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Ph.D. Course in Industrial Engineering

DEVELOPMENT OF A DESIGN OPTIMIZATION FRAMEWORK TO DEAL WITH CURRENT CHALLENGES OF ENGINEERING-TO-ORDER PRODUCTS

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Per aspera ad astra

Abstract

This thesis presents a methodological approach to supporting the multi-objective optimization of engineered-to-order products. The goal is to support engineers in designing economic products while meeting performance requirements. 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, little information on the order is available, and time available to formulate an offer is limited. Thus, parametric cost models and simplified 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 3D geometries and advanced parametric cost models are used in the optimization loop, which presents a restricted problem domain. In the last phase involving detailed design, a full 3-D CAD model is generated, and specific numerical simulations are performed. Cost estimations, given high levels of detail considered, are analytic and are performed using dedicated software. Two case studies to validate the presented approach are described. They concern the design optimization of a steel chimney and an air filtration system typically used in the oil and gas sector. The multi-objective optimization approach involves the minimization of costs related to manufacturing and assembly phases and the product performance enhancement.

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Chapter 1

Introduction

1.1 Background

In the modern industry, the responsiveness of a company with respect to customer demands plays a key role in increasing its attractiveness. Products must meet the growing needs of the market by achieving the right compromise between performance and cost. At the same time, they should be quickly introduced into the market, without losing competitiveness. However, in the case of complex and customized products it is not a trivial task. In fact, often, the goals to be achieved are conflicting and this means that there is not just a single solution, rather multiple solutions to the problem. [32] In addition, products require multi-disciplinary design efforts to design and manufacture, which enhance the importance of effective knowledge exchange as a base for decision-making process [55].
In case of Engineered-To-Order (ETO) products, the design process consists mainly of three phases [21]. The first one (conceptual design) starts when the company's commercial division receives a Request-For-Proposal (RFP) for a new system and it has to prepare the relative economic quotation. The analogical cost estimation approach is not applicable for such products because the high level of customization required by the customer. Therefore, it is necessary each time to perform a preliminary design of the system. The timing to produce this analysis is typically very short. Errors at this stage, especially in the phase of cost estimation, can lead toward a drastic reduction of the company's profit.
The second and third phase (embodiment and detailed design) starts when the offer becomes order. Depending by the complexity of the project, the engineering department, which leads this phase, has a time span between three and five

months for completing the detailed design.
In the first phase, the product optimization is a key aspect for achieving a competitive product. Optimizing a product means to determine the value of certain parameters (design variables) that allow to achieve the best measurable performance (objective function/s) under given constraints. However, the limited timeframe led engineers to a rough optimization. During the second and third phase, the optimization must be stressed. In fact, once the sale prize has been set in the first phase, the optimization process directly influences the product profit. Moreover, ETO products are generally configurable products where the design-sales-delivery process requires only systematic variant design, no adaptive or original design in the sense of Pahl and Beitz [44]. Therefore, they can be optimized since the early stages of the design process. Indeed, configurable products have pre-designed general structures on which designers can apply an optimization process.
Nowadays, the optimization process mostly depends on manual analyses [87] that lead to suboptimal solutions and the quality of the results depends by the time spent. A step-by-step approach, namely manual optimization, is a time-consuming process that does not allow a comprehensive exploration of the problem domain [87].
Furthermore, the evaluation of the product performances or production costs implies using specific software tools. For example, a Computer Aided Engineering (CAE) software for assessing the mechanical performance [25] or a Design to Cost (DtC) tool for estimating the manufacturing costs [23]. Nevertheless, these tools, due to the complexity of the FEA codes and the cost assignment process, requires a great deal of time to perform an evaluation [105]. Additionally, when the problem domain is very large (e.g. heavy machinery, civil large structures, etc.) the time increases rapidly making the cost-performance assessment not feasible within the timeframe requested by the customer. Definitely, to simplify and accelerate the identification of the optimal product configuration, in order to increase the product quality and the time-to-market (TMT), a quick and automatic design optimization framework is essential.

1.2 Research goals and objectives

To address the described challenges companies engineering departments need to implement methods and tools to capture valuable knowledge and reach optimal solutions during the designing phase. One possible countermeasure to address the challenges described above is to establish a knowledge base that spans all projects of an organization and integrate the design process with the use of dynamic and flexible tools able to perform in an automatic and effective way cost and performance assessment. All the different design analysis should be driven by an optimization engine able to reach the best possible design configuration. In this regards, the scientific literature contains several optimization approaches to be used during the design phase. For example, Park and Dang [81] presented a method for the structural optimization of mechanical products through the integration between commercial CAD-CAE software. This integration is reached by means of scripts, programming languages and Application Programming Interface (API). Castorani et al. [28] proposed a multi-objective optimization approach for mechanical products, by associating the Response Surface Methodology (RSM) and the Design of Experiments (DoE) techniques with an integrated platform made by CAD-CAE-DtC software tools. Cicconi et al. [33] developed a platform-tool for the automatic optimization of steel structures through virtual prototyping tools and Genetic Algorithms (GAs). They focused on the design of heavy reticular frame for oil & gas power plants. McKinstray et al. [67] studied the optimization of asymmetric and fully tapered portal frames via GAs. They considered as loading the combination of snow and wind and as objective function the weight reduction. Their approach led to weight savings up to 40%. Farshchin et al. [42] proposed a Multi-Class Teaching–Learning-Based optimization (MC-TLBO) technique for truss structural optimization. The MC-TLBO algorithm was a two-stage procedure, which allows a better overall performance of the search space exploration. Their approach achieved a 4.5% weight reduction. Barraza et al. [12] compared the use of Non-Dominated Sorting Genetic Algorithm (NSGA-II) and Particle Swarm Optimization (PSO) for steel structures under earthquake loads. They aimed to minimize the structure weight without violating strength requirements of the AISC-LRFD specification. They found that the solutions reached for PSO was in general better respect to the NSGA-II approach. Gong et al. [48] proposed a design optimization approach for steel buildings under earthquake loads. The objectives were a combination of minimum weight, minimum seismic input energy and maximum hysteretic energy of fuse members. The optimization problem was solved thanks to the integration of GAs with non-linear response history FEM (Finite Element Method). El Semelawy et al. [41] developed a tool for structural optimization of pre-stressed concrete slab. The tool used the FEM for structural analysis and GAs to solve the optimization problem. The objective function considered the costs of concrete and pre-stressing tendons. Li et al. [63] presented an optimization methodology for beam-plate structure based on two levels. At first, bidirectional evolutionary structure optimization (BESO) method is exploited to achieve the optimal topology of structure, then, RSM is used to reach the optimum section to find the best final solution.

However, the scientific researches mentioned above are focused on methods and tools for a performance or performance-cost optimization without considering the importance for quickness, especially in case of complex and customized systems with high manufacturing cost. For this reason, the overall goal of this thesis is to investigate the deployment of approaches, tools and methodologies to establish a framework for implementing a strategically oriented design optimization approach in the ETO product development process. This research work presents a rapid but accurate sequential and multi-objective optimization framework for the design of ETO products. This approach consists of three stages as the typical design phases for ETO products. During the RFP phase, an MOO is used to support an early evaluation of cost and product performance through a performance analysis. This optimization phase is performed using simplified simulation models (e.g., 1D-product models solved using lumped parameters models) opportunely automated to explore several solutions without the use of manual inputs. Subsequently, during the embodiment design phase, a simplified 3-D 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 product behavior of a full 3-D model, an optimal solution can be identified. This method allows for a complete exploration of the problem domain 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. The expected benefits are a more effective design process, less design efforts and rework, increased product performance, and enhanced organizational profit.

The proposed framework is validated through two real case studies concerning a self-bearing chimney and an air filtration system (AFS) for oil & gas power plant. The tower and the AFS examined are subject to forces (weight, winds, earthquakes, etc.) and conditions typical of conditions prevailing in the related installation site. The investigated cases are optimized in terms of cost and mechanical performance.

1.3 Structure of the thesis

This thesis has been structured as follows:

Chapter 2 sets the background of product customization.

Chapter 3 reviews key definitions, methodologies, and tools in the research fields: engineering design, knowledge-based design, design optimization, performance assessments and cost estimation.

Chapter 4 presents the developed framework.

Chapter 5 presents a case study to validate the proposed design framework and to make clearer the various steps of the approach.

Chapter 6 presents another case study to highlight how the proposed framework can be applied to other products adopting different methods and tools.

Chapter 7 summarizes the most important results derived from the research and presents the overall conclusion of the thesis. Further, it suggests potential areas for further work.

Chapter 2

Product customization

The field of product customization has grown over the past years, and it will continue to expand in the future (as shown in Fig. 2.1) [112]. Most part of companies report a growth, only very few activities indicate a decrease. Business analysts expect a further growth of product customization over the next 5 years [18].
This trend has been common to a wide variety of industrial sectors, though some differences can be observed. For instance, while the Configured-To-Order (CTO) business model is commonly used as a product practice in the automotive industry [65], the Engineering-To-Order (ETO) model is widely applied in different sectors such as the oil and gas sector [112]. CTO and ETO products differ in regards the presence of preconfigured and pre-scheduled production activities. While ETO products are engineered and built after an order is made [61], CTO 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. [96] 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.

2.1 Customization Business Drivers

To understand why product customization is growing, it is necessary to analyze what are the reasons (shown in Fig. 2.2) that drive the sale of customize products. The main reason is that customization helps companies to differentiate from their competitors. It is reported that 43 % of industrial equipment companies and 46 % of the automotive and transportation industries have a strategy to differentiate

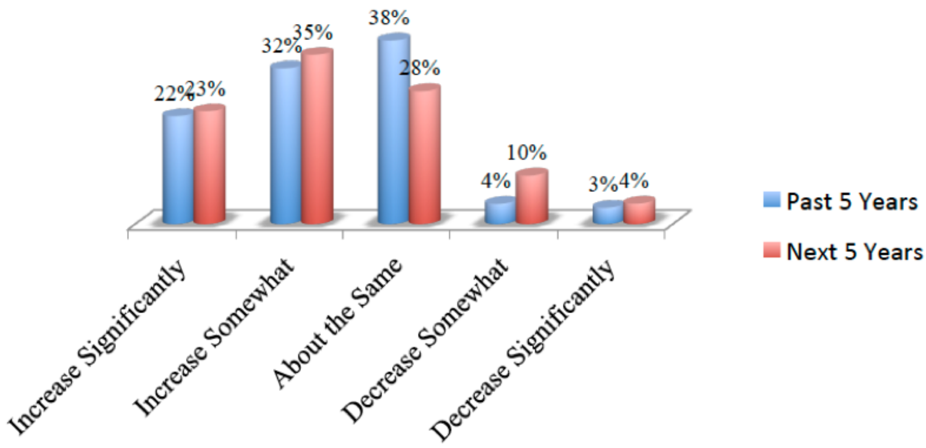


Figure 2.1: Growth in product customization [18].

based on customization [18]. Indeed, studies show that customization is second only to innovation as product differentiation strategy [58].
ETO business model is a great way to compete in modern global markets since it helps in encountering customers' requirements [22]. On the other hand, it is the nature itself of specific business sectors that leads to the necessity of customizing products. For example, a plant has to respect client specifications and also to be conform to site specification like footprint, loads, local legislation, standards and lots of other factors. Also, the companies where selling customized products is the rule are providing their customers with higher level of customization.
The possibility to grab higher prices is another motivation that pushes companies to customize products even if not always it is possible to charge a price premium [56]. For instance, among biomedical and consumer goods business activities, a great part customizes to command higher prices trying to satisfy more the customer necessities.

2.2 Differentiation in Customized Products

Customization is adopted by companies to differentiate their products, since it leads to be more competitive [56], but how do they differentiate their customized products? The answer is with a higher level of customization (as shown in Fig. 2.3). Being able to meet more customer requirements has been recognized as a winning strategy to differentiate a product. The more the client will be able to modify a product according to his personal expectations, the most it will be satis-

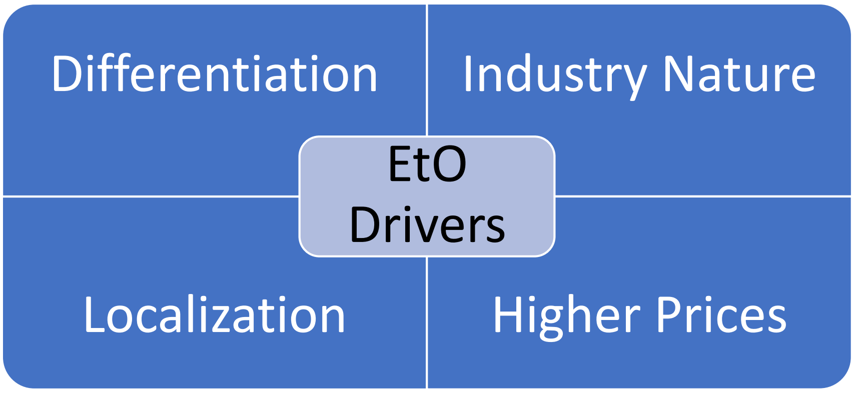


Figure 2.2: Business drivers for the ETO model.

fied. It is generally recognized as client satisfaction plays a key role in business success. These are not the only adopted product differentiation strategies in the sector of tailor-made products.

