed	Manual welding speed	Mm/min	Database(Function)	Thickness Material Geometry (e.g.,butt weld, fillet

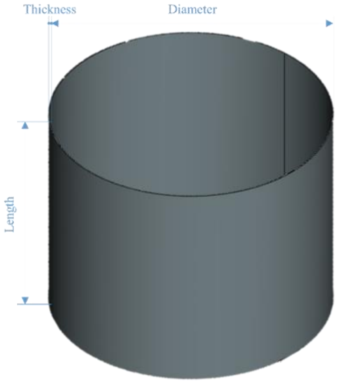
				weld) Welding type (e.g., continuous, intermittent)
DrilingUnitTime	Time required to drill a hole	Minutes	Database(Function)	Diameter Depth
SheetmetalCalenderingUnitCost	Unit cost of a sheet metal calendaring machine	€/hour	Database(Function)	Thickness Length Diameter
BeamCalenderingUnitCost	Unit cost of a beam calendaring machine	€/hour	Database(Function)	Thickness Length Diameter
WeldingUnitcost	Unit cost of a certified welder	€/hour	Database(Function)	Overall dimensions
LogisticUnitCost	Unit cost of logistic activities executed on the shop floor	€/kg	Database(Function)	Workshop
NDTUnitCost	Unit cost of Nondestructive testing	€/m	Database(Function)	Overall dimensions
NDTCostPercentage	Cost of Nondestructive testing measured as a percentage of the assembly cost	%	Database(Function)	Constant
DrillingUnitCost	Unit cost of a drilling machine	€/hour	Database(Function)	Overall dimensions

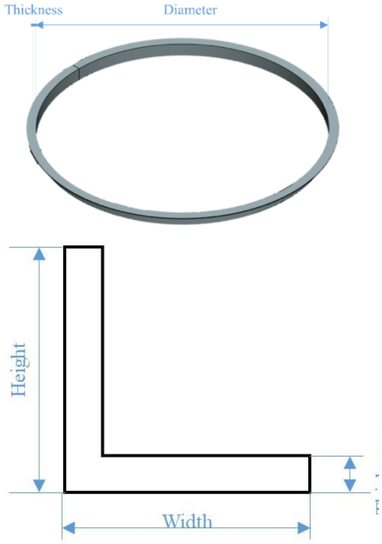
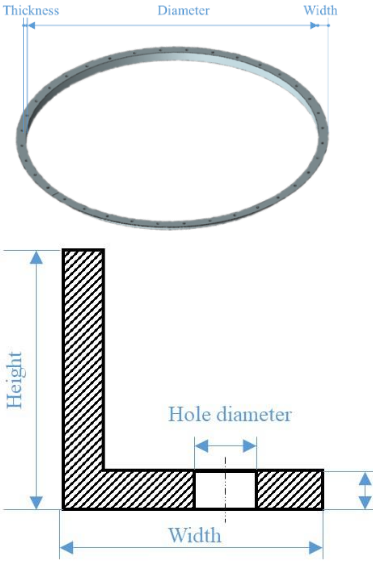
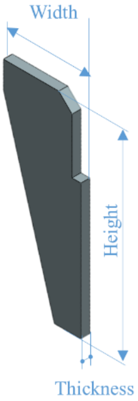
The manufacturing cost models of each component are illustrated in Table **4**, such that hereafter, the authors provide only a brief description of the casing used.

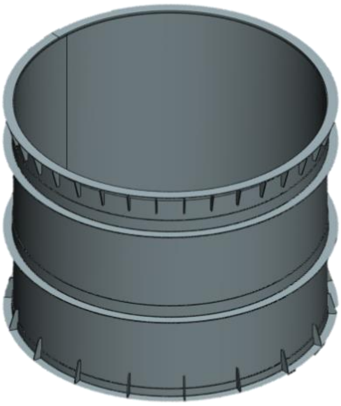
The *casing* consists of precut sheet metal (laser or oxyfuel cutting, depending on the thickness and composition of the material used) that is calendered and then welded to form a round tube. The raw material cost considers the cost required for the cutting operations and scraps related to the cutting process. The scrap rate is a percentage based on the shape involved (sheet metals or beams). The calendering and welding costs are determined by multiplying the manufacturing time by the unit cost of the cost center used for each operation. The calendering time is retrieved from a database of standard times and is dependent on the sheet metal thickness and the length and diameter to be achieved. The welding time is computed by dividing the welding length by the welding speed (as a function of the welding dimensions, materials, geometries and types). Cost models for the other components (*casing stiffeners*, *flanges* and *flange stiffeners*) use similar equations.

The assembly operations involve welding the casing with stiffeners, flanges and relative stiffeners. The logistic costs relative to the transport of parts between production departments are computed by multiplying the overall weight of the stack by a unit cost specific to the workshop in which the assembly is realized. The NDT test costs used to control the welding are the product of the welding length and a unit cost.

Table 4 Manufacturing cost models for each stack component

Illustration	Component	Cost model
	Casing	$\boldsymbol{CasingWeight} = (CasingDiameter \cdot \pi \cdot CasingLength \cdot CasingThickness) \cdot CasingMaterialDensity$ $\boldsymbol{CasingMaterialCost} = CasingWeight \cdot \left(1 + \frac{CasingScrapeRate}{100}\right) \cdot CasingMaterialUnitPrice$ $\boldsymbol{CasingCalenderingCost} = SheetmetalCalenderingUnitTime \cdot SheetmetalCalenderingUnitCost$ $\boldsymbol{CasingWeldingCost} = \frac{CasingLength}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{CasingManufacturingCost} = CasingWeldingCost + CasingCalenderingCost$

	Casing stiffener (isometric view and cross section)	$\boldsymbol{CasingStiffenersWeight} = (CasingStiffnerHeight + CasingStiffenerWidth - CasingStiffnerThickness) \cdot CasingStiffenerThickness \cdot \pi \cdot CasingDiameter \cdot CasingStiffenerMaterialDensity$ $\boldsymbol{CasingStiffenerMaterialCost} = CasingStiffenerWeight \cdot \left(1 + \frac{CasingStiffenerScrapeRate}{100}\right) \cdot CasingStiffenerMaterialUnitPrice$ $\boldsymbol{CasingStiffenerCalenderingCost} = BeamCalenderingUnitTime \cdot BeamCalenderingUnitCost$ $\boldsymbol{CasingStiffenerWeldingCost} = \frac{2 \cdot (CasingStiffenerHeight + CasingStiffenerWidht)}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{CasingStiffenerManufacturingCost} = CasingStiffenerCalenderingCost + CasingStiffenerWeldingCost$
	Flange (isometric view and cross section)	$\boldsymbol{FlangeWeight} = (FlangeWidth + FlangeHeight - FlangeThickness) \cdot FlangeThickness \cdot \pi \cdot CasingDiameter \cdot FlangeMaterialDensity$ $\boldsymbol{FlangesMaterialCost} = FlangesWeight \cdot \left(1 + \frac{FlangesScrapeRate}{100}\right) \cdot FlangeMaterialUnitPrice$ $\boldsymbol{FlangesCalenderingCost} = BeamCalenderingUnitTime \cdot BeamCalenderingUnitCost$ $\boldsymbol{FlangesDrillingCost} = DrillingUnitTime \cdot FlangeHolesQuantity \cdot DrillingUnitCost$ $\boldsymbol{FlangeWeldingCost} = \frac{2 \cdot (FlangeHeight + FlangeWidht)}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{FlangesManufacturingCost} = FlangesCalenderingCost + FlangesWeldingCost + FlangeDrillingCost$
	Flange stiffener	$\boldsymbol{FlangeStiffenerWeight} = \frac{(FlangeStiffenerWidth + FlangeStiffenerHeight)}{2} \cdot FlangeStiffenerThickness \cdot FlangeStiffenerMaterialDensity$ $\boldsymbol{FlangeStiffenersMaterialCost} = FlangeStiffenerWeight \cdot \left(1 + \frac{FlangeStiffenerScrapeRate}{100}\right) \cdot FlangeStiffenerMaterialUnitPrice$

	Fabricated tube	$\boldsymbol{CasingStiffenersWelding} = \frac{CasingDiameter \cdot \pi \cdot 2 \cdot CasingStiffenersQuantity}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{FlangeStiffenersWelding} = \frac{(FlangeStiffenerWidth + FlangeStiffenerHeight) \cdot 2 \cdot FlangeStiffenersQuantity}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{FlangeWelding} = \frac{CasingDiameter \cdot \pi \cdot 2 \cdot FlangesQuantity}{WeldingSpeed} \cdot WeldingUnitCost$ $\boldsymbol{LogisticsCost} = (CasingWeight + CasingStiffenersWeight + FlangesWeight + FlangeStiffenersWeight) \cdot LogisticUnitCost$ $\boldsymbol{NDTCost} = TotalWeldingLength \cdot NDTUnitCost$

The cost estimation method used in the third optimization stage involves analytically evaluating the manufacturing process from a 3-D CAD model. Several software tools can be used for this purpose, and this is why the authors prefer to use commercial tools. Among the tools available, LeanCOST® (by Hyperlean srl) was selected for the following reasons:

- Due to the availability of manufacturing processes used to develop fabricated tubes;
- Due to the availability of a module for customizing cost models;
- Due to the availability of 3-D feature recognition algorithms for automatically computing the manufacturing processes of each component and of assembly.