Also, product reliability and service/support provided to a client have an important role. Customers are looking for assurance that the product will work in a satisfactory manner over its entire life with no unplanned stop. In the worst scenario that a failure will happen, they want to be able to count on a ready and effective service that will repair in a cost-effective way their product.

Building a strong brand is recognized as a powerful way to success in today's business world [69]. Brand differentiation is the means by which a brand is set apart from the competitors, by relating a greater performance aspect with numerous client benefits.

Businesses-man across different industries have quickly realized that speed can be used to develop a competitive advantage. Speed can be categorized under a number of different labels, including speed to market, speedy delivery and speedy service, but the root word stays the same. Anytime a business can do something faster than the competition, they're going to experience some level of success. In industries that are particularly price competitive, speed can be the distinguishing competitive advantage.

Other important factors, but not the key to success in ETO sales, are the rapid quotes and global reach. Surprisingly, the price is the least influent in differentiating products. In this particular sector, clients want their requirements satisfied and they are prepared to pay for that. Moreover, you may be cheapest today, but a competitor can always drop their price [59].

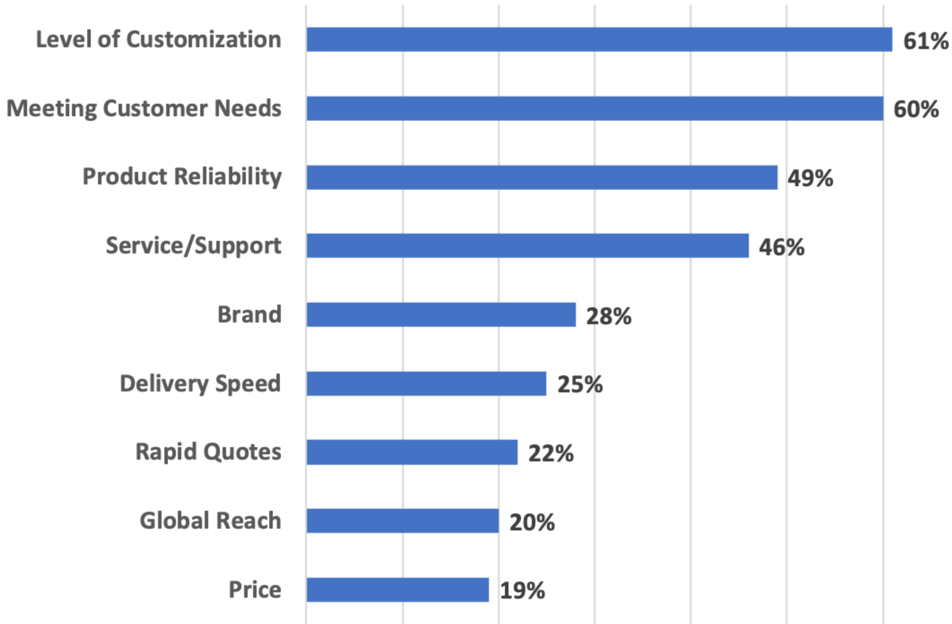


Figure 2.3: Product differentiation strategies for customized products [18].

Researches highlighted that differentiation strategies are different from one industrial sector to another. For instance, aerospace and defense industries exploit their capabilities in offering a deeper level of customization and meeting customers specifications as the leading way toward product differentiation. Differently, reliability is the key factor in safety-critical companies. Industrial equipment is more concentrated on encountering client needs than most industrial sector, while the biomedical industry competes much more on quote and delivery speed.
The choice of a proper strategy makes a great difference in terms of business achievements.

2.3 Manufacturing styles

One or more manufacturing style can be adopted by companies, that range from producing standard items that can be created and sold *off of the shelf* to merely custom products to manufacture a large variety of items designed on the basis of customers' requirements. Traditionally, we can distinguish, depending on the adopted manufacturing style, the following products:

Standard Product that do not demand supplementary definition other than a part number when ordered or manufactured.

Configured-to-Order (CTO) Products are configured, manufactured and assembled based on client specifications using features and options (such as size, material, color, etc.). All items are designed prior to take them to the market, no more engineering efforts needed when client requirements are known. The product configuration process consists of selecting the proper items and assemble them into a valid product. The ordering process of a car or a personal computer with all its options can be seen as a typical CTO process.

Engineer-to-Order (ETO) Products are designed, engineered and produced, according to customer specification, after an order has been received. They are *one of a kind* products that require designing new parts to encounter client's needs. During the proposal and order fulfillment process a significant engineering effort may be required.

Job Shop/Pure Custom Products that, in order to satisfy client needs, demand for an engineering and designing process. This kind of items are unique and not repeatable as they do not follow any logical or replicable design rules.

Hybrid Product produced mixing CTO and ETO manufacturing styles.

Considering this classification an ambiguous aspect could be the distinction between CTO and ETO. The main difference is that ETO products demands for additional design effort to achieve a quotation and manufacturing information [110]. Typically, ETO is based on engineering calculations and decision-making process that increase design process complexity demanding additional engineering effort and expertise. While, CTO consists in just picking and choosing part numbers to assemble together.

2.4 Engineer to order

Engineer-to-Order ETO products are complex 'one of a kind' systems and involve highly variable products [8] designed to satisfy client specifications. The ETO scheme is used as an optimal means to compete in modern industry whereby the responsiveness of companies with respect to customers' demands plays a key role in enhancing a company's attractiveness [38]. However, it involves designing new parts to cater to customer needs [112]. In bidding preparation and order fulfillment processes, meaningful project-based efforts may be warranted. This typically involves engineering calculations and decision-making processes [112]. Growing levels of customization introduce more design complexity [100], which in turn creates different problems: incorrect quotations, late deliveries, missed financial targets, etc. André et al. [8] have highlighted that ETO business could benefit from the introduction of design platforms that support the development of highly customized products. Krisanto et al. [61] have noted that a lack of modularization lengthens the duration of engineering change orders.

In accordance with Pahl and al. [44], 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 as accepted by the customer is generally very short. Errors made at this stage and especially in terms of cost estimations can lead to a severe reduction 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 functional, strength, dimensional, cost requirements are met. Time allotted to this phase depends on the complexity of the design concerned and can generally varies from few weeks to several months.

In the third phase (detail design) an executive project must be completed. For example, in case of 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.

In Fig. 2.4 are reported the typical steps from the request for proposal phase to the site installation of the system. This kind of design, manufacturing and installation process presents various issue: long-lead times, proposal could lack of content, guess-work erodes margin, lower win rates, order engineering detracts from new product introduction, changes difficult to manage, errors cause scrap and rework liquidated damages etc.

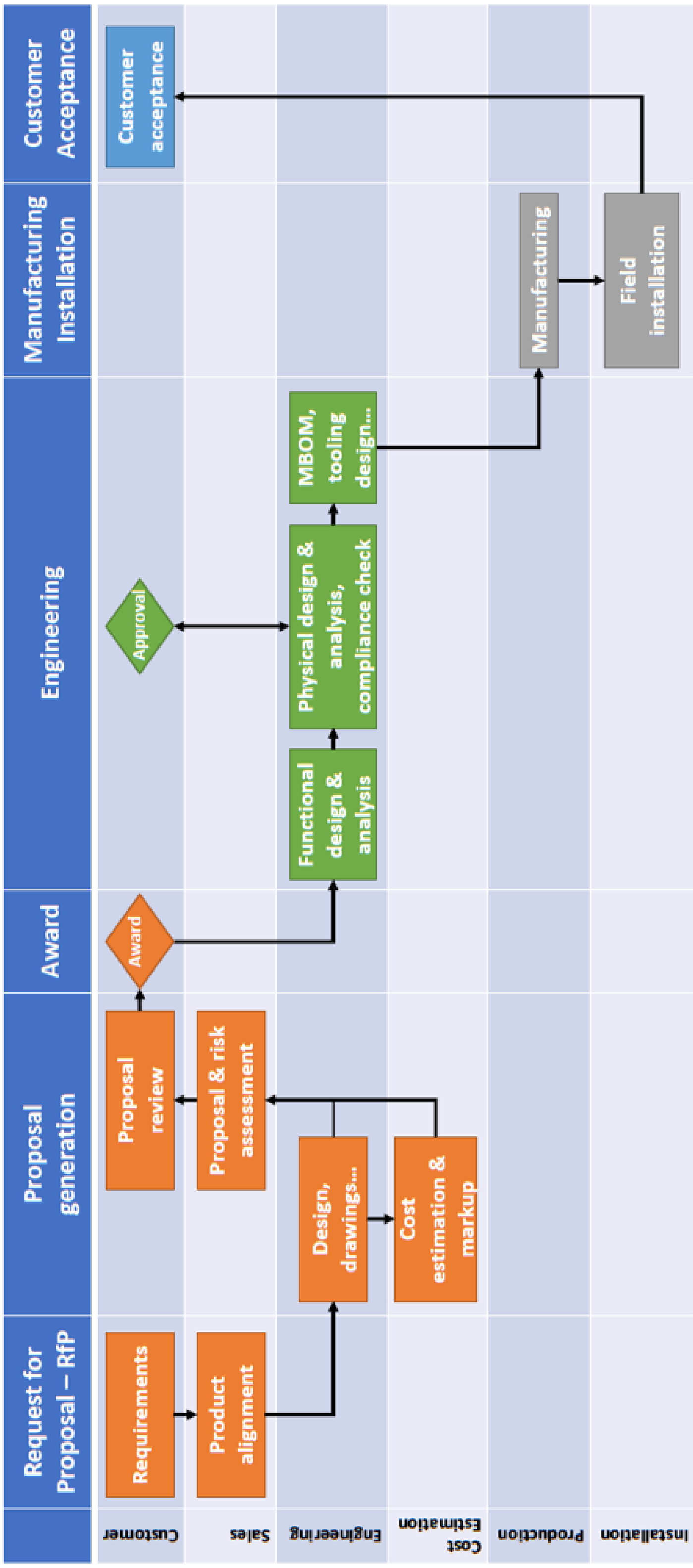


Figure 2.4: Traditional design process for ETO product.

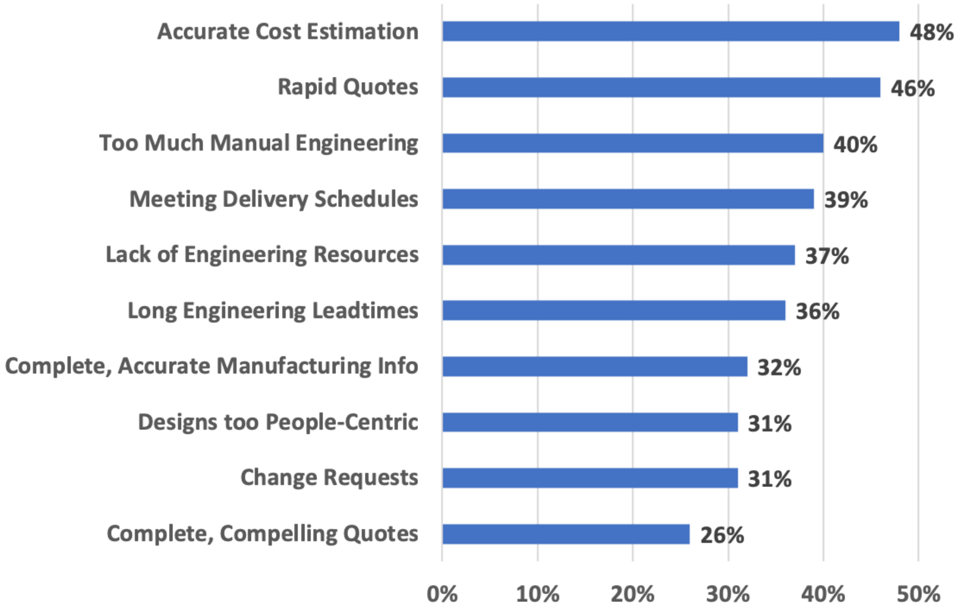


Figure 2.5: Challenges in designing ETO products [18].

2.5 Customization Challenges

Today's products are complex. It is generally recognized that they are complex to design, to produce and to support. This challenge is even more hard when we talk about customized products. Indeed, this kind of items demand for engineering based on order requirements. Clients are increasingly requiring more innovation and quality expectations have risen. Therefore, being able to manage product complexity is a relevant business issue.

Considering ETO products, the two major challenges are related to sales quotes (as shown in Fig. 2.5). Estimating properly the cost and being able to produce rapidly a quotation are the most difficult tasks for manufacturers.

Creating an accurate cost model is the most common challenge that can have a relevant impact on product profitability [83]. Achieving an accurate cost and schedule estimation requires lots of knowledge about the product that generally are not available during the request for proposal phase. Even though most companies are able to produce a quotation relying on a number of cost key drivers, to achieve an accurate estimation a detailed designs and specific knowledge about different products and manufacturing aspects (i.e., materials, machines, work-center times, custom tools, labor costs and times, etc.) are needed [22].