For a single component or an assembly system, a 3-D CAD model with Product Manufacturing Information (material, roughness, tolerances, heat treatment, etc.) is first read by LeanCOST® to extract a BOM, characteristic dimensions, etc. The software program then identifies raw materials, manufacturing processes and the related costs of each component. Once each component has been analyzed, the tool determines the assembly operations (e.g., welding, NDT testing and logistics for a fabricated tube).

For the cost estimations, the software considers each elementary operation required to create a product (sheet metal, beams, a prismatic part, etc.) and related assembly operations (welding, tackling, manual assembly, etc.). The tool was initially customized to manage commercial items available within a BOM (that should not require manufacturing). Further customization is required to manage general attributes (i.e., surface coatings and materials) to automatically define related manufacturing processes. Before the tool is used, a database of cost models and related parameters is marginally customized to specify the data consolidated by the experience such as the unit costs of cost centers and of raw materials. The database of materials and attributes managed by the tool is linked to a corresponding database defined within the CAD model. Moreover, a customized report is developed for collecting cost data according to the breakdown defined in the first optimization stage.

4 Case study

The presented approach has been validated through a case study. This section presents a case study considering the design of a modular steel tower. Specifically, an oil and gas self-bearing chimney used to carry and discharge atmospheric exhaust gases from a GT for power generation is designed.

Figure 6: Representation of the self-bearing chimney

Generally, the design of this type of structure is guided by the CICIND - the Model Code for Steel Chimneys [27], which provides guidelines on the design and construction of steel chimneys based on the newest technologies. These best practices apply to self-bearing steel structures with circular sections that are more than 15 meters tall. Other standards must also be followed to define loads and assessment criteria. The standards to be used depend on where structures are to be erected. For example, for US territory, the loads to be applied are described in the ASCE 7-05 standards [45], while the ANSI/AISC 360-10 standards [46] provide assessment criteria. Similarly, for Australian territory designers must follow AS1170 [47] and AS4100 [48].

Chimneys are composed of shell elements referred to as stacks. These stacks can be of different lengths and thicknesses and can have standard (commercial) or custom dimensions in accordance with design specifications. Stacks are connected to one another by flanges welded at the ends and are manufactured from welded shell plates of carbon steel.

The CICIND standards cite Fe360, Fe430, Fe510 or equivalents as raw materials used for steel chimneys [49]. These chimneys are internally insulated with basalt wool to guarantee a maximum external average temperature of 60°C for safety reasons. The internal diameter of the stacks is defined by the so-called "*gas path*" and by necessary insulation levels. The "*gas path"* is based on the GT types, exhaust gas temperatures and pressure levels and is calculated by applying a gas speed of 30 m/s. To limit vibrations and to stiffen the structure, the stacks can include welded "L" shaped rings. However, the CICIND standards suggest that stiffeners be positioned at a maximum distance of 9 times the outer diameter of the stack apart.

The most critical part of a chimney is the so-called "*stack base,*" which serves as a point of connection to the horizontal duct and which includes a side opening to allow for the passage of gas that weakens the structure. This connection is created by means of an antivibration joint that absorbs relative displacement between the two ducts. Despite its name, it does not necessarily form the base component of a structure. Its positioning is bound by the height of a horizontal duct. It includes an internal closure to direct exhaust gas to the upper part of a chimney, and thus stacks underneath the stack base do not require internal insulation.

The CICIND standards describe the features of the concrete or steel foundations used to fix a self-bearing chimney to the ground by means of anchor bolts. These anchor bolts are generally made from S355 steel or from similar materials.

In the following subsections, the three optimization levels and results found for the self-bearing chimney are described.

4.1 First optimization stage

During the preliminary design phase, the system layouts and components are defined to meet the customer's requirements. In this phase, different features such as inner chimney diameter or materials are addressed. Once the gas turbine is fixed, the geometric and nongeometric constraints of the chimney can be defined. For example, the height of the exhaust duct horizontal axis defines the location of the stack base while the exhaust temperature influences the internal insulation levels.

In Table **5**, the specifications and design constraints for the chimney analyzed in this case study are reported.

Table 5: Main chimney design specifications and constraints.

	Specification
Type of machine	GT: Gas Turbine
Machine power level	117 [MW]
Exhaust temperature	440 [°C]
	Constraints
Chimney height	45000 [mm]
Inner diameter	5112 [mm]
Insulation thickness	180 [mm]

In accordance with the presented methodology, a one-dimensional model for the system was developed. The stacked chimney was modeled as a beam fixed at one end. Related analytical calculations consider the simplified beam model as a set of variable segments. Each item is solved based on the characteristics of a tubular shell element. The thicknesses and heights are considered as geometric variables of each item. The inner diameter is constant because it is an input specification related to the employed GT machine. As prescribed by the CICIND, three structural steel materials are used: Fe360, Fe430, and Fe510.

This chimney is designed for use on US territory, and for this reason, the ASCE/SEI 7-05 [45] and ANSI/AISC 360-10 [46] standards were respectively used to define the loads and assessment criteria. Moreover, the CICIND was used for the definition of the strength criteria. These standards describe different load cases to be considered during structural verification: dead loads, live loads, wind loads, seismic loads and internal pressure levels. Dead loads include all loads that remain relatively constant over time, including the weight of a structure and of equipment. Live loads are temporary dynamic loads such as vibrations generated by a system. Wind and seismic loads are environmental loads generated by natural forces that are strongly dependent on where the structure is positioned. Internal pressure levels represent a characteristic load generated by the system attached to a chimney.

The four load conditions prescribed by the ASCE/SEI 7-05 [45] are schematically reported in Figure 7.

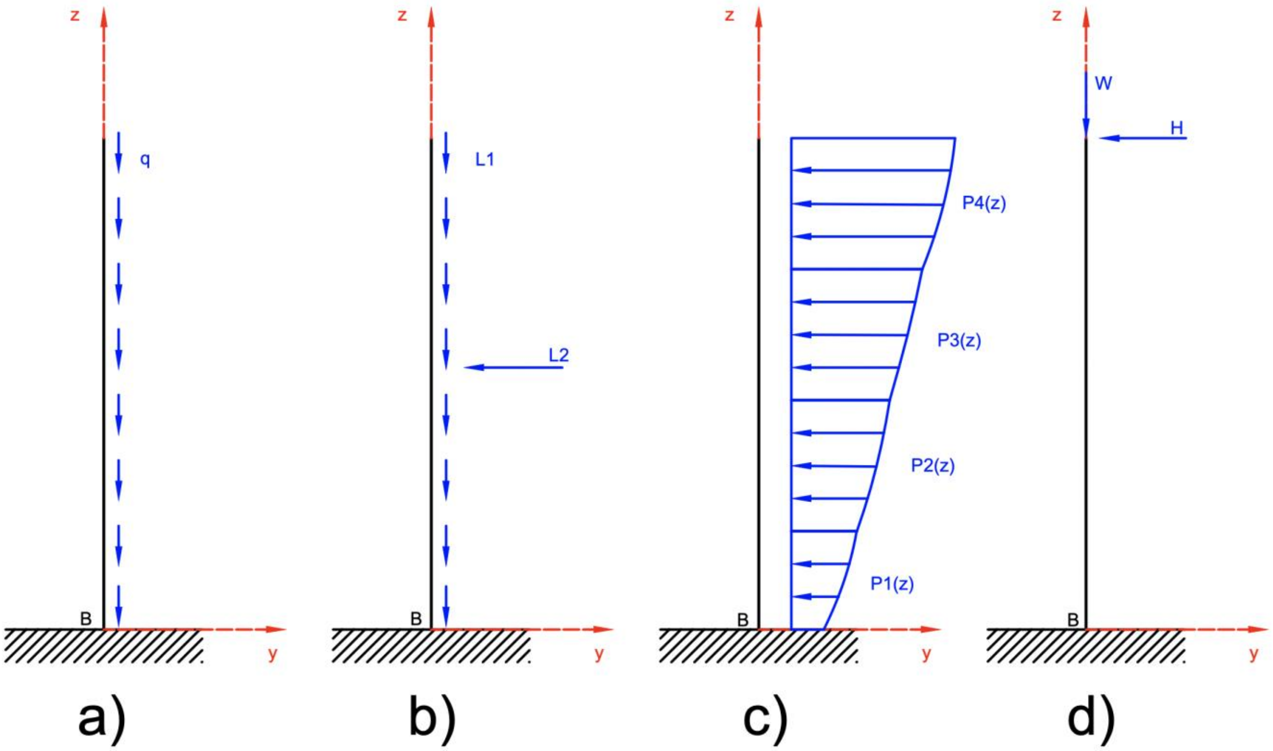


Figure 7: Scheme of load conditions prescribed by the ASCE/SEI 7-05: a) dead load, b) live load, c) wind load, d) seismic load

The one-dimensional structure is approximated as a De Saint-Venant beam and is solved by applying the model through a MATLAB® script following the calculation procedure provided in [46].

Using the same MATLAB® script, the parametric cost model reported in paragraph 3.5 is used to estimate the cost of the chimney.

The parameters that can be optimized in this design phase (as reported in Table 2) include the following: stack thicknesses, stack heights and materials. The latter directly influences the cost of an entire structure and strength criteria. As stack thicknesses we consider the following values: 8, 10, 12, 15, and 18 [mm]. The height of each shell element is analyzed as a stepwise variable with a step of 500 mm ranging from 2000 to 7000 mm. The same total height of a steel chimney can be obtained from a larger number of shorter stacks or vice versa. Similarly, the same structural behavior can be obtained from different combinations of materials, thicknesses and heights. However, when the height of a steel shell is a standard dimension, the costing tool employed considers this aspect in the calculation of the related material costs.

The objective is to minimize costs and weights. The minimization of weights does not necessarily reduce the cost. For example, the use of lightweight materials can increase acquisition costs. However, weight reduction is crucial to facilitating the transportation and the assembly of this type of product.

The multi-objective optimization process was performed using the modeFRONTIER® tool developed by Esteco®. This optimization software program employs DOE techniques, GAs and response surface methodologies to solve multi-objective and multidisciplinary optimization problems. modeFRONTIER® can be used with external software tools such as CAD systems (CATIA, NX, etc.), CAE systems (ANSYS Workbench, LMS Virtual.Lab, etc.) and general-purpose tools (Microsoft® Excel, MATLAB®, LabVIEW®, etc.). In this case study, the capacity to directly interface with MATLAB® is exploited to perform a structural-cost optimization. The optimization workflow used is reported in Figure 8.

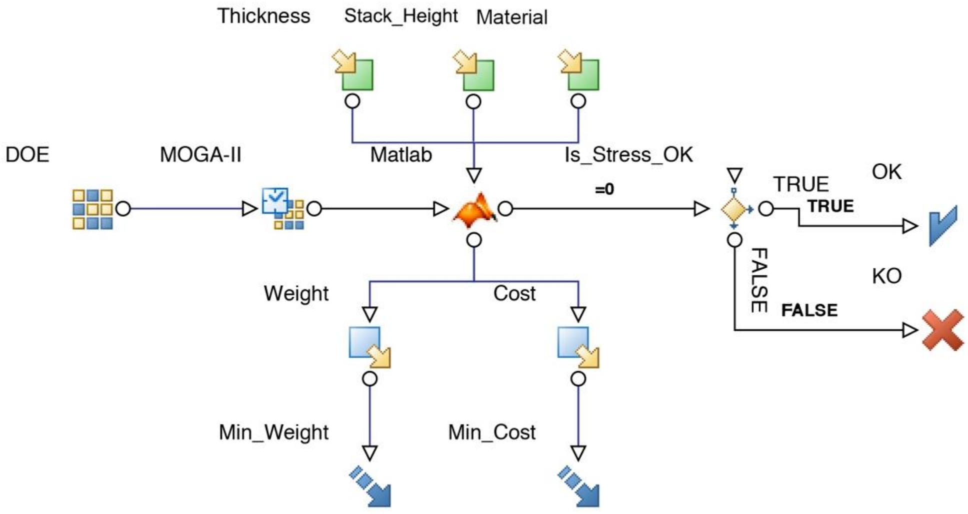
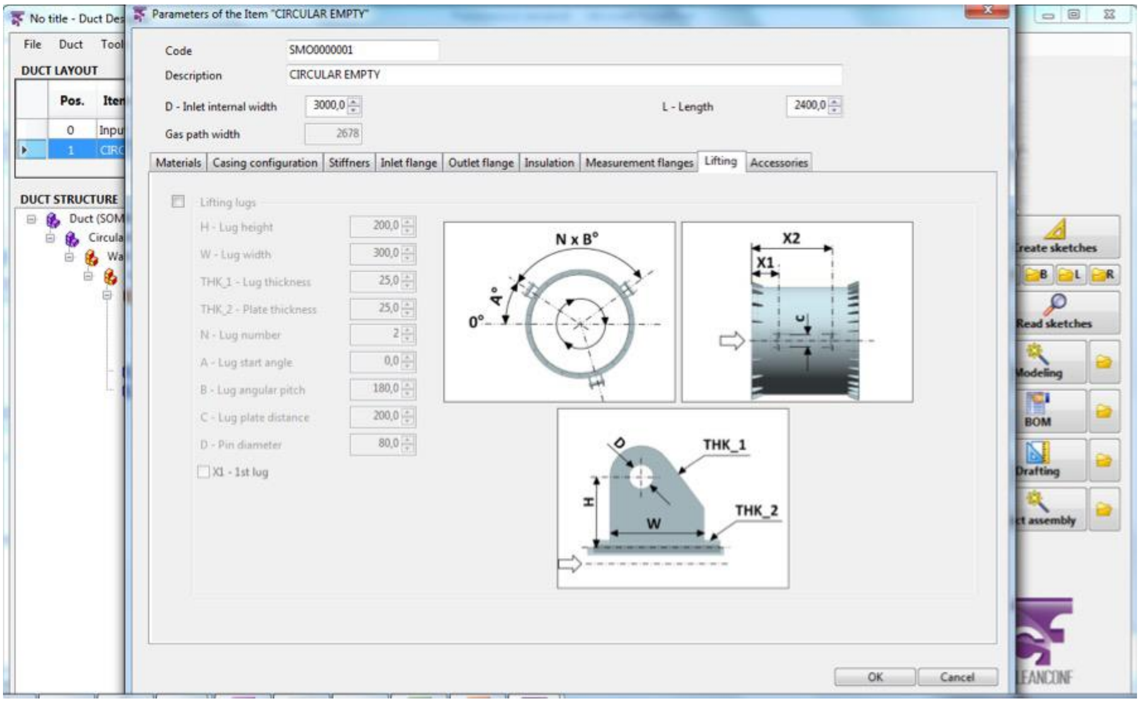


Figure 8: Workflow of the first MOO stage

To limit the problem domain, the thicknesses must not increase with the chimney height, and as a constraint between two bordering stacks, the lower value must be equal to or greater than the higher value. Indeed, for a beam fixed at one end, the thickness levels tend to decrease to homogenize the internal stress placed on stacks.

4.2 Second optimization stage

The second optimization phase involves embodiment design. In this stage, a 3-D shell model is created for the execution of FEM simulations. This model was created by exploiting the configuration tool provided by the company and is shown in Figure 9. The 3-D shell model is a simplified model that includes only relevant components for the required level of detail as reported in Section 3.3. Each duct item is represented by a shell surface, and internal insulation levels are not modeled even when weights are considered as dead loads in the FEM model used for structural analysis.


Parameters of the Item "CIRCULAR EMPTY"

Code: SMO0000001
Description: CIRCULAR EMPTY
D - Inlet internal width: 3000,0
L - Length: 2400,0
Gas path width: 2678

☐ Lifting lugs
H - Lug height: 200,0
W - Lug width: 300,0
THK_1 - Lug thickness: 25,0
THK_2 - Plate thickness: 25,0
N - Lug number: 2
A - Lug start angle: 0,0
B - Lug angular pitch: 180,0
C - Lug plate distance: 200,0
D - Pin diameter: 80,0
☐ X1 - 1st lug

Figure 9: Screenshot of the configuration tool

SAP2000® software was used for the structural simulations. This FEM software is used for the analysis of large civil structures. Following the presented methodology, the same load and boundary conditions used in the first stage are applied within the model. The structural stress and displacement values are verified in accordance with the Ultimate Limit State and Serviceability Limit State methods.

The parametric cost estimation method is based on formalized rules described in Section 3.5.

The optimization process is similar to that of the first level. The modeFRONTIER® tool is used for the cost-performance optimization using the MOGA-II algorithm. However, SAP2000® cannot be directly interfaced with modeFRONTIER®. For this reason, we created dedicated Visual Basic (VB) scripts to launch the FEM solver. The optimization workflow defined under the modeFRONTIER® framework is reported in Figure 10.

In the second MOO stage, the variables to be optimized are thicknesses related to each steel stack. The material used becomes a constraint once an offer is accepted. Furthermore, the domain of the problem is reduced by setting thicknesses of 8, 10, 12, and 15 [mm]. Indeed, the result of the first stage of optimization shows that a thickness of 18 [mm] is excessive for the first stack and thus also for the others. Moreover, the result allows us to discard a thickness of 15 [mm] from the third stack onward, a thickness of 12 [mm] from the sixth stack and a thickness of 10 [mm] from the last stack.