The incapacity to estimate accurately costs can lead to two different limit situations. On the one hand, too much buffer is added making the offer less attractive, on the other hand, an aggressive price is proposed risking of losing money on the order. A right trade-off between these two situations is not so easily found.
Quote response times represent the second major challenge for ETO companies [109], 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. Often, the available time is so short that, at best, a guess-work is carried-out. Moreover, long engineering lead-times significantly affect the development of ETO products. Time-related problems are mainly attributable to the required customizations to develop a product and typically without the use of systematic approaches or specific tools. This often results in a need for more complex design efforts than were expected, causing considerable delays in project development [17].
The quotations presented to clients are more than just a price. They contain rich product content like drawings, 3D models, technical details, performance assessments etc. This material is necessary to make customers aware how the proposed solutions satisfy their requirements.
Another big challenge in selling customized products is the capability for manufacturer to meet agreed delivery schedule. This is probably related to the fact that lots of design tasks are carried out manually along with long engineering lead times and lack of engineering resources. Manual designing is likely the cause also for the long lead-time needed to produce a quotation. Industries requiring too much manual designing tasks will experience long quotation and order fulfillment lead time.
Due to the short design time and few available information (especially in the request for proposal phase) is not so easy to retrieve accurate and complete manufacturing information.
The engineering time is further extended since the design process is too people-centric. This people-centricity leads also to the fact that the company's knowledge is often owned by few engineers. When these engineers go out from the company a vacuum of knowledge is produced.
During the engineering process is not so unusual that requests for changes are advanced by clients and, in this so structured context, it is difficult to accommodate these requests.
These difficulties lead to the last but not the least challenge: reaching a com-

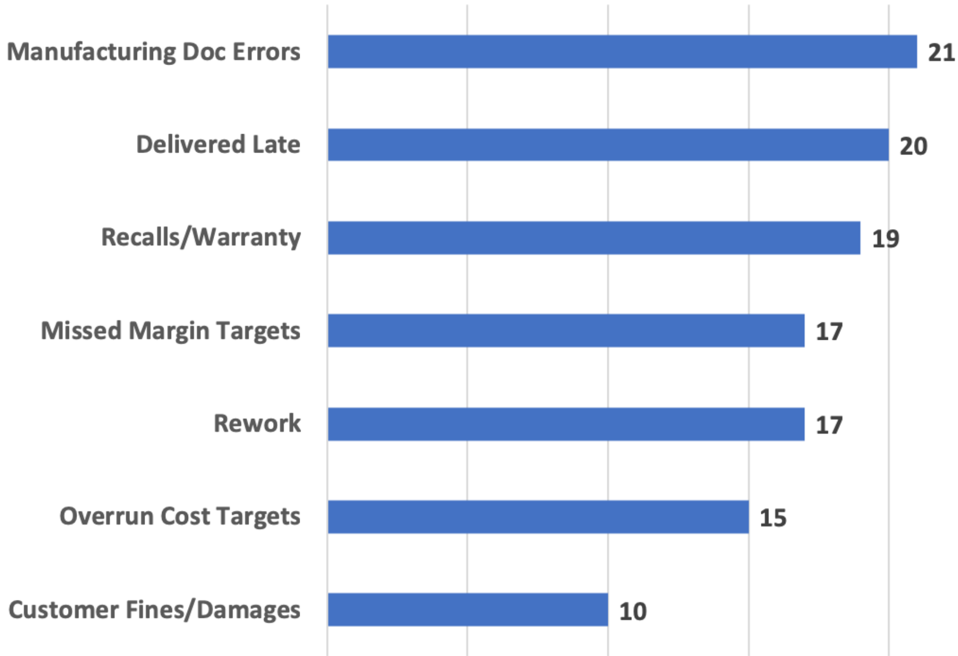


Figure 2.6: Negative impacts of customization [18].

pelling and accurate quotation.

Ultimately the reached design is in the best scenario a sub-optimal design.

All the challenges described above lead to relevant and negative consequences (as shown in Fig. 2.6). Research studies highlight that companies producing customized product suffer often of order errors. It is estimated that averagely 20 % of custom orders suffer of late delivery and about 17 % miss financial targets. Almost the same number of orders need recalls or warranty repairs due to errors in manufacturing documentations. The 10 % result in request for damages compensation by the customers. Moreover, the cost target, in 15 % of cases, are not respected and overrun happen [18].

These concrete problems can have a serious impact on company profitability, reputation and relationship with clients. It is extremely important to highlight that many often orders suffer more than just only one error making the problem even more serious.

2.6 Technical enablers to customization

Analyzing the most common challenges in the ETO product development process, it seems to be a lot of rooms for improvements. These improvements can be reached along all the ETO design phases: selling, engineering, manufacturing and installation. Different can be the tools and methods helpful to make more efficient and accurate the PDP for ETO products. In particular, we can cite:

- product configurator;
- cost estimation;
- numerical simulation;
- design optimization;
- design automation.

Product configurator is an interesting tool able to improve efficiency and reducing design errors. It can be seen as a valid and effective implementation of the knowledge-based design paradigm. This tool could be able to perform three different action: configuring the product, estimating a price, generating a quote. The configuring task can be seen as the process of finding, choosing and combining together product options to create a valid product configuration taking into account all rules and constraints (e.g. manufacturing limitations, standards, functional restrictions etc.).
Estimating a price means deciding how much the client should pay to acquire that kind of customized product while considering all the configuration and additional circumstances (e.g. financial margins, manufacturing costs, quotation competitiveness etc.).
The quote generation is a crucial action, since it enables the redaction of a synthesis document describing the proposed solution with the relative price.
In this context, two different kind of configurator can be identified:

Sales configurator Software tool that enables sales department to generate a valid product configuration with enough information to estimate a sales price and generate a quotation. To perform this kind of operation, the software exploit configuration and quotation rules captured within the system and automate the bidding process. The sales configurator is generally integrated into CRM and ERP tools.

Technical product configurator Software tool that enables design engineers to produce in an automated way a detailed technical product configuration. The output of this tool is a rich model with sufficient information to manufacture the product. To perform this kind of operation, the software exploit design and configuration rules captured within the system. It automates the generation process of the BoM - Bills of Materials and work instructions. Technical product configurator may be also able to create CAD models, technical drawings and specifications.

Generally, sales configurators manage product configuration at order level based on product features and options, providing a quote with the relative price of a valid configuration. Differently, technical configurators imply an analysis and decision-making process to engineering the specific order. These two different kinds of configurators, even if are distinct tools, are used both independently by companies.
Product configurators are able to solve different issues of the ETO design process:

- slow quote process;
- long time in proposal generating;
- low accuracy in the reached quotation;
- losing opportunities for up-selling and cross-selling;
- few information on pricing changes.

Estimating costs is an important task to perform as early and as accurately as possible in the product development process. This is particularly true when referring to ETO products where costs directly influence the company's win rates and profit. It is generally accepted that the greatest part of costs is committed when the conceptual solution has been selected and the embodiment design is concluded [40]. The opportunities to reduce costs during the manufacturing and installation phases are relatively few. Therefore, it is crucial to begin cost optimization as early as possible. Indeed, every design change that has to be made during production is generally very costly. Cost estimation and optimization practice could prolong the PDP, but it is more economical and convenient than reducing cost lately to do not lose financial margin. Different are the available methods and tools to identify cost during the all design process. Each method has its own specificity. Introducing cost estimation practice, instead of guess work, will help enormously in reducing missed financial target and improving bid win rates.

Performance assessment is central to the design of all kind of product. In particular, referring to ETO designs, it is focused on the delivery of performing and cost-effective products to meet client's needs. Often, this kind of assessment is carried out manually performing analytical calculations and experimental test. This kind of procedure is time consuming and makes complex the parametric study of the product. Numerical simulation, in particular physics-based simulation, can be a valid allay of the engineer to evaluate performance of the product in an accurate and rapid way [24]. The physics-based simulation tools likely minimize the necessity for product experimental tests. Due to the fact that solid modeling and virtual analysis are carried-out, accidental design defects experienced during the physical tests are lowered, thus reducing the feedback loop for design changes. Furthermore, the manufacturing phase is smooth as it has been scheduled and simulated. Possible issues related to manufacturing will have been broadly resolved in earlier design stages. The evaluation of product performance by means of physics-based simulation in the computer environment is commonly called virtual prototyping or VP. The advancement in simulation methods and tools has meant that more and more engineering questions have been found a more realistic answer through numerical analysis, thus minimizing the demands of physical testing. Nevertheless, some key questions cannot be answered for very complex engineering problems. VP will probably never substitute physical experiments entirely, however the savings it reaches for less complicated problems is relevant and beneficial.

A very helpful practice that is not widespread across engineering departments is the product optimization. Very often, products are designed, fabricated, and used regardless of whether they are the *best one*. It is a challenge for engineers to project performant and cost-effective solutions without compromising any design aspect. Lots of optimization methods and tools have been developed and employed to design better products. The optimization has been evolved to the stage of automatic design optimization through the use of dedicated platforms, such as ModeFrontier® or ISight®. These software are able, in a single framework, to integrate and communicate with each other CAD/CAE/DfC (Design for Cost) tools with optimization algorithms and methodologies. Optimization analysis have been playing a crucial role in developing competitive products. The

optimization of an existing product can be dictated by several factors such as: regulation, market needs, customizations, company strategies, etc. The integration of an optimization phase inside the traditional design processes can increase delays and cost. This risk grows when complex software tools are used during product design. However, this risk is well compensated to the enormous benefits in reaching an optimal solution.
Another category of tools able to improve ETO design efficiency is design automation. Design automation can be defined according to Cederfeldt and Elgh [29] as *'computerised automation of tasks that are related to the design process through the implementation of information and knowledge in tools or systems.'* These tools typically automate engineering and design calculations integrating themselves with CAD, CAE, ERP and spreadsheets. Often, technical configurators are equipped with heavy design automation capabilities. The configurators that integrate design automation can automate manual engineering that is a bottleneck in all the design phases. This practice allows to reach more product configuration competing at the same time on quick quotations and order delivery, since automation is able to speed-up the design process, reducing errors and providing more precise manufacturing documentation. Automatic bid generation allows to avoid costly and time-consuming effort in developing quotes and to exploit 3D CAD models to create more visual and convincing bids.

2.7 Summary

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 [71] [111] and to beat competitors during the preliminary design stage when an RFP must be prepared [96]. As noted in the following chapter, 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 and especially in the sector of complex ETO products [45]. Enhanced MOO achieved during the preliminary design phase can drastically enhance the competitiveness of a product and of a company's profits. However, this is not a trivial task due to the presence of time constraints and due to limit product knowledge. Optimization must also be stressed in design stages that follow. In fact, once a sale price has been determined in the first phase (order received), the optimization process

directly influences product profit margins.
Therefore, as stated in the previous chapter, the aim of the present study is to formulate a framework to produce an optimized design of ETO products. In this context, a sequential and multi-objective optimization method for the ETO design has been developed.

Chapter 3

State of the art

In the previous chapter it was made clear that ETO manufacturers can experience great benefits in rethinking their design process integrating methods and tools concerning the design optimization, cost estimation, virtual performance assessment and knowledge-based design. Therefore, in this chapter, the state of the art about methods and tools available in these fields is presented.

3.1 Design Optimization

In the ETO sector, one of the main priorities is the identification of the optimal solution, which is namely, the solution that allows to achieve the best measurable performance (objective function/s) under given constraints. Therefore, multi objective optimization has become very popular in this sector [33]. 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 achieve a solution [46]. The use of such expensive computational methods has been facilitated by recent progress made in the development of computing technologies [72]. In this context, research on this topic has become even more popular.

3.1.1 Optimization Problem

Formulating a design problem as an optimization problem, various aspect have to be taken under consideration. At first, it is important to define what are the properties that the system should have and how to measure them (*objective functions*). Then, the *design variables* to be manipulated in order to achieve the

best possible solution has to be identified. Finally, the constraints to be respected have to be described. In formulating an optimization problem, all have to be formalized in a mathematical way. This formalization transforms a qualitative description of a problem into a quantitative statement.
In general, the mathematical form of a single-objective optimization problem is given as:

$$\begin{aligned} &\text{Minimize } f(\vec{x}) \\ &\text{Subject to: } \begin{cases} \vec{g}_i(\vec{x}) \leq 0, & i = 1, m \\ \vec{h}_j(\vec{x}) = 0, & j = 1, p \end{cases} \\ &\vec{x}_k^l \leq \vec{x} \leq \vec{x}_k^u, \quad k = 1, n \end{aligned} \tag{3.1}$$

where $f(\vec{x})$ is the objective function; $\vec{g}_i(\vec{x})$ is the ith inequality constraint; m is the total number of inequality constraints functions; $\vec{h}_j(\vec{x})$ is the ith equality constraint, p is the number of equality constraints; $\vec{x}$ is the vector of design variables; n is the total number of design variables; $\vec{x}_k^l$ and $\vec{x}_k^u$ are the lower and upper bounds of the kth design variable x_k respectively.
After a proper formulation of the optimization problem, the model has to be solved for an optimal solution. The solving process involves choosing the most appropriate optimization algorithm or technique. Engineers needs to know and understand the main concepts and the advantages and disadvantages of the different optimization methods, since an optimization problem is typically solved numerically. Graphical methods are the best choice when it comes to simple problems with two or less variables. Moreover, when the objective function and constraints are explicitly expressed in terms of design variables, the necessary and sufficient condition of the optimality can be exploited to solve the problem.
Optimization problems can be classified in different ways. The design problem described by Eq. 3.1 is called *single-objective* (or *single-criterion*) problem since only one objective function is considered to be optimized. When multiple objective functions are involved in the design process, it is called *multi-objective* (or *multi-criterion*) problem. In this case, the aim is to optimize all the objectives at the same time.
Equality and inequality constraints can be present for an optimization problem. When they are present it is called *constrained* optimization problem. If no constraint is involved, these problems are defined *unconstrained*. Moreover, the nature of the formulation for the objective functions and constraints determine a

further classification: linear, nonlinear and quadratic optimization problems. If all the functions are expressed through linear correlation, such problem is called linear optimization problem and linear programming techniques are used for the solving process. Otherwise, if only one of these functions is non linear, the problem is called nonlinear, and they are solved by the use of nonlinear programming techniques. This kind of classification is particularly useful in choosing the most suitable optimization algorithm since special methods have been developed for the solution of particular class of problems. Therefore, one of the first task for an engineer is determining the kind of problem encountered or formulated. That, in most cases, will rule the choice of the solution method to be adopted.
Another important classification come from the number of disciplines of the physical models involved in the optimization analysis. We can have *single-disciplinary* or *multi-disciplinary* design optimization MDO problems.
Ultimately, a further classification can be reached based on the deterministic nature of the analyzed variables. We can have deterministic or stochastic optimization problem. A stochastic problem implies that one or all the variables are expressed in a probabilistic way.