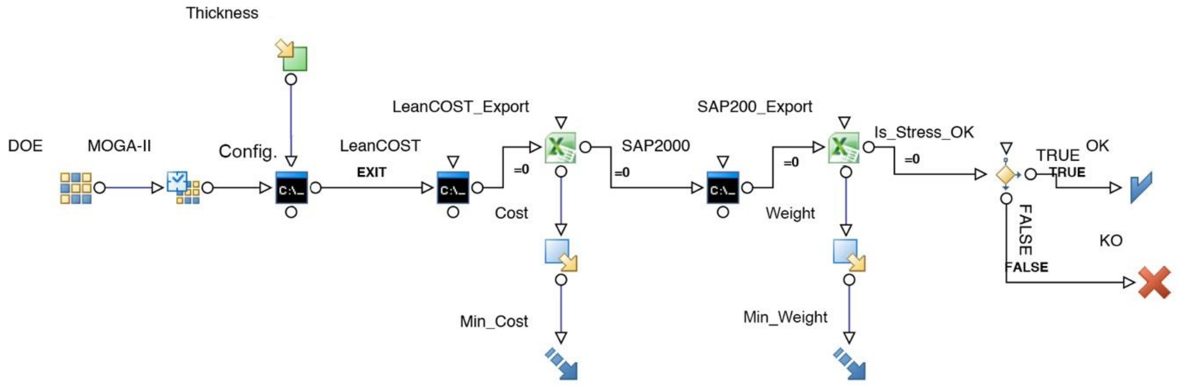


Figure 10: Workflow of the second MOO stage

4.3 Third optimization stage

In this stage, a detailed 3-D CAD model is generated. The outputs of this phase are the executive project and relative technical drawings. The latter are created through an automated process involving the use of a configuration tool to create 2-D drawings from selected items.

In this phase, dedicated simulations are performed to verify specific aspects that cannot be considered in the shell model. In this case study, the connection of a stack base to a horizontal duct, stress exerted on anchor bolts (reported in Figure **11**) and flange deflection values are analyzed from an FEM model with a solid tetrahedral mesh.

As an example, the optimization of the stiffeners supporting flanges is reported. Stiffeners are trapezoidal elements welded on flanges to reinforce the connections between two consecutively stacked elements (Figure 11). The aim of the optimization method is to reduce the quantity and dimensions of the stiffeners involved while minimizing the material and manufacturing costs and weights.

ANSYS Workbench® was used to conduct the simulations. Analytical cost estimations were made using LeanCOST® software, which analyzes CAD models and identifies raw materials, installation methods and assembly costs [18], as reported in Section 3.5.

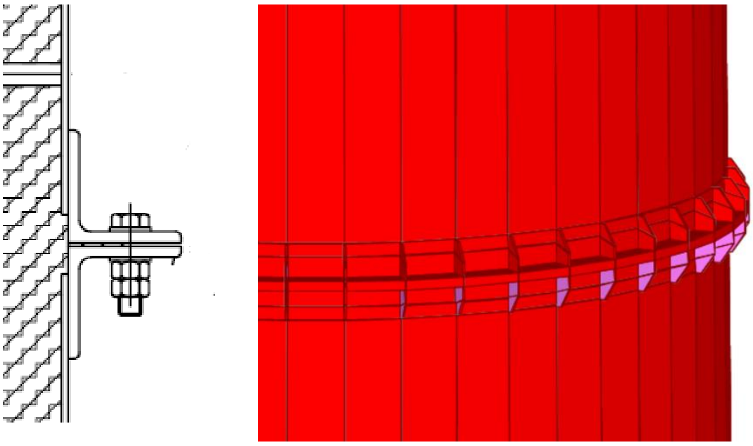


Figure 11: Detailed representation of a flange with stiffeners

The modeFRONTIER® platform was also used for the third stage of the MOO. In the Figure 12, the workflow of the optimization process is reported. Firstly, a Design of Experiments (DOE) table was defined taking into account the design variables and their range of variation. Then MOGA-II was selected as the algorithm for solving the MOO problem. The workflow also shows a script-object for linking the variables of the MOO problem with the configuration analysis (*Configurator*). This phase allows the weight of the structure to be calculated through an analytical analysis. Moreover, the code implemented into the script-object can perform the import of the simplified CAD-model from Configurator to the FEM solver (Ansys Workbench®). After that, the FEM analysis was performed and the safety factor calculated. Lastly, for the cost analysis, LeanCOST was used and the cost was derived. Concluding, this MOO workflow presents three optimization objectives to be minimized using the MOGA-II algorithm: weight, safety factor, and cost.

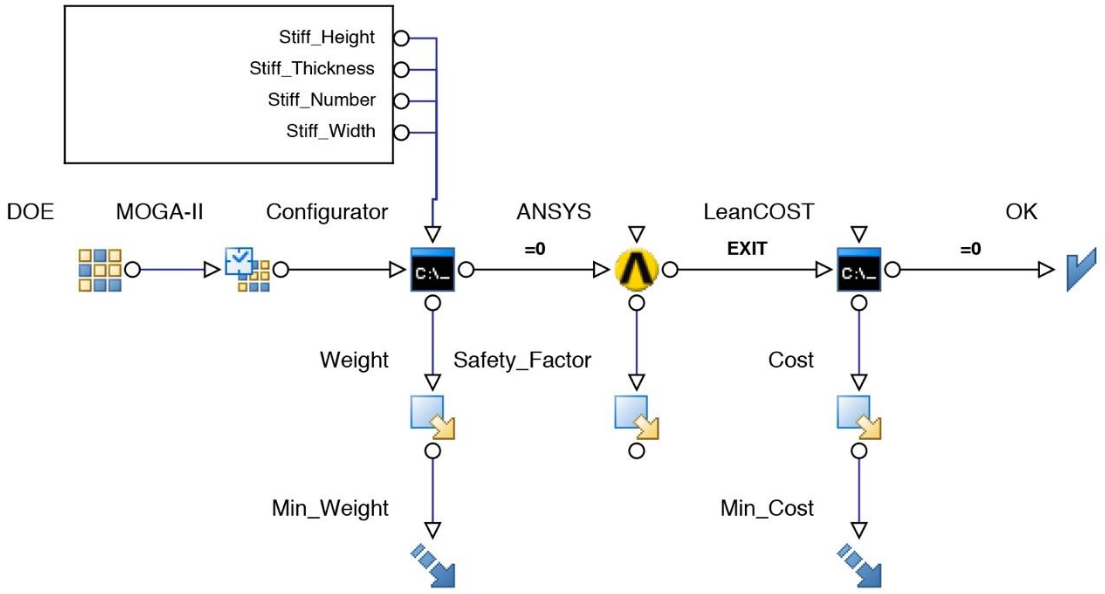


Figure 12: Workflow of the third stage of MOO

5 Results

5.1 First optimization stage

Figure 13 presents a report generated from the first MOO process. In particular, this figure describes the configuration of the optimal chimney, as analyzed in the first design level. The cost and items thickness are reported for each component. However, the cost and weight are reported as percentages of total values for data confidentiality reasons. The optimization, based on 475 different configurations, shows that the one with eight stacks is the least expensive. The installation costs, as shown in Figure 13, increase with the chimney height due to an increase of the erection costs. The thickness instead decreases along the chimney axis. Indeed, the structural analysis confirms that the stack base is the most stressed component.

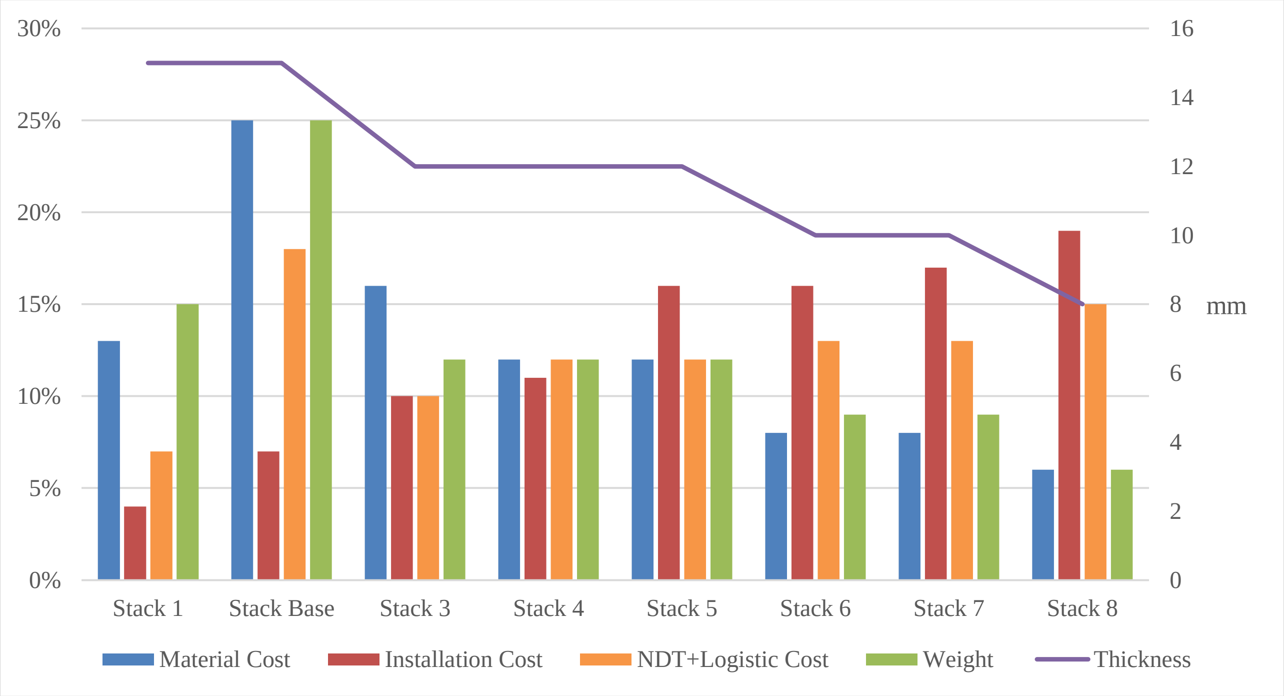


Figure 13: Results of the first optimization stage: 8 stacked items with different thicknesses (mm), weights (%) and costs (%)

The resulting configuration also verifies the normative checks, which are defined as boundary conditions in the analytical model. Other costs are representative of nondestructive testing (NDT) and logistical costs. The breakdown of the chimney costs is reported in Figure 14. Using this simplified method, many configurations can be easily evaluated. The identified optimal solution represents the starting point of the second optimization stage. The approach used for the selection of an optimal solution involves adopting the least expensive configuration passing stress tests with a ratio of 0.85 (equivalent stress level per maximum value allowed) for each duct segment.

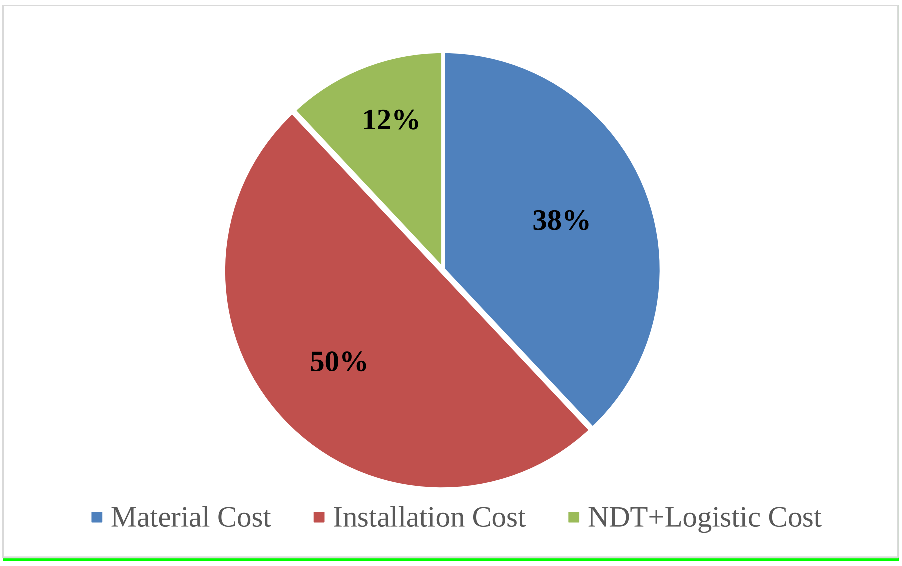


Figure 14: Breakdown of the cost for the first optimization level

5.2 Second optimization level

The results of the second MOO process are reported in Figure 15, which describes the optimal configuration obtained from the proposed optimization process. Comparing Figure 13 and Figure 15, the thickness decreases from 15 to 12 [mm] for the *stack base*, from 12 to 10 [mm] for *stack 5*, and from 10 to 8 [mm] for *stack 8*. This lightweight of the structure is also related to a cost reduction.

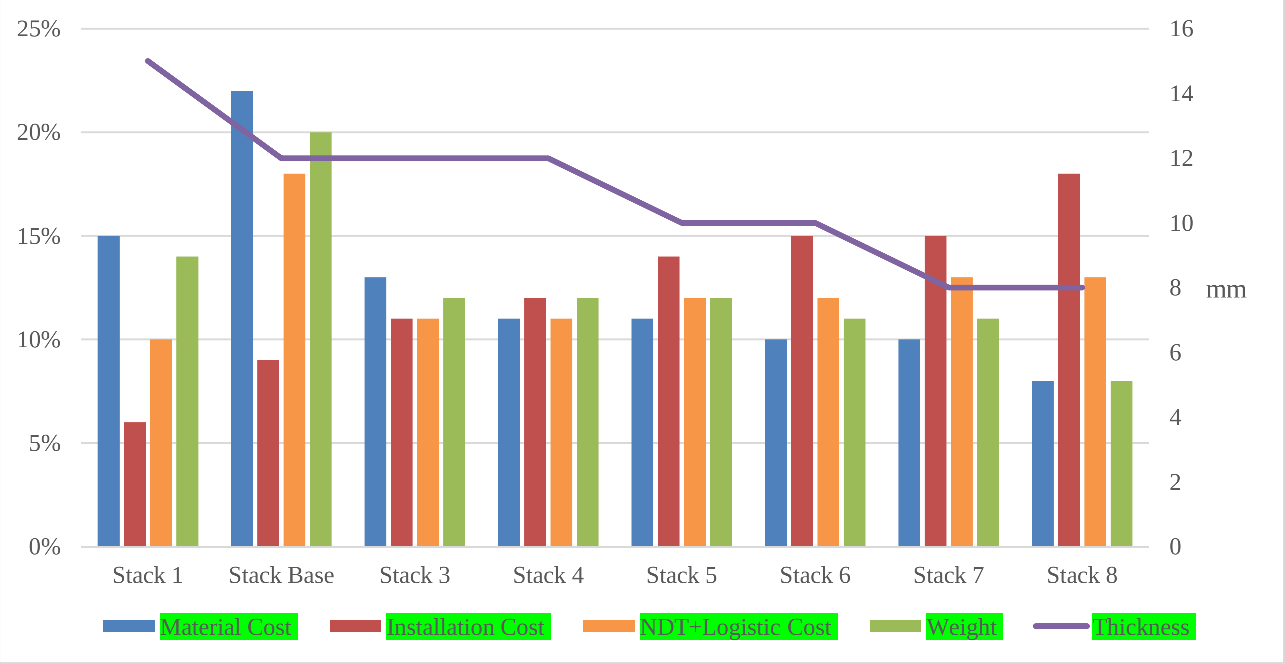


Figure 15: Results of the second optimization stage: 8 stacked items of different thicknesses (mm), weights (%) and costs (%)

As noted above, the second MOO stage involves the use of an FEM numerical solver to analyze the structural behavior of equivalent 3-D shell models based on the stacked tower to be optimized. Structural normative checks are applied to the FEM model as boundary conditions. Even though the computational efforts of this process are more substantial than those of the first step, better results were achieved. Indeed, only 124 different configurations were analyzed. In total, 7% in cost savings was achieved. This result is attributable to the restriction of the problem domain resulting from the first stage. The breakdown of the cost is reported in Figure 16 and, comparing the latter figure with the Figure 14, it can be noted that installation and NDT/logistic costs tend to decrease during the second optimization level due to the reduced thickness of the stacks. Moreover, a detailed parametric approach was applied for the product cost calculations. From our cost reduction results, the company can maximize profits after the RFP phase. The approach used for the selection of an optimal solution is the same as that proposed for the first MOO stage.