Multi-objective problem

Engineering optimization problems typically involve the simultaneous minimization or maximization of different criteria. For example, designers would like to minimize weight maximizing stiffness; or minimize cost maximizing production volume etc.
The mathematical form of a multi-objective optimization problem is given as:

$$\begin{aligned}
&\text{Minimize } F(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), \dots, f_j(\vec{x})]^T \\
&\text{Subject to: } \begin{cases} \vec{g}(\vec{x}) \leq 0 \\ \vec{h}(\vec{x}) = 0 \end{cases} \\
&\vec{x} \in \mathbb{R}^n, \quad \vec{f}(\vec{x}) \in \mathbb{R}^k, \quad \vec{g}(\vec{x}) \in \mathbb{R}^m \quad and \quad \vec{h}(\vec{x}) \in \mathbb{R}^q \\
&X = \{\vec{x} | g_m(\vec{x}) \leq 0, \quad m = 1, 2, \dots, m\} \\
&\{h_q(\vec{x}) = 0, \quad q = 1, 2, \dots, q\} \\
&S = \{F(\vec{x}) | \vec{x} \in X\}
\end{aligned} \tag{3.2}$$

where $\vec{x} \in \mathbb{R}^n$ is the vector of design variables and n is the number of decision variables. $k \geq 2$ is the number of objective functions and $F(\vec{x}) \in \mathbb{R}^k$ is the objective functions vector in which $f_i(\vec{x}) : \mathbb{R}^n \to \mathbb{R}^1$. m is the number of inequality con-

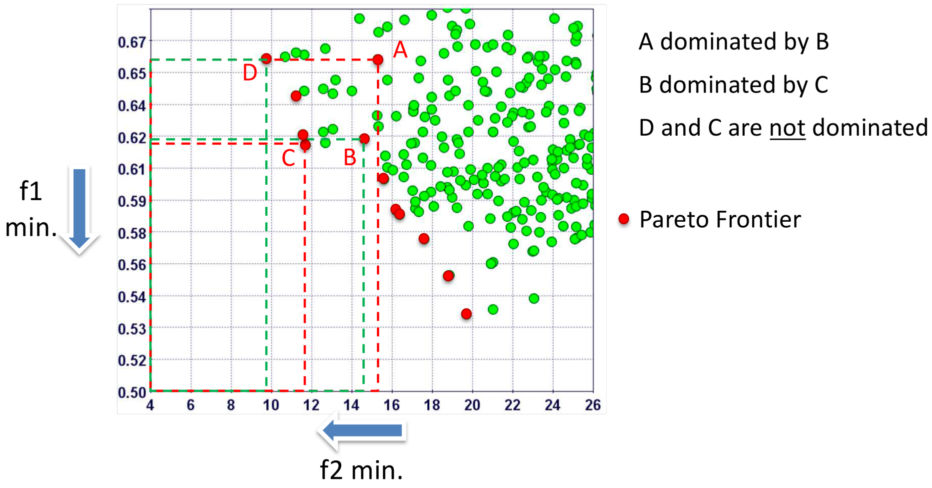


Figure 3.1: Illustration of Pareto optimal set.

straints and $\vec{g}(\vec{x})$ is the inequality constraints vector. q is the number of equality constraints and $\vec{h}(\vec{x})$ is the equality constraints vector. X is the feasible decision space and S is the criterion space.
Optimizing a single function simply means determining a set of stationary points and finding the global optimum (absolute minimum or maximum). Differently, identifying an optimal solution for multi-objective problems could be no so easy. Indeed, in case of functions that have opposite characteristics (i.e. what increases the value of one function may results in decreasing the value of another and viceversa) is not so definite what optimum means. Therefore, a central concept when it comes to multi-objective optimizations is the *Pareto optimality*. In case that none of the objective functions can be improved without worsening the performance of the other, the solutions of such problem are called *non-dominated* and form the so-called *Pareto Frontier*.
According to the definition proposed by Pareto [80]: "a point x^* in the feasible design space S is *Pareto optimal* if and only if there does not exist another point x in the set S such that $f(x) \leq f(x^*)$ with at least one $f_i(x) < f_i(x^*)$."
The set of all Pareto optimal points is called the *Pareto optimal set* (shown in Fig. 3.1). The preceding definition means that x^* can be called Pareto optimal, if no other point in the feasible space S is present that enhance at least one objective function.

A concept related to Pareto optimality is that of *weak Pareto optimality*. At these points, it is possible to enhance some objective functions without worsen-

ing others. A *weakly Pareto optimal* point is defined as [80]: "a point x^* in the feasible design space S is weakly Pareto optimal if and only if there does not exist another point x in the set S such that $f(x) < f(x^*)$. That is, there is no point that improves all of the objective functions simultaneously; however, there may be points that improve some of the objectives while keeping others unchanged."
Another important concept in multi-objective optimization is *efficiency*, it is defined as [80]:"A point x^* in the feasible design space S is efficient if and only if there does not exist another point x in the set S such that $f(x) \leq f(x^*)$ with at least one $f_i(x) < f_i(x^*)$. Otherwise, x^* is inefficient. The set of all efficient points is called the efficient frontier."
Non dominated and *dominated* points are other common concepts, which are defined as [80]:"A vector of objective functions $f^* = f(x^*)$ in the feasible criterion space X is non dominated if and only if there does not exist another vector f in the set X such that $f \leq f^*$, with at least one $f_i < f_i^*$. Otherwise, f^* is dominated."
The *utopia* point in the criterion space is defined as [80]:"a point f^0 in the criterion space is called the utopia point if f_i=$min[f_i(x) \mid$ for all x in the set $S]$, $i = 1$ to k. It is also called the ideal point." This point is obtained by minimizing each objective function without considering the other objective functions.

Multi-disciplinary problem

The constantly increasing complexity of engineering systems has led to the developing of *Multi-Disciplinary* design optimization MDO techniques and to their integration in the design process. MDO simplifies the exploration of interdisciplinary interactions to reach a better solution.
The first attempts to introduce MDO in the PDP occurred in '70s and have been progressing since then, showing great capabilities to enhance product performance and reducing at the same time costs and lead-time. MDO is widely applied in different industrial sectors including automotive, industrial, biomechanics, electronics, aerospace where the interest is particularly intense [79].
According to Sobieszczanski-Sobieski [91] MDO consists of mainly 5 components: Mathematical Modelling, Design-Oriented Analysis, Approximation Concepts, Optimization Procedures, System Sensitivity and Human Interface. The main issues in implementing MDO are related to computational costs and organizational challenges. To overcome these limitations numerous strategies and methods have been developed. These includes: All-in-One (A-i-O), Individual Discipline Feasible (IDF), Multidisciplinary Feasible (MDF), Collaborative Optimization

(CO), Concurrent Sub-Space Optimization (CSSO), and Bi-Level Integrated System Synthesis (BLISS) methods.
As in any type of optimization process also in the multi-disciplinary one, the choice of a suitable approach to formulate and solving the optimization problem affects the solution results. Balling and Sobieszczanski-Sobieski [91] compared and assessed six different strategies: single-level vs. multilevel optimization, system-level simultaneous analysis and design vs. analysis nested in optimization and discipline-level simultaneous analysis and design vs. analysis nested in optimization. Two main conclusions can be drawn by their analysis: no single approach is fastest for all implementation cases and no single approach can be identified as being always the slowest. Therefore, the selection of the approach should be realized only after a deep analysis of all the factors involved in the problem.

3.1.2 Optimization techniques

The techniques to solve an optimization problem, constrained or unconstrained, can be classified into three categories (as shown in Fig. 3.2):

1. optimality criteria methods (classical methods);
2. graphical methods;
3. search methods using numerical algorithms.

The optimality criteria methods can be exploited to find the unconstrained maximum and minimum of a function of several variables. The hypothesis at the base of these techniques is that the function is differentiable twice considering the design variables and the derivatives are continuous. The Lagrange multiplier method can be used in case of problems with equality constraints. Otherwise, in case of problems with inequality constraints, the Karush–Kuhn–Tucker (KKT) conditions can be exploited to reach the optimal condition. A great disadvantage of these methods is the fact that they can lead to equations difficult to solve.
Graphical methods are very simple approaches that can be used only when maximum two design variables have to be optimized. They are able to solve both linear and non linear problems. Graphical techniques are able to clearly represent the feasible region and iso-lines of the objective functions. In this way it is possible to identify in a very simple way the optimal solutions.

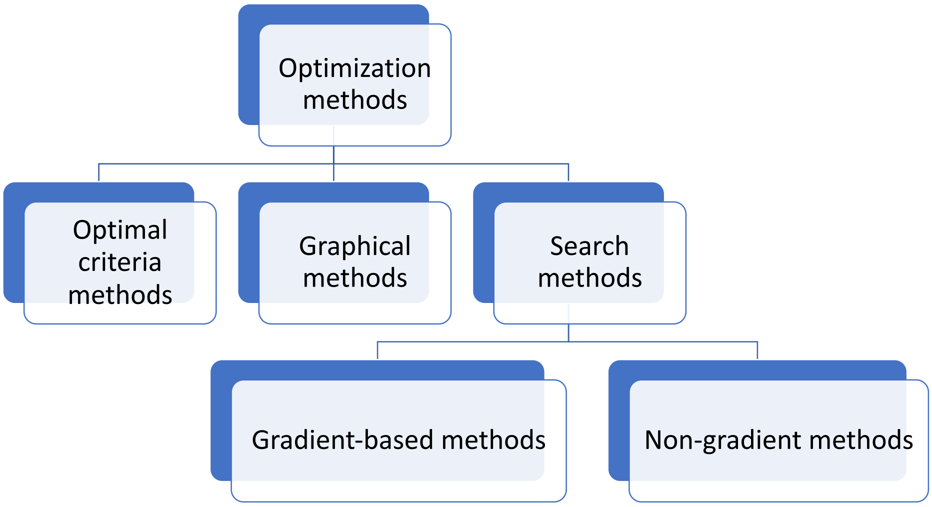


Figure 3.2: Classification of solution techniques for optimization problems.

It is important to highlight that neither classical methods nor graphical methods ask for numerical calculations to achieve a solution.
The most common and used techniques to solve for optimality are search methods based on numerical calculations. These methods look for the optimal solution in an iterative way beginning from an initial design point. To drive the optimum search process some approaches rely on gradient information, i.e. derivatives of objective and constraint functions with respect to design variables. These techniques are called gradient-based techniques. Other approaches exploit certain rules that do not require for gradient information in the searching process. These are named non-gradient-based techniques. Gradient-based methods are accurate algorithms while non-gradient-based methods are robust algorithms. The robustness of an optimization algorithm is the ability to reach the absolute extreme of the objective function. While, the accuracy measures the capability of the optimization algorithm to find the extreme of the objective function. Robust algorithms reach global extremes while, Non-Robust algorithms get stuck in local extremes.