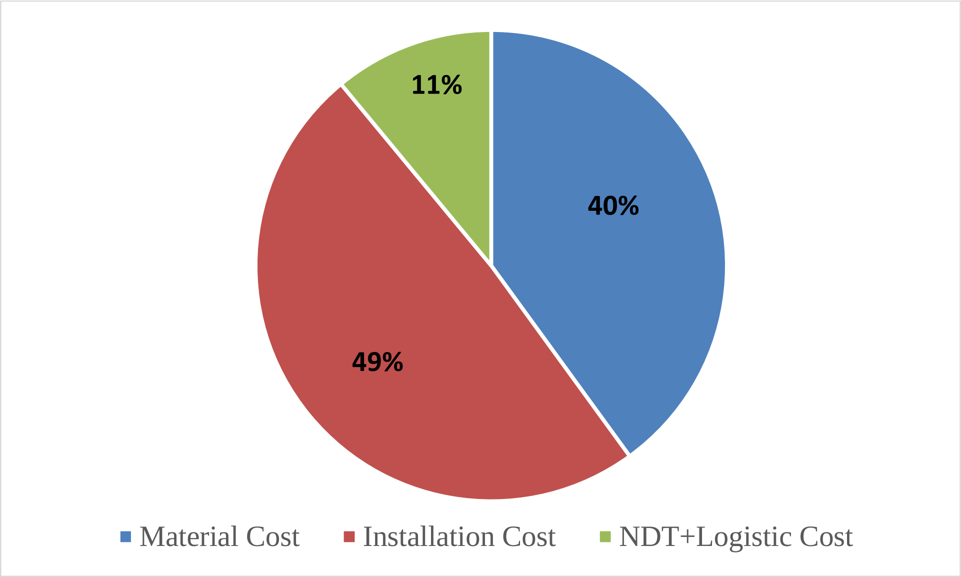


Figure 16: Breakdown of the cost for the second optimization level

5.3 Third optimization stage

The last stage involves the optimization of the specific chimney components. As an example, the optimization of the stiffeners that support the flanges is described. For the connection of the stack base to the third stack, 24 equidistant stiffeners with a mass of 1.2 kg were simulated. About 35 simulations were automatically performed using the optimization software for achieving an optimal solution. The optimization analysis was performed using a GA method and using ANSYS Workbench® as FEM numerical solver. A comparison between the first experiment and best configuration is shown in Figure 17.

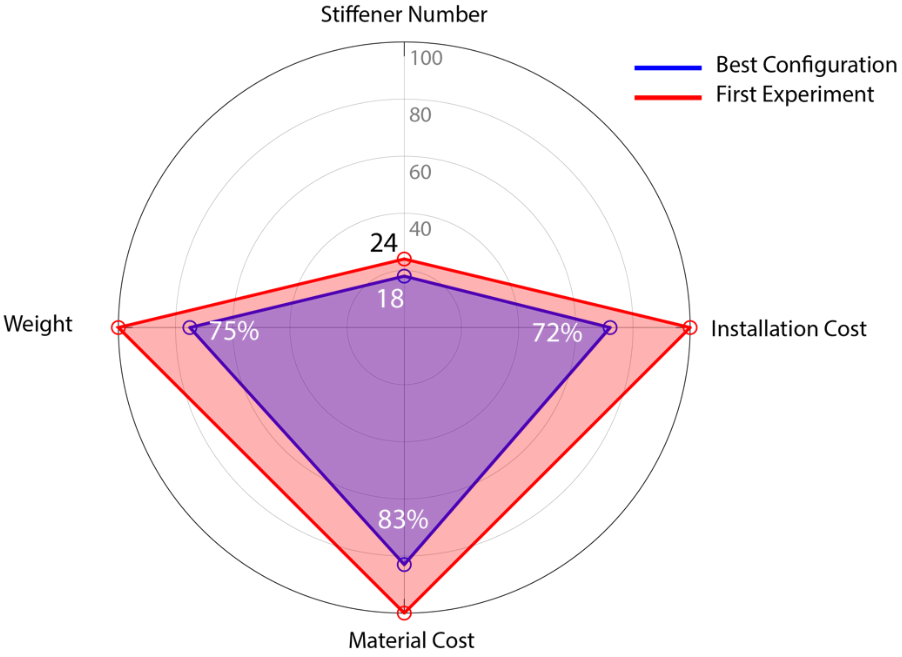


Figure 17: Comparison of the first attempt and the best configuration

5.4 Optimal configuration

The case study presented in this paper concerns the optimization of a past chimney project. Table 6 compares the configuration reached by means of the use of the proposed framework and the first configuration (past project). Objects of the comparison are the thickness and the number of the stacks, the total weight and the total cost of the chimney. Table 6 shows the stacks thickness values and the maximum height from the ground of each stack of the two models.

Table 6: Comparison between the real case and the one reached using to the proposed approach.

First configuration			Optimal case		
Stack #	**Thickness [mm]**	**H [m]**	**Stack #**	**Thickness [mm]**	**H [m]**
Stack 1	18	3,5	Stack 1	15	3,2
Stack 2	15	7,1	Stack 2	12	6,4
Stack 3	15	9,5	Stack 3	12	12,4
Stack 4	15	12,4	Stack 4	12	21,9
Stack 5	15	21,9	Stack 5	10	27,9
Stack 6	10	25,4	Stack 6	10	34,0
Stack 7	10	29,1	Stack 7	8	40,0
Stack 8	8	32,7	Stack 8	8	45,0
Stack 9	8	34,7			
Stack 10	6	38,3			
Stack 11	6	41,9			
Stack 12	6	45,0			

The number of stacks in the first configuration is greater than the new model (optimal case). This is due to the fact that the optimized structure maximizes the use of standard items, which are 6.05-m ducts. Every stack is connected to the other by means of bolted flanges. In the first case, the presence of a greater number of stacks determines a higher number of flanges. However, since the stacks adopted in the first configuration have a lower height, there is a lower necessity to use reinforcing rings (typically a standard stack has two reinforcing rings).

It is interesting to note that, in the as-is case (first configuration), the stack at the base of the chimney has a thickness significantly bigger than the one adopted in the optimal case. In general, this is true for the comparison of each duct item.

The first configuration is a past project analyzed and optimized using a traditional one-stage process. In particular, the one-stage optimization was based on the CAD-model of the chimney elaborated during the embodiment design. The limits related to a one-stage approach concern the employment of a pre-defined structure with a fix number of items. In fact, without a first analytical MOO level, the number of the duct items must be defined by the designer using his/her know how. Even if further model changes are possible, a similar iterative process requires a lot of time for repeating design, setting, and optimization running. Moreover, the first MOO level can be used during the order definition to improve the answer to the RFP phase in terms of results and efficiency. Therefore, a multi-step optimization can be more suitable to support the design workflow for typical ETO products.

In conclusion, an important reduction of weight and total cost of the chimney is reached thanks to the use of the proposed approach. In particular, it was possible to decrease the chimney weight of 7,19 % and the chimney total cost of 9,23 %.

6 Discussion

The major contribution of this research is the development of a sequential and multi-objective optimization method for supporting the design of Engineering-to-Order steel towers. The proposed approach aids designers in developing competitive products that minimize manufacturing and installation costs while meeting performances requirements. Even if the test case is focused on oil & gas chimneys, the method can be extended and used for the design optimization of similar structures (fabricated circular tubes) such as wind turbine towers.

The main outcomes reached with the proposed design optimization framework are listed as follow:

- faster design of optimized ETO product (high-performance and cost-effective);
- reduction of design errors;
- increasement of the company’s success rate in a competitive bid;
- increasement of the company’s competitiveness (faster design and more cost-effective products);

The relevant outcome of the proposed work was the definition of a design optimization framework to deal with the current challenges of Engineering-to-Order products. In this research, a case study demonstrates the applicability of at the design stage.

Experimentations reveal that the use of this design process leads to relevant improvements in the product performance, cost and design effort. Furthermore, the framework enables also less experienced engineers to reach optimal design solutions thanks to the formalization of the company's knowledge within the configuration tool.

It is important to underline how the proposed approach can be used starting from the early activities of the PDP. This is fundamental in order to reduce the timespan and the effort required for the design process, enhancing, at the same time, product quality.

The presented framework is intended for practical use in industry. However, there are some practical issues that need to be considered when applying MOO to solve real-world problems. Examples of such practical problems include the validation of virtual models, uncertainty management, selection of the right optimization algorithms, and setting of the computing methods. Further studies to address these issues are all suitable directions for future work.

Moreover, a deeper research activity is necessary in the field of system engineering. In case of very complex products, how is it possible to manage the outcome of different design activities? Can be the value-driven design paradigm an effective method for the decision-making process? Furthermore, more improvements must be made to reduce errors in estimating manufacturing cost using parametric cost models. A lifecycle assessment analysis could be added to the proposed optimization workflow for considering the environmental impact of a product.

Regarding the optimization methods, this paper is focused on genetic algorithms. In particular, MOGA-II has been tested and proposed for the highlighted test case. As a future research, this optimization method could be compared with other approaches such as Constraint Satisfaction Problem (CSP) and Particle Swarm Optimization (PSO). While the use of a PSO algorithm is still a heuristic approach, the CSP solution regards the mathematical representation of a set of engineering constraints to be evaluated inside a domain of solutions.

7 Conclusions

In this work, a sequential and multi-objective optimization method for supporting the design of engineer-to-order products is proposed. The aim is to support engineers in the development of products and in reducing manufacturing and installation costs while meeting structural requirements. The paper focuses on the design of tall modular towers such as the steel structures of chimneys used in oil and gas power plants.