Gradient-based approaches

Gradient-based approaches have a solution strategy based on the calculation of the derivatives of objective and constraint functions exploiting numerical algorithms. They are able to solve both constrained and unconstrained problems

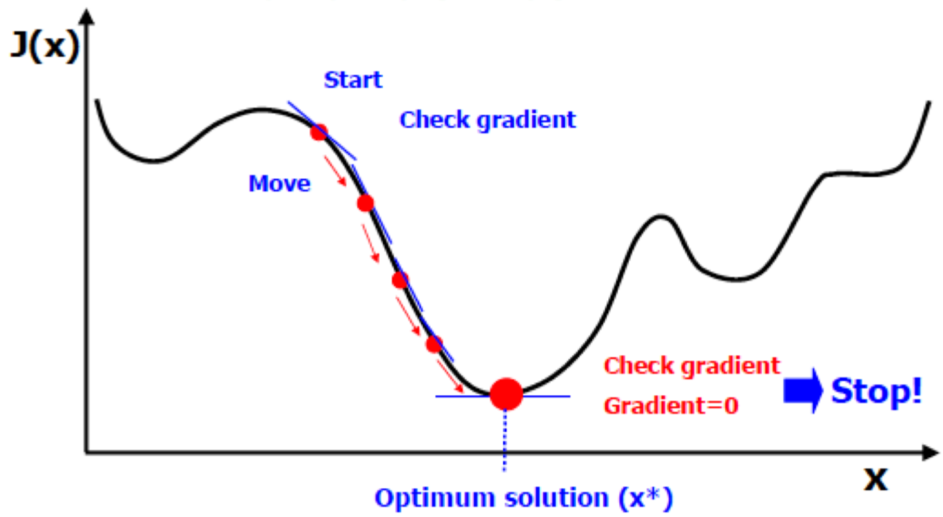


Figure 3.3: Illustration of the gradient-based search method.

of one or more design variables. As every numerical approach, also the gradient-based one starts from an initial design point. Through an iterative process, it searches for a local minimum (or maximum) that is the nearest to the initial point. In case of constrained problems, if the initial design is in an infeasible region, the first goal of the algorithm is to bring the research into a feasible zone. A stopping criterion needs to be defined to terminate the search when a local optimum is found. After a certain number of design iterations, the stopping criterion must stop the research even if no optimal solution is found.
In Fig. 3.3 is illustrated the main procedure of a gradient-based algorithms. An initial design is given as x_0. The derivative of the objective function in x_0 is computed as $f'(x)$. The search direction is determined by the derivative of the objective function $f'(x_0)$. Once the search direction is defined, the step size is researched. Typically, a large step δx size is assumed. Once $x_1 = x_0 + \delta x$ is determined, the objective function $f(x_1)$ and its gradient $f'(x_1)$ are calculated. The same step size is usually used to find the next design until the search direction is reversed. Once it is reversed, the step size is decreased to $\delta x/2$. This iterative process stops when the convergence criterion is reached. The convergence criterion can be defined in different ways.

Non-gradient-based approaches

The non-gradient-based approaches, unlike the gradient based ones, use only the values of the objective functions without taking into consideration gradient information. These kinds of method are very general and can be applied to a wide variety of engineering problems. Moreover, they are able to find global optimum solutions as opposed to the local optimum determined by gradient-based approaches. Even if no gradient has to be calculated, the solution process is an expensive process since a great deal of function evaluations is required. For large-scale problems that will result in long computational time. Furthermore, there is no certainty that a global optimum can be found. The most popular and representative algorithms of the non-gradient approach are the genetic algorithms (GAs) [14].
The genetic algorithms are very general algorithms that can be applied to all different types of problem: continuous, discrete, non-differentiable. Moreover, these methods are easy to use and program and achieve global optimum solutions. GAs are based on Darwin's theory of natural selection: *survival of the fittest*. The idea at the base of these methods is to begin with a set of designs generated in a random way. A fitness value is attributed to each design point. A subset, from the in-use set of designs, is randomly selected with a bias assigned to the fittest elements of the set. New design points are generated through a random process from the picked subset of designs. As new designs are generated from the elements of the set with higher fitness values, the probability to have more fit design in the next sets is greater. The process is iterated until stopping criterion is encountered.
The main phases of genetic algorithms can be synthesized in the following steps (as shown in Fig. 3.4):

1. GAs iteration starts with the definition of an initial population (design points are generated using the allowable values for each design variable) and of a fitness function;

2. fitness values are evaluated and assigned to the respective designs;

3. reproduction, a set of design are selected (the selection is biased toward the more fit elements) from the current population and carried into the next one;

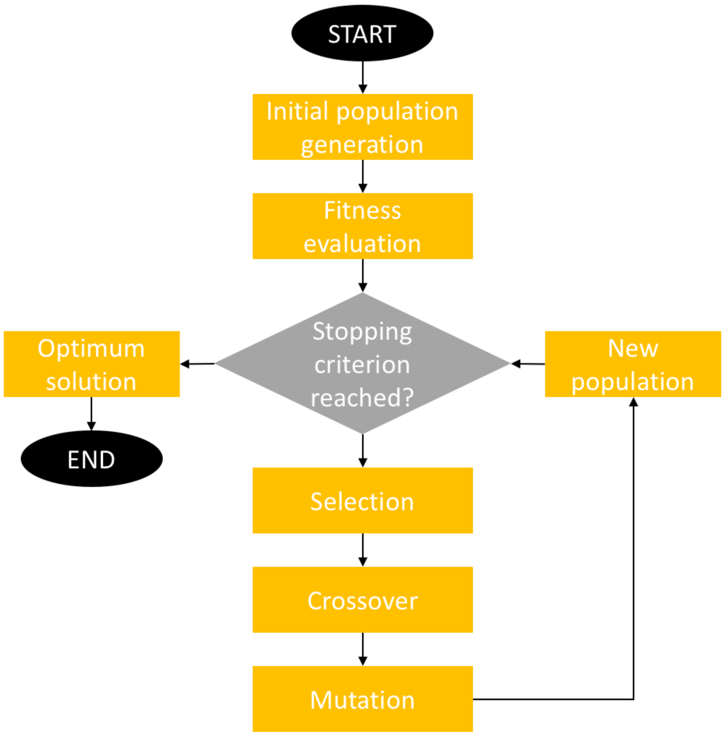


Figure 3.4: Genetic algorithms sequence.

4. crossover, picked elements of the new generation exchange characteristics among themselves;

5. mutation, this process avoids that the reproduction and crossover phases result in a loss of valuable genetic materials;

6. if the stopping criterion is met the optimization is concluded and the optimum is found.

Scientific literature reports various genetic algorithms to be used in solving optimization problems. The most used ones are the MOGA-II [47], in case of multi-objective problems on discrete base, and the NSGA-II [47], in case of multi-objective problems on continuous base.

Meta-models

Many practical engineering design problems require detailed and rich model of the system to predict system response under different conditions. These models

can be very large and complex, requiring long computational time to be solved. Optimization of these systems can be almost impossible. To solve this kind of issue, meta-modelling techniques have been developed.
Response Surface Methodology - RSM [15] consists of a group of statistical and mathematical techniques useful in the development, improvement and optimization of systems/processes/services. This method is widely used in industry, especially in situations where there are many input variables that potentially affect the measurements of the system characteristics [52]. The goal is to simultaneously optimize the levels of these variables in order to obtain the best performance. Input variables (or independent variables), the values of which can be controlled and set by the experimenter, are called factors. The response variable (or dependent variable) is the measured quantity, the value of which is affected by the levels factors changes. The application of RSM takes concrete form by determining the approximate functional relationship between the input variables and the response of the system to be optimized. Typically, second order polynomials expressions are used. The relationship between the response and the inputs is given by:

$$y = f(x_1, x_2, \dots, x_n) + \epsilon \tag{3.3}$$

where y is the response, f is the unknown function of response, x_1, x_2, ..., x_n denote the independent variables, n is the number of the independent variables and ϵ is the statistical error. Epsilon is generally assumed to have a normal distribution with mean zero and variance. RSM consists of the following steps:

1. Choice of the factors of major effect on the system and delimitation of the experimental domain;

2. Design a set of experiments in order to have adequate and reliable measures of the interest response;

3. Determine the mathematical model that best interpolates data obtained from designed experiments;

4. Identify the optimum values for the input variables that lead to the maximum(or minimum) value of the response.

To design the set of experiments on which developing the meta-model, Design of Experiments techniques can be used. The Design of Experiments [16] is a statistical methodology to approach the design and organization of experiment that allows to get as much information as possible with the minimum amount of resources (i.e. with the smaller number of experiments). Usually, the most immediate experimental procedure consists in performing one or more tests, for each value of the investigated independent variables, leaving unchanged all the other conditions: One Factor At a Time (OFAT) approach. OFAT method does not study contemporary the variations effects of two or more parameters. On the other hand, the DoE methodology is based on tests characterized by the simultaneous variation of more parameters [36]. The first step of the DoE is the choice of the factors, the number of the levels, the range of the variability intervals and the response variables. Then, the proper experimental design is defined and the experiment is realized. Finally, the obtained data are statistically processed to generate the response surface. There is a large amount of experimental designs in the literature.

The response of a system may be affected by several factors and it is practically impossible to identify and study each minimum contribution. Additionally, more are the effects to consider and less accurate will be the experimental fitting of the obtained data. Therefore, to limit the usage of computational resources and to increase the accuracy of the analyses, it is necessary to choose those factors with the greatest impact on the response. In case of complex design, where it is not easy to know the cause-effect relationship between factors and response, a screening design should be carried out to find out those variables with the most significant effects.

3.1.3 Current Challenges in Optimization

According to scientific literature review, various are the challenges in design optimization [14]. In particular, we can cite: constraints handling, large-scale optimization and speed-up the optimization process.

Constraint handling

Engineering design optimization problems frequently involves a number of constraints, which can derive from different design aspects such as safety, regulations, customer's requirements and/or limit on time and resources. From a mathematical point of view, constraints have the effect to make unfeasible a more or less large portion of the searching area. As a consequence, optimization methods struggle in searching for optimum design through restricted feasible area. Therefore, an efficient constraints mechanism is necessary to make capable an algorithm to search effectively through the research space.

Large-scale optimization

The large-scale of a problem can have a negative impact on the performance of most algorithms. Two kinds of large-scale optimization problems can be identified:

Many-objective problems most of the multi-objective optimization algorithms mainly use non-dominated sorting to drive the population towards the Pareto frontier. Nonetheless, non-dominated sorting is a defective approach to create a selection pressure towards the optimum if the problem has more than three objectives. Problems with more than three objectives are named many-objective optimization problems.

Many-variable problems some engineering problems can be characterized by a large amount of design variables (even hundreds or thousands). The space of research grows exponentially with the number of variables and so does the effort to search for optimum. That is a major issue for optimization algorithms, especially for the most common ones that do not use any mathematical relationship between variables during the research process.

Speed-up optimization process

MOO is a computationally demanding task and 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. Most of this research has focused on *sequential optimization*. Such approaches enable designers to find appropriate solutions for the different design phases. In this way, 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 study [114] is based on two sequential optimizations with the aim of reducing 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. [78] 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). Bruno et al. [19] developed an iterative optimization approach to network arch bridges based on three stages involving phases considering increasing levels of detail in terms of loads and constraints. Steponavič̌e et al. [94] addressed 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 generated solutions applied an approximation method to create a computationally inexpensive surrogate problem. In a third stage, the solution best matching that of the second stage is identified for the original problem.

All research studies 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 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.

3.2 Knowledge Based Design

Product Configurator, as application of Knowledge Based Design - KBD, represents one of the main technologies for companies to be more responsive to client's requests, under the mass customization paradigm [97]. Product configuration theories aim to develop design software tools able to generate in a rapid manner the main product concepts with the related technical documentations. Starting since the 80's, numerous approaches to product modeling have been proposed in different fields: Computer Aided Design, Design Theory, Production, Configuration, and so on.

3.2.1 Product engineering knowledge

Product engineering knowledge refers to the knowledge matured in all engineering fields that are crucial for the product development process. Therefore, this knowledge includes, not only aspects strictly related to the product design (like

design parameters, concept solutions, functionalities etc.), but also information about manufacturing processes, quality, performance, reliability as well as architectural aspect [107] and background knowledge [95]. Nevertheless, knowledge, being handled among individuals, cannot solely be related to products.
Knowledge, according to Schubert et al. [89], can be viewed as "understanding gained through experience" and "the sum of what has been perceived, discovered, or learnt". The wisdom hierarchy model proposed by Ackoff [1] is the most common strategy for knowledge management. According to this model, the content of human mind can be classified in a hieratic way in four categories (as shown in Fig. 3.5):

Data can be defined as the symbols or signs representing properties of objects, events and their environment and they are product of observation. They simply exist (in any form, usable or not) with no significance other than their existence.

Information is data that have been processed giving them meaning through relational connection. This meaning can be useful or not.

Knowledge is the proper collection of information with the aim to make it useful. The knowledge is deterministic and has a useful meaning, but it does not provide an integration such as would infer further knowledge.

Wisdom is the process to put knowledge into a context. It is extrapolative and non-deterministic. It collects all the previous level to give understanding and it goes further understanding itself.

In knowledge management a fundamental issue is the distinction between *individual* and *organizational* knowledge. Individual knowledge can be seen as the sum of what has been viewed, experience, and learned by a person into an organization. Individual knowledge can be classified according to Løwendahl and al. [66] into: information-based, experience-based and personal knowledge. Organizational knowledge is built across the interaction between individuals, at various level, into an organization.