The proposed method is based on three stages of optimization. The first involves preliminary design, applied when companies receive a request for proposal (RFP). At this point, minimal information about the order is available, and limited time is available to formulate an offer (a few weeks). Thus, parametric cost models and simplified 1-D geometries are involved in an optimization loop performed by GAs. The second stage, based on the results of the first stage, involves embodiment design. Simplified shell geometries and detailed parametric cost models are used in this optimization loop, which involves a restricted problem domain. In the last stage involving detailed design, a full 3-D CAD model is generated, and specific FEM simulations are involved in the optimization and validation of engineered solutions. Cost estimations, given their high level of detail, are analytical and are performed using dedicated software.

The method was used for the redesign of a steel chimney used in the oil and gas sector that is designed to discharge exhaust gas from a 117-MW GT. It is installed in the US and is 45 [m] tall. Its inner diameter is approximately 5 [m], and the gas temperatures reach 440 [°C]. To validate the proposed method, a comparison between the typical design process and that one based on the proposed method was carried out. For cost estimations, a company may propose an offer 10% less expensive than that already made. Once an order is made, a company can save 7% on costs while remaining within structural constraints using the presented method. Regarding time considerations, a company that can present an offer within 47 days can use the proposed method to produce a product within only 35 days. Regarding the other steps, it takes 211 days to produce technical drawings using the original method, whereas only 156 days are required when applying the proposed method.

Though the present case study focuses on a steel chimney, the proposed methodological approach can be extended to all complex ETO products involving dedicated optimization throughout the design process. For example, the proposed sequential multi-objective optimization process can be used for the development of compressors, ducts, gas turbines, piping systems, wind turbines, etc. Future studies may focus on validating the method for other ETO products to demonstrate its effective application to products other than steel chimneys.

REFERENCES

[1] P. Zheng, X. Xu, S. Yu, C. Liu, Personalized product configuration framework in an adaptable open architecture product platform, J. Manuf. Syst. 43 (2017) 422–435. doi:10.1016/j.jmsy.2017.03.010.

[2] L.L. Lim, G. Alpan, B. Penz, A simulation-optimization approach for sales and operations planning in build-to-order industries with distant sourcing: Focus on the automotive industry, Comput. Ind. Eng. 112 (2017) 469–482. doi:10.1016/j.cie.2016.12.002.

[3] Y. Kristianto, P. Helo, R.J. Jiao, A system level product configurator for engineer-to-order supply chains, Comput. Ind. 72 (2015) 82–91. doi:10.1016/j.compind.2015.04.004.

[4] A. Sylla, D. Guillon, E. Vareilles, M. Aldanondo, T. Coudert, L. Geneste, Configuration knowledge modeling: How to extend configuration from assemble/make to order towards engineer to order for the bidding process, Comput. Ind. 99 (2018) 29–41. doi:10.1016/j.compind.2018.03.019.

[5] S. André, F. Elgh, J. Johansson, R. Stolt, The design platform–a coherent platform description of heterogeneous design assets for suppliers of highly customised systems, J. Eng. Des. 28 (2017) 599–626. doi:10.1080/09544828.2017.1376244.

[6] A. Duchi, F. Tamburini, D. Parisi, O. Maghazei, P. Schönsleben, From ETO to Mass Customization: A Two-Horizon ETO Enabling Process, in: Manag. Complex., Springer, Cham, 2017: pp. 99–113. doi:10.1007/978-3-319-29058-4_8.

[7] F. Elgh, Decision support in the quotation process of engineered-to-order products, Adv. Eng. Informatics. 26 (2012) 66–79. doi:10.1016/j.aei.2011.07.001.

[8] A. Trentin, E. Perin, C. Forza, Product configurator impact on product quality, Int. J. Prod. Econ. 135 (2012) 850–859. doi:10.1016/j.ijpe.2011.10.023.

[9] R. Raffaeli, A. Savoretti, M. Germani, Design knowledge formalization to shorten the time to generate offers for engineer to order products, Lect. Notes Mech. Eng. (2017) 1107–1114. doi:10.1007/978-3-319-45781-9_110.

[10] F. Caron, A. Fiore, “Engineer to order” companies: how to integrate manufacturing and innovative processes, Int. J. Proj. Manag. 13 (1995) 313–319.

[11] O. Willner, J. Gosling, P. Schönsleben, Establishing a maturity model for design automation in sales-delivery processes of ETO products, Comput. Ind. 82 (2016) 57–68. doi:10.1016/j.compind.2016.05.003.

[12] A. Brière-Côté, L. Rivest, A. Desrochers, Adaptive generic product structure modelling for design reuse in engineer-to-order products, Comput. Ind. 61 (2010) 53–65. doi:10.1016/j.compind.2009.07.005.

[13] K.H.G. G. Pahl, W. Beitz, J. Feldhusen, Engineering Design : A systematic approach, Springer, 2004. doi:10.1007/978-1-4471-3581-4.

[14] A. Myrodia, K. Kristjansdottir, L. Hvam, Impact of product configuration systems on product profitability and costing accuracy, Comput. Ind. 88 (2017) 12–18. doi:10.1016/j.compind.2017.03.001.

[15] S. Gholizadeh, A. Baghchevan, Multi-objective seismic design optimization of steel frames by a chaotic meta-heuristic algorithm, Eng. Comput. 33 (2017) 1045–1060. doi:10.1007/s00366-017-0515-0.

[16] P. Cicconi, M. Germani, S. Bondi, A. Zuliani, E. Cagnacci, A Design Methodology to Support the Optimization of Steel Structures, Procedia CIRP. 50 (2016) 58–64. doi:10.1016/j.procir.2016.05.030.

[17] P.E. Uys, J. Farkas, K. Jármai, F. van Tonder, Optimisation of a steel tower for a wind turbine structure, Eng. Struct. 29 (2007) 1337–1342. doi:10.1016/j.engstruct.2006.08.011.

[18] P. Cicconi, R. Raffaeli, M. Marchionne, M. Germani, A model-based simulation approach to support the product configuration and optimization of gas turbine ducts, Computer-Aided Design and Applications, vol. 15, no. 6, pp. 807–818, Apr. 2018. doi:10.1080/16864360.2018.1462564.

[19] P. Duverlie, J.M. Castelain, Cost estimation during design step: Parametric method versus case based reasoning method, Int. J. Adv. Manuf. Technol. 15 (1999) 895–906. doi:10.1007/s001700050147.

[20] G.S. Papavasileiou, D.C. Charmpis, Seismic design optimization of multi–storey steel–concrete composite buildings, Comput. Struct. 170 (2016) 49–61. doi:10.1016/j.compstruc.2016.03.010.

[21] N.D. Lagaros, M.G. Karlaftis, Life-cycle cost structural design optimization of steel wind towers, Comput. Struct. 174 (2016) 122–132. doi:10.1016/j.compstruc.2015.09.013.

[22] I. Giagkiozis, P.J. Fleming, Methods for multi-objective optimization: An analysis, Inf. Sci. (Ny). (2015). doi:10.1016/j.ins.2014.08.071.

[23] A.-T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to

building performance analysis, Appl. Energy. 113 (2014) 1043–1058. doi:10.1016/j.apenergy.2013.08.061.

[24] V. Castorani, A. Vita, M. Mandolini, M. Germani, A CAD-based method for multi-objectives optimization of mechanical products, Computer-Aided Design and Applications, vol. 14, no. 5, pp. 563–571, Jan. 2017. doi:10.1080/16864360.2016.1274528.

[25] K. Martini, Multiobjective structural optimization of frameworks using enumerative topology, Comput. Struct. 173 (2016) 61–70. doi:10.1016/j.compstruc.2016.05.020.

[26] S. Arnout, G. Lombaert, G. Degrande, G. De Roeck, The optimal design of a barrel vault in the conceptual design stage, Comput. Struct. 92–93 (2012) 308–316. doi:10.1016/j.compstruc.2011.10.013.

[27] P. Hao, B. Wang, G. Li, Surrogate-based optimum design for stiffened shells with adaptive sampling, AIAA J. 50 (2012). doi:10.2514/1.J051522.

[28] N.C. Brown, C.T. Mueller, Design for structural and energy performance of long span buildings using geometric multi-objective optimization, Energy Build. 127 (2016) 748–761. doi:10.1016/j.enbuild.2016.05.090.

[29] C. Tort, S. Şahin, O. Hasançebi, Optimum design of steel lattice transmission line towers using simulated annealing and PLS-TOWER, Comput. Struct. 179 (2017) 75–94. doi:10.1016/j.compstruc.2016.10.017.

[30] X.K. Zou, C.M. Chan, G. Li, Q. Wang, Multiobjective Optimization for Performance-Based Design of Reinforced Concrete Frames, J. Struct. Eng. 133 (2007) 1462–1474. doi:10.1061/(ASCE)0733-9445(2007)133:10(1462).