Knowledge classification

Chandrasegaran et al. [30] classifies knowledge into three different dimensions (as shown in Fig. 3.6):

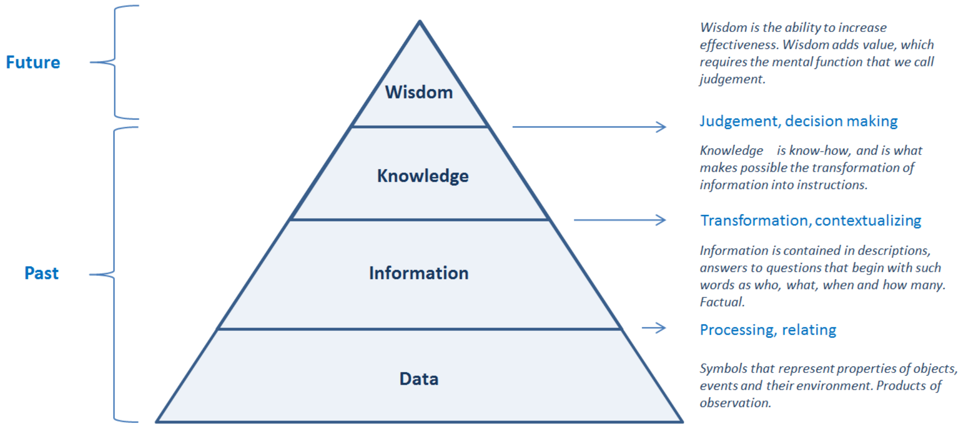


Figure 3.5: Knowledge hierarchy model [1].

Formal vs Tacit Formal knowledge is embedded in product documentation, repositories, database, routines etc [77]. It is the base to build the necessary intellectual platform to design and manufacture a product. Tacit knowledge is the personal know-how and skills owned by personnel and hence difficult to formalize. It is fundamental to add value to a product. Generally, it is acquired over a long period of time with experience and a learning process. It can be transferred only by the willingness of people to share. This kind of knowledge can be lost with the defection of people from the organization.

Product vs Process Product knowledge involves all the information and knowledge about product along its life-cycle. It includes geometry, relationships between parts and assemblies, requirements, functions, behavior, constraints, design rules etc. Process knowledge contains all the information and knowledge about design process, manufacturing process, and business process. Product and process knowledge are not independent of each other, they represent only different aspects of the same problem and, therefore, they worth separated consideration.

Compiled vs Dynamic Compiled knowledge is basically knowledge acquired from previous experience and PDP that can be formalized into rules, best practices, standards etc. The solutions are explicit. Dynamic knowledge is the knowledge needed to generate new additional knowledge, not encompassed by compiled knowledge. The solutions are implicit. It can be classified into qualitative and quantitative knowledge [92].

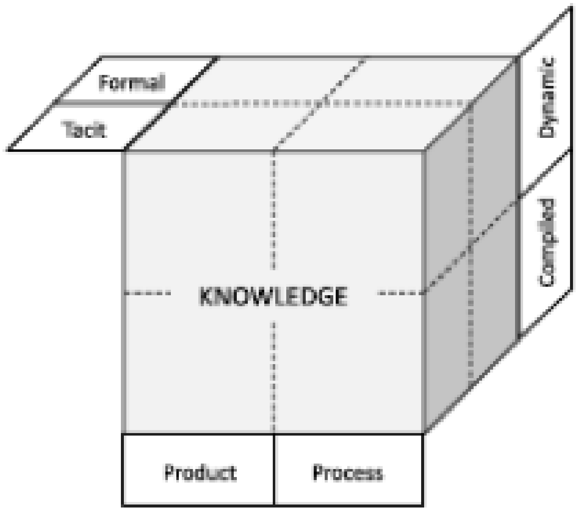


Figure 3.6: Knowledge classification according to [30].

3.2.2 Knowledge transformation

Knowledge is treated by individuals and, hence, dependent on social and cognitive aspects. Therefore, social and cognitive aspects of organizational learning and knowledge transformation have to be analyzed. Organizations, according to Alavi and Leidner [2] can be seen as knowledge systems consisting of four sets of knowledge processes: creation, storage, transfer and application. All these phases are necessary for a proper management of organizational knowledge since the knowledge transformation processes are strictly intertwined.

Knowledge creation

The creation of organizational knowledge consists in developing new content or replacing old ones, in terms of both formal and tacit knowledge. According to Nonaka [74], knowledge in organization is generated, shared, increased and substantiated through social processes as well as individual's cognitive processes. To describe the process of knowledge creation four different modes have been identified: socialization, externalization, internalization and combination. This process begins with creating own tacit knowledge through social interactions and shared experience (socialization). The externalization and internalization involve interactions and conversion between formal and tacit knowledge. Externalization converts knowledge from tacit to formal, making possible to share knowledge among individuals. Internalization, instead, converts knowledge from formal to tacit, enlarging the tacit knowledge base. Combination refers to sharing and transferring formal knowledge. The four modes are highly interconnected and interdependent. Each mode relies on, contributes to, and benefits from the other ones.

Knowledge storage

Several studies report that companies, as well as building knowledge and learning, they also tend to forget [2]. Therefore, it is crucial to store organizational knowledge, also called as *organizational memory*, in order to achieve an effective KM. Organizational memory can be individual or organizational as well as semantic (i.e., referring to general and explicit knowledge) or episodic (i.e., referring to knowledge acquired in specific context and situation). Researchers highlighted that memory can have both positive and negative aspects [108]. An advantage is that memory can help in storing and exploiting past solutions, through best practices and standards, thus avoiding wasting resources in repeated problem solving. On the other hand, memory can negatively influence both individual and organization. At individual base, it can lead to decision-making bias [93], while, at organization level, it may lead to maintaining the status-quo.

Knowledge transfer

Knowledge transfer is one of the most important process in knowledge management. Transfer can occur at various organization levels: between individuals, between and across groups, from individuals to groups or explicit sources etc. An important aspect of knowledge transfer is to be able to transfer knowledge where it is needed and can be exploited. A necessary condition for transferring knowledge is a mutual understanding among individuals. Gupta and Govindarajan [50] described knowledge transfer in terms of five key-points: (1) perceived value of the source unit's knowledge, (2) the willingness of the source to share knowledge, (3) existence and richness of transmission channels, (4) the willingness of the receiver to acquire knowledge from the source, and (5) the ability of the receiver to utilize the knowledge.

Knowledge application

The capability of an organization of applying knowledge is the real source of competitive advantages rather than knowledge itself. Grant [49] discussed as directives (i.e. rules, standards, procedures and instructions), organizational routines (i.e. task performance and coordination patterns, interaction protocols and process specifications) and self-contained task teams are the main mechanism for knowledge application. Technology can support the application and integration of knowledge even if some challenges are present. A common understanding is crucial in knowledge application to enable finding and use of the required information.

3.2.3 Standardization

Standardization, in product design, can be seen as the rationalization of product development by achieving the same function with the same conceptual solution and properties in a widespread range of sizes.
Modular products architectures and platforms are able to provide a great rationale in various design situations. They play a crucial role in creating dynamic knowledge standard. *Modular products* refer to parts and assemblies that carry-out several overall functions by means of the combination of different function units or modules. Modular systems are able to provide favorable technical and economic conditions. The main cons of adopting modular architectures is that the products are more or less predefined. However, their main properties have already been tested so no new experimental campaign and design effort are needed.

Product architectures

Ulrich [102] described the *product architecture* in engineering design highlighting its particular importance. He defined three fundamental elements of a product architecture: (1) the structure of *functional elements*, (2) the association of *functional elements* to *physical components* and (3) the definition of the *interfaces* between components.
According to Pahl et al. [44] product architecture is "a scheme showing the relationship between the function structure of a product and its physical configuration". In this context, they defined the terms related to product modularization as follows:

Modularity is the degree of purposeful structuring of the product architecture.

Modularization is the purposeful structuring of a product in order to increase its modularity.

Modules are units that can be described functionally and physically and are essentially independent.

The modularity of a product can be described according to the functional and physical independency of its parts. A part is functionally independent if it is able to carry out a sub-function. While, a part can be defined as physically independent if it is a coherent unit before the assembling phase. For example, this implies that a component can be developed, tested and upgraded independently from the rest part of the system. It is important to note that the aim of modularization is not the maximization of modularity, that would lead to an unnecessary number of interfaces, but the optimization of the possibilities to reach different objectives.
The adoption of modular systems leads to several advantages both for clients and for manufacturers. For example, manufacturers can benefit of: ready documentation, design efforts are due only for unforeseeable orders, simplified scheduling and improved delivery dates, simplified calculations, favorable assembly conditions, etc. Instead, user can experience the following advantages: short lead-time, easier maintenance, possible changes of functions, almost total elimination of failures, etc.
Nevertheless, pitfalls in designing modular products are also present. For example, since the interests both of manufacturers and users have to be taken into consideration, the identification of the optimal modular configuration may be a very complex task. Changes to the design of the product can only be considered at long period since the designing cost are high.

Product platform

The modules of a product can be classified as *standard* or *customer-specific design* [53]. Standard modules are shared modules that satisfy the requirements of several product variants of the same architecture. They can be exploited within various product configurations. Differently, customer-specific design modules cannot be reused being different across the various product variants.
A very common approach to design variant-rich products is the construction of a *product platform*. Product platform, according to Meyer and Lehnerd [68], can be seen as a "set of subsystems and interfaces that form a common structure from which a stream of derivate products can be efficiently developed and produced."

The platform is defined from a functional point of view. In this context, standard modules can be seen as a platform across several products deliveries. Modules are independent from the platform and, therefore, can evolve separately.
The knowledge related to modules can be classified in the same way as the module classification. *Standardized knowledge* is the compiled knowledge correlated to standard designs, functions and modules that can be reused over the time.

3.2.4 Enablers for representation of products and product knowledge

A proper representation of knowledge is crucial to create a shared understanding and to implement dynamic knowledge into standards. Researches reports many methods and tools to support the explicit representation of the engineering knowledge: pictorial, symbolic, virtual, or algorithmic approaches [77].
The content and context of knowledge are represented by means of structural and declarative representations. The most valuable representations are the structural ones since engineers can exploit them as a cognitive structure to reach the searched knowledge artifact [77]. Knowledge artifacts are explicit objects that capture explicit knowledge.
Structural knowledge can be represented by functional structures, causal diagrams, product architectures, etc. Examples of structural representations are reported in scientific literature: architectural modelling techniques, model-based systems engineering (MBSE) strategies, or approaches for using product life cycle management (PLM) systems, methods for product customization, product-process relations mapping, or product KM support.
The most used tools for declarative representations are: A3-reports, '8 disciplines' method, problem analysis flowcharts, root-cause analyses, and 5-Whys.

Product configurator

Product configurators are a very powerful tools able to improve ETO efficiency and reducing design errors, storing and externalizing organizational knowledge. Product configurators are IT systems able to support the configuration of customizable products. The configuration process typically involves two steps: (1) a representation of the problem has to be reached and (2) algorithms, that based on problem representation will produce a product configuration, have to be implemented. The key-point of each configurator is the *product model*. It is a logical structure that represents the options and features of the offered product

variants with all the relative constraints. The main item of a configurator system are the *modeler* and the *configuration engine*. The modeler allows to build and modify product models by describing features and constraints. The configuration engine implements algorithms supporting the configuration process.
According to Junker [60], three main strategies can be identified to configure a product:

Rule-based reasoning was the first approach to be developed. These systems, also called as expert systems, exploit *production rules* as a strategy to describe both domain knowledge and control strategy. A production rule is expressed in the *if-then* form. Rules explicate either *directed relationship* (domain knowledge) and *actions* (procedural knowledge). The solutions are reached in a forward-chaining manner. The algorithms are executed after the choices have been made, therefore, illegal choices could be made. In case of large rule-based systems the building process as well as the maintenance is complex.

Case-based reasoning provides a model to represent past experience and use it to solve configuration problems. CBR exploits concrete knowledge acquired through past experience. A new problem is addressed and eventually solved by identifying a similar past case. Moreover, the knowledge acquired from new designs is immediately available. Literature reports several CBR approaches that can be classified in 5 classes: exemplar-based reasoning, instance-based reasoning, memory-based reasoning, case-based reasoning and analogy-based reasoning.

Model-based reasoning was developed to overcome the main weakness and limitations of rule-based and case-based reasoning approaches. It divides the description of the problem from the algorithm that solve it. Therefore, the analysis of the problem does not depend on the chosen approach. The model of the system to be configured is the base on which the description of the problem is reached. Moreover, this approach requires the definition of a closed space of possible configurations.

Numerous research studies described framework to support the development of configurators. In particular, in ETO companies there is an urgent need to create a strategy to develop and implement configuration system due to the high product complexity and variants. For example, Haug et al. [60] proposed approaches to build configurators in ETO companies by implicating different specialist (product experts, knowledge representation experts and configuration software experts) in the development and implementation process. While, Hvam et al. [57] and Forza and Salvador [43] provided complete frameworks analyzing and standardizing all the processes involved in configuration projects.

3.3 Cost estimation

Complex dynamics of global markets force companies to offer more customized products reducing at the same time costs and lead-time. This is particularly true for ETO business with highly tailored products. In ETO companies, the manufacturing phase begins after an order has been received and many single orders are the starting point of the order processing. Moreover, the final products have to perfectly match customer's requirements, thus every new order is generally a new product variant. This leads towards a drastically increased system complexity and a greater number of variants. As yet highlighted in the introduction, in ETO manufacturing an accurate cost estimation has to be generated starting from the request for proposal phase [99, 37]. Moreover, a revised cost estimation is needed every time a change in the design is requested by the client [75]. These critical aspects lead to design several cost estimation methods and tools to provide a precise and consistent economical quotation. Most of these methods have been developed not only to achieve the optimal design solution but also to satisfy more clients in terms of low-cost, high-performance and low lead-time [37, 73].
The accuracy and reliability of product cost estimates must increase as the product development progresses [13]. However, engineers can reduce efficiently the product cost modifying the design, if cost estimation can be done during the preliminary design phases [76, 20]. Therefore, using methods and tools for cost estimation it is a highly desirable practice for companies, since it is able to improve efficiency and robustness of PDP.
The traditional PDP suffers from the *design paradox* [101]. This refers to the dichotomy or better to the misalignment that exists between the knowledge of the designer about the product to be developed and the number of decisions to be taken (Flexibility) throughout the product development cycle. The main design decisions are usually taken in the initial design phase, when the product is not well understood. As a result, technical changes are often required in the later stages of product development, when design evolves and is better understood,

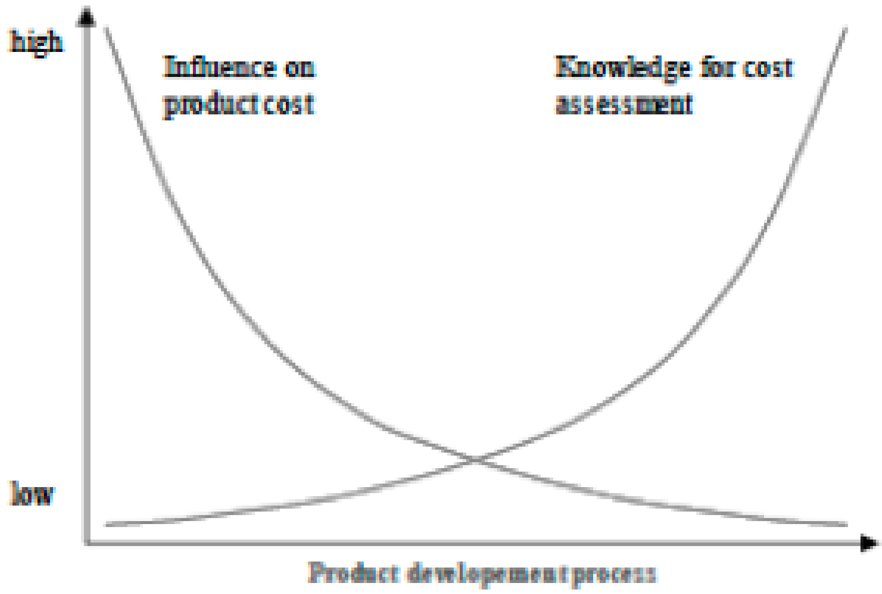


Figure 3.7: Cost paradox along the product process development process.

to correct previous decisions. In Fig. 3.7 is shown the paradox referring to costs. The needed knowledge to reach an accurate product price is available only later in the PDP process, where the possible impact on product cost is low.
One of the primary approaches during the preliminary design is to rely on expert judgments to carry-out a costification. This costification will be achieved mainly based on previous experience and frequently at macro-level. During the first phases of the design, the only reliable source of knowledge is the expert. Although expert's opinions are a valuable and cost-effective approach, the results of the estimation are often very subjective [84]. To overcome this limitation a structured costing approach has to be exploited.

3.3.1 Cost factors

The total cost to produce a product can be divided into direct costs and indirect costs (overheads). Direct costs are those that can be assigned to specific cost items, such as material and labor costs [40]. Indirect costs are those that can't be assigned directly, such as the plant management or energetic costs. Some costs are a function of the number of items ordered, the degree of facility utilization or the batch size. For example, labor costs or material costs increase with higher number of parts to be produced. In a cost calculation these are variable costs.

Fixed costs are those that do not change, such as rent of space or interest on borrowings.
The manufacturing cost is the overall cost to produce a product including material and additional costs like production tooling, design, test etc. The manufacturing cost is composed both of variable and fixed costs. The designer can influence directly only variable costs. Therefore, to optimize a product, from a cost point of view, only variable costs should be considered [44]. For example, different material, production rates, batch sizes, manufacturing processes or assembly methods can be chosen.
Variable and fixed indirect costs are accounted in different way in the various companies. Typically, they are coupled with direct costs through multiplication factors. In general, to compare the costs of different product variants designers can calculate only variable direct costs.

3.3.2 Cost Calculation

Manufacturing cost estimations have been widely examined in research studies and characterized by numerous methods. In reference to this context, Duverlie et al. [39] 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 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, materials, etc.). 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 denote the best fields of application. The adoption of such methods depends on levels of product model maturity determined by phases of the product design process. For instance, the analytical method requires the use of a detailed product model with almost all information defined and 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 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 the combination of parametric and analytical methods is required to facilitate the entire product development process. Niazi et al. [73] proposed a decision model to support the choice of the most suitable cost estimation method. In Tab. 3.1 is reported the classification proposed by Niazi et al. [73] for the cost estimation techniques.

Intuitive Cost Estimation Techniques

Intuitive cost estimation techniques are based on exploiting past experience. The cost estimates are reached systematically using the knowledge owned by domain experts. This knowledge can be elicited and formalized through rules, decision trees, judgments, etc. Literature reports different intuitive techniques but the most important are:

Case-Based Methodology Case-based methodology or case-based reasoning (CBR) tries to exploit the information contained in past projects by choosing and adapting from a database a previous design that has very analogous attributes to the new design. The process starts analyzing the specifications of the new project, followed by retrieving from the projects database the most similar design. In the retrieved design, the parts and assemblies to be modified are identified. Changes are carried-out both by recovering similar parts and/or assemblies and designing ex-novo the new ones. The new parts are stored in the CBR database. This approach is very helpful during the first stages of the PDP since the use of past cost data allow to reach new estimates minimizing the estimation time [86]. Nevertheless, this approach can be used only when similar past designs are available to extrapolate the necessary cost data for the new projects [73].

Decision Support Systems Decision Support Systems (DSS) are helpful tools in assessing design alternatives. The main aim of this kind of tool is to aid estimators in making good decisions at different level of PDP using the stored knowledge by domain experts. The experience of the experts is

Table 3.1: Classification of the cost estimation techniques.

		Product Cost Estimation Techniques	Key Advantages	Limitations
Qualitative	Intuitive	Case-Based Techniques	Innovative design approach	Dependence on past cases
		Rule-Based Systems	Can provide optimized results	Time-consuming
		Fuzzy Logic Systems	Handles uncertainty, Reliable results	Estimating complex feature costs is tedious
		Expert Systems	Quicker, more consistent & more accurate results	Complex development & programming is necessary
	Analogical	Regression Analysis Model	Simpler method	Data intensive, High dependency on data quality, Linearity issues
		Back Propagation Neural Network Model	Deal with uncertain & non-linear problems	Completely data-dependent, Higher establishment cost
Quantitative		**Parametric**	Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified, Complex development
	Analytical	Operation-Based Cost Models	Alternative process plans can be evaluated to get optimized results	Time-consuming, Require detailed design & process planning data
		Break-Down Cost Models	Easier method	Detailed cost information required about the resources consumed
		Cost Tolerance Models	Cost effective design tolerances can be identified	Require detailed design information
		Feature-Based Cost Models	Features with higher costs can be identified	Difficult to identify costs for small & complex features
		Activity-Based Cost Models	Easy & effective method using unit activity costs	Require lead-times in the early design stages

incorporated by means of artificial intelligence (AI) [73]. The most common way to store knowledge about design, manufacturing and other constraints is as a set of rules. Fuzzy logic or other non-conventional approaches are used to overcome problems related to uncertainty and nonavailability of heuristic data.

Analogical Cost Estimation Techniques

Analogical cost estimation techniques compare a new product with an analogous one, that was typically designed in the past, for which there is accurate cost data. Similarity criteria are employed to choose past design with which compare the new one. Among the analogical methods the most used ones are:

Regression Analysis Models Historical data are analyzed in order to find a linear relationship between the product cost of past projects and the values of certain design parameters. The retrieved relationship is used to forecast the cost of new products. Proper assumptions and accurate data are needed to achieve reliable results. The data acquisition and analysis process are time consuming [40].

Back-Propagation Neural-Network Models These models are particularly helpful in uncertain conditions and adaptable to deal with nonlinear problems [40]. These features come from the fact that the models are build using a neural network. The neural network can be trained to store knowledge to infer answers to questions that have never been asked before. The back-propagation neural network is the most common and suitable network types for product cost estimates.

Parametric Cost Estimation Techniques

Parametric cost models are achieved applying statistical methods and by formulating cost as a function of a certain number of variables. The complexity of the function depends on the complexity of the product and the number of parameters [84]. These techniques are effective in all those situations where the cost drivers can be easily found. For example, the manufacturing costs of a brake disk can be formulated as a function of the weight of the raw disk, unit cost of raw material, and the number of cores. Parametric models allow to reach cost estimates quickly and systematically. However, to derive an accurate model lots of effort is needed along with a great quantity of accurate historical data. Literature reports a wide range of parametric models for cost estimation in ETO manufacturing. They can be used partially also in early design stages.

Analytical Cost Estimation Techniques

Analytical cost estimation methods express the costs as a summation of different contribution. This approach requires to decompose a product into elementary items, operations and activities representing different resources consumed during the manufacturing process. These techniques can be further classified into different categories:

Operation-Based Approach This approach is one of the first attempts to evaluate manufacturing costs. The method allows the manufacturing cost estimation as a summation of the costs related with manufacturing processes, nonproductive and setup times. It is typically used in the final design phases since the type of needed information.

Breakdown Approach The overall product cost is estimated by summing all the cost items incurred during manufacturing cycle, considering also material and indirect costs. Detailed data about the resources used to produce the product (including purchasing, processing and maintenance details) are needed.

Tolerance-Based Cost Models This kind of model aims to determine the cost of a product considering design tolerances of a product as a function of its cost.

Feature-Based Cost Estimation This approach identifies the product's cost features and estimates the related costs. To identify and quantify the product features that play a significant role in determining the total cost a considerable research have to be carried out. These features can be either design related or process oriented. This methodology presents limits in dealing with complex or very small geometric features.

Activity-Based Costing (ABC) System The ABC method is concentrated in calculating the costs incurred on performing activities to produce a product. It is a valid approach to distribute indirect costs proportionally to the activities carried-out to produce a product. It was proved to be an accurate cost

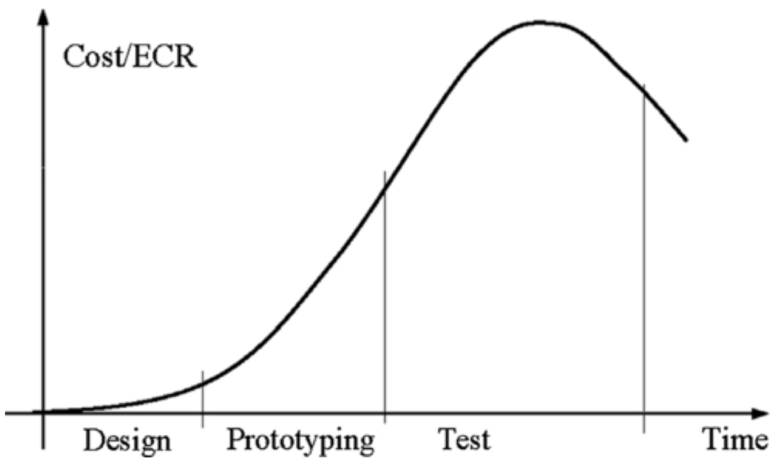


Figure 3.8: Cost/ECR versus time in a conventional PDP.

estimation method [7]. The ABC system is a helpful tool for engineers to assess the results of different design options on product cost [98].

3.4 Virtual Engineering

The conventional product development process makes use of a design-build-test philosophy. All the product assessments, in terms of performance and reliability, rely heavily on physical tests, which imply the manufacturing of prototypes and a time-consuming experimental campaign. Manufacturing prototypes typically involves, for a very small amount of production volume, the planning of the fabrication processes and fixtures and tooling. This process, especially when design changes are needed to correct issues found during the testing phase, can be expensive and long [104].

A big issue of the conventional PDP is that design and manufacturing tend to be disconnected. Manufacturing problems typically appear when the design is concluded, and tests have been executed. Indeed, product manufacturability is not taken into consideration during the design phases. Issues correlated to the manufacturing operations are found too late to be resolved. As consequence, more fabrication operations or reworks are needed, leading to higher product price [51].

Therefore, the PDP tends to be lengthy, expensive and product quality is often jeopardized to avoid additional delay. In Fig. 3.8 is reported the correlation that exists between cost and engineering change requests (ECRs).