[31] A. Kaveh, K. Laknejadi, B. Alinejad, Performance-based multi-objective optimization of large steel structures, Acta Mech. 223 (n.d.) 355–369. doi:10.1007/s00707-011-0564-1.

[32] H. Shin, M.P. Singh, Minimum life-cycle cost-based optimal design of yielding metallic devices for seismic loads, Eng. Struct. 144 (2017) 174–184. doi:10.1016/j.engstruct.2017.04.054.

[33] J.C. Liang, L.J. Li, J.N. He, PERFORMANCE-BASED MULTI-OBJECTIVE OPTIMUM DESIGN FOR STEEL STRUCTURES WITH INTELLIGENCE ALGORITHMS, Int. J. Optim. Civ. Eng. Int. J. Optim. Civ. Eng. 5 (2015) 79–101.

[34] H.M. Negm, K.Y. Maalawi, Structural design optimization of wind turbine towers, Comput. Struct. 74 (2000) 649–666. doi:10.1016/S0045-7949(99)00079-6.

[35] F. Karpat, A virtual tool for minimum cost design of a wind turbine tower with ring stiffeners, Energies. 6 (2013) 3822–3840. doi:10.3390/en6083822.

[36] N. Bazeos, G.. Hatzigeorgiou, I.. Hondros, H. Karamaneas, D.. Karabalis, D.. Beskos, Static, seismic and stability analyses of a prototype wind turbine steel tower, Eng. Struct. 24 (2002) 1015–1025. doi:10.1016/S0141-0296(02)00021-4.

[37] A. Kaveh, Optimal Analysis of Structures by Concepts of Symmetry and Regularity, Springer Vienna, Vienna, 2013. doi:10.1007/978-3-7091-1565-7.

[38] X.-K. Zou, Optimal seismic performance-based design of reinforced concrete buildings, 2012. doi:10.4018/978-1-4666-1640-0.ch009.

[39] M. Ozturk, S. Kocaoglan, F.O. Sonmez, Concurrent design and process optimization of forging, Comput. Struct. 167 (2016) 24–36. doi:10.1016/j.compstruc.2016.01.016.

[40] D. Bruno, P. Lonetti, A. Pascuzzo, An optimization model for the design of network arch bridges, Comput. Struct. 170 (2016) 13–25. doi:10.1016/j.compstruc.2016.03.011.

[41] I. Steponavičė, S. Ruuska, K. Miettinen, A solution process for simulation-based multiobjective design optimization with an application in the paper industry, Comput. Des. 47 (2014) 45–58. doi:10.1016/j.cad.2013.08.045.

[42] G. Li, R.-G. Zhou, L. Duan, W.-F. Chen, Multiobjective and multilevel optimization for steel frames, Eng. Struct. 21 (1999) 519–529.

[43] A. Amrani, S. Zouggar, M. Zolghadri, P. Girard, Supporting framework to improve Engineer-To-Order product lead-times, IFAC Proc. Vol. 43 (2010) 102–107. doi:10.3182/20100908-3-PT-3007.00022.

[44] J.M. Vasconcellos, M. Harduim, P. Araujo, Multi-criteria optimization applied to tankers preliminary design, in: Marit. Technol. Eng., CRC Press, 2014: pp. 309–314. doi:doi:10.1201/b17494-43.

[45] American Society of Civil Engineers, ASCE STANDARD ASCEISEI 7-05 Minimum Design Loads for Buildings and Other Structures, 2006.

[46] American Institute of Steel Construction, ANSI/AISC 360-10: Specification for Structural Steel Buildings, Specification for Structural Steel Buildings, (2010).

[47] Australian Standard, AS1170 - 2011: Structural design actions, 2011.

[48] Australian Standard, AS 4100 - 1998: Steel structures designs, 1998.

[49] CICIND (Organization), Model code for steel chimneys, CICIND, 1999.

Please, find in red the answers to Reviewer-1 and Reviewer-2. Authors would like to thank all the referees for their valuable reviews.

Reviewer #1

The paper is a very interesting one which addresses a problem of practical value and investigates it properly. It is also generally well-written, well-structured, and graphically pleasant. Addressing the following issues can make the paper ready for publication:
Thank you for appreciating the manuscript.

The title of the paper is somewhat uncommon and should be altered to something like "A multi-objective sequential method for manufacturing cost and structural optimization of modular steel towers". The title should also suggest that "tubular shells" are considered.
Thank you for this comment, the Title was changed. The topic “tubular shells” was included by the keyword “tubular steel towers” (this is a new keyword).

I suggest that the authors compare the results of their proposed method with a one stage optimization procedure to further signify the capabilities of their method.
Thank you for pointing out this clarification, which was not presented in the manuscript you revised. We included a new paragraph in section 5.4 that explains the configuration used for evaluating the benefits of the structure obtained adopting the MOO approach presented in this paper.
“*The first configuration is a past project analyzed and optimized using a traditional one-stage process. In particular, the one-stage optimization was based on the CAD-model of the chimney elaborated during the embodiment design. The limits related to a one-stage approach concern the employment of a pre-defined structure with a fix number of items. In fact, without a first analytical MOO level, the number of the duct items must be defined by the designer using his/her know how. Even if further model changes are possible, a similar iterative process requires a lot of time for repeating design, setting, and optimization running. Moreover, the first MOO level can be used during the order definition to improve the answer to the RFP phase in terms of results and efficiency. Therefore, a multi-step optimization can be more suitable to support the design workflow for typical ETO products*.”

I suggest that the authors compare their results with those of more recently developed optimization methods. Most probably these methods (even more recent variations of GA) will improve the quality of the results.
Many thanks for this suggestion. Authors included a new chapter (6. Discussion) which aims to present the advantages of the presented MOO approach. This chapter presents future research about the optimization algorithms to be furtherly explored for the presented MOO method.
Hereunder an extract of chapter 6.
“*Regarding the optimization methods, this paper is focused on genetic algorithms. In particular, MOGA-II has been tested and proposed for the highlighted test case. As a future research, this optimization method could be compared with other approaches such as Constraint Satisfaction Problem (CSP) and Particle Swarm Optimization (PSO). While the use of a PSO algorithm is still a heuristic approach, the CSP solution regards the mathematical representation of a set of engineering constraints to be evaluated inside a domain of solutions. In this paper a MOGA-II algorithm and a tool have been chosen to reduce effort and time in the definition of the optimization problem.*”

What is the logic behind the list of acronyms? For example, why exactly PSO is mentioned in the list but ES and DE are not? (None of these methods are utilized).
The Nomenclature was deleted because all the acronyms were presented in the text.

It can be interesting if the authors comment on more general regularity as introduced in:
A. Kaveh. Optimal Analysis of Structures by Concepts of Symmetry and Regularity, Springer, 2013.
The reference to the suggested paper was included and commented. Authors have also included another interesting publication of the same author concerning multi-objective optimization.

The English of the paper should be improved. There are some grammatical error, nonstandard word usages and typos that should be eliminated. For example: "This paper proposes a methodological approach to supporting the multi-objective…" should read "This paper proposes a methodological approach for supporting the multi-objective…" Also the verb "support" does not seem to fit properly here and in the title. "… models are used in the optimization loop, which presents…" should read "….models are used in the optimization loop, which present…" The problems with the English of the paper are not limited to the abovementioned examples.
This paper was previously revised by an English Editing Service. After this comment, we sent back this paper for a new language revision. Thank you for this important comment.

Reviewer #2

In this paper, authors proposed a sequential and multi-objective optimization method for supporting the design of engineer-toorder products. The method supports engineers in the development of products and in reducing manufacturing and installation costs. The paper specially focused on the design of tall modular steel towers in oil and gas power plants.

Authors should explain Figure 13,14 and 15 more.
Thank you for this comment. Figure 13 and 14 were revised to increase the readability of the data. The cost breakdown originally included on these figures were moved in two separate graphs (Figures 14 and 16 of the revised manuscript version).
Furthermore, authors included explained better graphs reported in the mentioned figures.

Authors should explain some differences between design.
Many thanks for this suggestion. Authors included a new chapter (6. Discussion), which aims to present the advantages of the presented MOO approach, and a new subsection (5.4 Optimal configuration), which present technical details of the reference and optimized design

Authors may explain whether the proposed method will use for designing wind turbine towers.
Authors explained the applicability of using the proposed method also for wind turbine towers made of fabricated circular tubes. Reference to this possibility was included in the new chapter (6. Discussion) and in the conclusions.
"*Even if the test case is focused on oil & gas chimneys, the approach can be extended and use for the design optimization of similar structures such as wind turbine towers" (from Discussion)*.

There is some english mistakes in Figure 5.
This paper was previously revised by an English Editing Service. After these comments, we sent back this paper for a new language revision. Thank you for this important comment.

I recommend this paper for publication with minor changes.
Many thanks for appreciating the manuscript.

English Editing Proof

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