It is known that the design phase weights for only the 8 % on the product budget but it is responsible for the 80 % of the lifetime product cost [6].
Today's global markets are asking always more to design new product of better quality, at lower cost and with reduced lead-time. Therefore, lots of approaches have been developed over the years to improve product development process.
A part of these innovative approaches is along the line of virtual prototyping (VP). VP is a method based on simulations that aid engineers to reach a deeper understanding of product behavior and to take more informed design decisions in a virtual environment. The virtual environment is a computational framework in which all the product properties in terms of geometry and physical aspects are properly represented and simulated [85].
Even though, numerous strategies have been developed to improve the design process and successful applications have been reported; companies at large are not exploiting the full advantages offered by these new paradigms. The main reason is that small and mid-size companies do not have proper competences and resources.
The using of virtual tools leads to a new design paradigm: e-Design. It is a combination of virtual and physical prototyping along with a systematic and quantitative approach for the decision-making process. It can also be seen as the simple implementation of the concepts typical of the concurrent engineering. The paradigm makes use also of design for manufacturability (DFM), design for manufacturing and assembly (DFMA), and manufacturing cost estimates theories .
Thanks to the intensive knowledge captured by virtual analyses the design paradox can be broken (as shown in Fig. 3.9(a)) and more informed design decisions can be made. Moreover, the cost and the time of the design process can be reduced, since even more physical tests can be replaced by virtual analyses. This paradigm is able to modify the cost and ECR distributions throughout the PDP according the Fig. 3.9(b).
An effective virtual environment can be build combining together various tools such as computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM). Tool integration is at the base to create a powerful virtual design framework [88].
Three are the main concepts on which e-Design is founded:

1. Exploiting virtual prototyping to bring consideration about product performance, quality and manufacturing cost in the early phases of the design

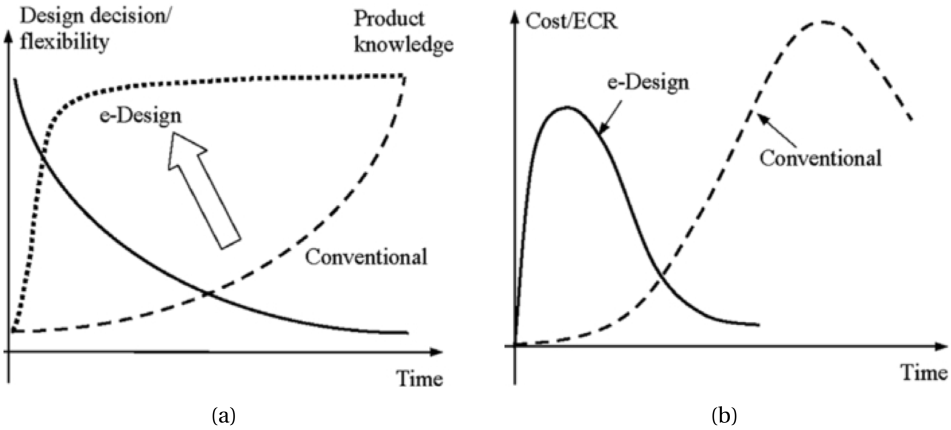


Figure 3.9: (a) Cost/ECR versus e-Design PDP time; (b) product knowledge versus e-Design PDP time

process;

2. Design decisions should be made through quantitative assessments for both preliminary and detailed design;

3. Making use of rapid prototyping techniques to fabricate prototypes for tests and design validation.

In e-Design, the product is modeled by design engineer through a solid model using CAD tools. The first product concept is typically achieved exploiting the experience and expertise of designer along with data about past projects. It is highly desirable to capture and formalize this kind of knowledge to support design decisions. As discussed earlier, KBE is a very helpful and valid approach to improve the decision-making process. Moreover, KBE integrated with a CAD tool can be capable to automatically generate a solid model of the initial concept that can be used for the downstream virtual analyses. The CAD model is typically parametrized to enable engineers to explore design alternatives and trade-offs. This CAD parametrization is reached defining geometrical dimensions of the parts and by identifying relationships between dimension. Through this parametric model, changes can be made simply by modifying a few dimensional values. Performance, reliability and manufacturing cost of the product can then be simulated at the same time. All the achieved results are brought together to be analyzed by a cross-functional team. The product designed in this virtual environment can then be manufactured by rapid prototyping and tested. The utilization of virtual prototyping does not eliminate the necessity for physical tests but only minimize it. Indeed, every virtual model needs to be validated through physical experiments. VP is able to accommodate in an easier way, without high cost and delay, the ECR. Moreover, virtual analyses reduce unexpected design defects minimizing the necessity for design modifications. The manufacturing process is also made smoother since it has been planned and simulated. A great amount of software tools is available on the market that provide a suite integrating CAD/CAM/CAE capabilities.

3.4.1 Product modeling techniques

One of the biggest problems in e-Design is the choice of best way to represent a physical problem in a virtual environment. How can I model, in the most possible accurate way, a physical problem? Traditionally, two different class of analysis techniques can be distinguished:

Analytical analysis they use mathematical solutions of the governing equation that are uniform in space (hypothesis of homogeneous medium) and steady over the time (hypothesis of stationarity of the phenomenon).

Numerical analysis they solve the differential governing equations using different methods of discretization with non-uniform properties and irregular geometries. They can take into account the non-stationarity of the phenomenon and the presence of a heterogeneous system.

Each of these methods present pro and cons. These pro and cons must be carefully analyzed to choose the most suitable modeling strategy. Every product development process will have its own circumstances and requirements that will affect the choice. Typically, it is mainly influenced by schedule, cost and design.

Analytical analysis

The analytical analysis put more emphasis on data coming from physical experimental tests rather than analysis. First, handmade calculations are performed exploiting the basic theories and laws of mechanics, thermodynamics (heat transfer), fluid mechanics, electromagnetism, etc. A proper safety margin is always applied to the reached solution. Typically, the safety factor to be applied have to be sizeable to ensure conformance to design requirements. According to the

achieved results the solution can be refined/developed, and prototypes fabricated. The initial design will be validated, while subsequent experimental tests may show further area of improvement.
The main advantages of an analytical approach are that it is fast and relatively inexpensive. Moreover, the prototypes are usually remarkably representative of final product and an analytical approach provides validation of design from real hardware. However, to make possible the representation of reality in an analytical way, lots of simplifications to geometry, systems, etc., are needed. A great issue is related to the fact that prototyping often has to be outsourced, risking losing the scheduled development.

Numerical analysis

Numerical analysis is that discipline, of applied mathematics, which studies the practical resolution of mathematical problems through stable and efficient algorithms. This science is both theoretical and experimental, in the sense that it is not based only on axioms, theorems and rigorous demonstrations, but also on empirical data. The solution calculated by any numerical algorithm is always an approximation of the real solution.
Numerical analysis algorithms are implemented through programming languages within numerical software, and often adapted to the characteristics of particular computing environment. Numerical software are divided into:

- Libraries for programmers (NetLib, NAG, GNU, Scientific Library, ...);
- Interactive environments to solve problems of mathematics and computational sciences (Mathematica, Matlab, GNU Octave, ...);
- Applications to solve problems in particular areas, for example for engineering (CAE systems).

Different are the methods to solve engineering problems exploiting numerical analysis. The most common ones are:

FVM Finite Volume Method Numerical analysis using the finite volume method integrates the partial differential equations within a volume (domain) defined by the boundary conditions. The domain is divided into many elementary volumes of finite dimension; the smaller the size, the more the final solution will be precise, yet such volumes can never be infinitesimal. The relationships between two adjacent volumes are described by the integral equations of the analyzed problem. The finite volumes numerical analysis is very widespread for the solution of problems typical of computational fluid-dynamics. The partial differential equations describing the fluid-dynamic phenomena are usually solved by numerical techniques because of their non-linearity which makes analytical integration impossible. The finite-volume discretization of differential equations, involving the integral form of differential equations, automatically satisfies the laws of conservation of mass, energy and momentum. The analysis of a thermo-fluidynamic phenomenon begins with the creation of the geometric model and then continues with the construction of the calculation grid (mesh) and with the choice of the physical models and the boundary conditions. After building and creating the mesh, the CFD solver performs the calculations and displays the results in output [70].

FEM Finite Element Method The finite element method is a discretization procedure which, through the use of a mathematical model and numerical calculation techniques, makes it possible the study of particularly complex problems. The method can be applied both for the analysis of structures and for the investigation of problems of heat transmission, fluid dynamics, acoustics and others, possibly coupled to each other. As regards the mechanics of structures, elastic linear problems can be tackled, but also problems of non-linear elasticity, plasticity and viscoplasticity, stable, stationary, dynamic and even impulsive mechanics problems. Therefore, with the Finite Elements Method is possible to solve the problem of determining the stress and deformation state in elements under load conditions for which the analytical solution cannot be found or obtained. It is possible to discretize the continuous, which has infinite degrees of freedom, with a set of elements of finite dimensions, interconnected among each other in predefined points (nodes). A structural analysis with finite elements primarily involves the subdivision of the structure (or body) into elements. The various elements interact with each other and with the terrain (i.e. with the surrounding world) only in a finite number of points, called nodes. On each element the displacement field is expressed as a function of a certain number of parameters (called degrees of freedom), which usually coincide with the components of displacement of the nodes. From the modeling of

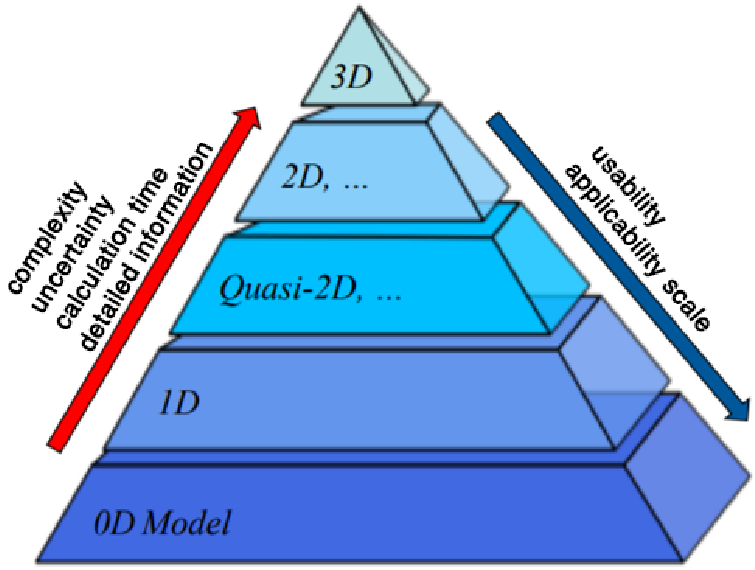


Figure 3.10: Applicability of the different model spatial domain.

the displacement field descends the field of deformations in the element. While, the modeling of the field of deformations determines the field of stresses. The solution to the structural problem provided by the FEM is, in general, only an approximation of the exact solution [113].

Before choosing the most suitable algorithm, engineers have to make a choice on the type of analysis to be performed, i.e. which dimensional domain should be considered [85]. This choice greatly affects the calculation time of the simulation since obviously larger spatial dimensions will certainly lead to a number of higher finite elements and therefore to longer calculation times. A 3D solid model will be more consuming than a 3D shell model or 2D model (as shown in Fig. 3.10). Numerical analysis is able to support the investigation of complex geometry. It is important to highlight that, as the intricacy of the problems grows, the effort to reach a solution, in term of computational resources and time, increase exponentially. These techniques enable engineers to solve for non-linear, non-steady state and dynamic problems. They allow to reach a comprehensive understanding of the system, providing specific and detailed values of results as they vary across the product. They are the most suitable tool to be used to perform design optimization studies. However, this approach of analysis presents some drawbacks. Indeed, typically, the software and hardware needed to perform numerical analyses have high procurement costs. Moreover, they are very complex tools to be used and skilled personal is needed [27]. Another issue is related to the fact that it often has to be outsourced, risking to lose the scheduled development. Another aspect to which attention must be paid is the analysis of the results. A mathematically correct result does not imply that it is also physically correct. In fact, simulation software solve approximate differential equations and stop when they converge, i.e. when they are mathematically acceptable. It is up to the user to understand if the result is correct also from a physical point of view. Simulating a problem without having any idea about the expected results can lead to serious errors. For this reason, it is always necessary to compare the results of a numerical model with those obtained from experimental tests [11]. Oftentimes simplifications to geometries, systems, etc. have to be made to facilitate analysis.

Chapter 4

Materials and method

This chapters describes the developed framework. As yet stated in the previous chapters, the aim of the proposed methodological approach is to support the design and multi-objective optimization of ETO products. The multi-objective optimization strategy involves the minimization of costs related to manufacturing and assembly phases while maximizing product performance. To achieve these results different methods and tools have been used and integrated. In particular, design optimization techniques along with product configuration tools (knowledge-based design), costs estimation and performance assessment methods have been exploited. The framework, that will be described, is based on three optimization levels. The first is used during the preliminary design phase when a company receives a request for proposal. Here, little information on the order is available, and time to formulate an offer is limited. Thus, parametric cost models and simplified 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 3D geometries and advanced parametric cost models are used in the optimization loop, which presents a restricted problem domain. In the last phase involving detailed design, a full 3-D CAD model is generated, and specific numerical simulations are performed. Cost estimations, given high levels of detail considered, are analytic and are performed using dedicated software.

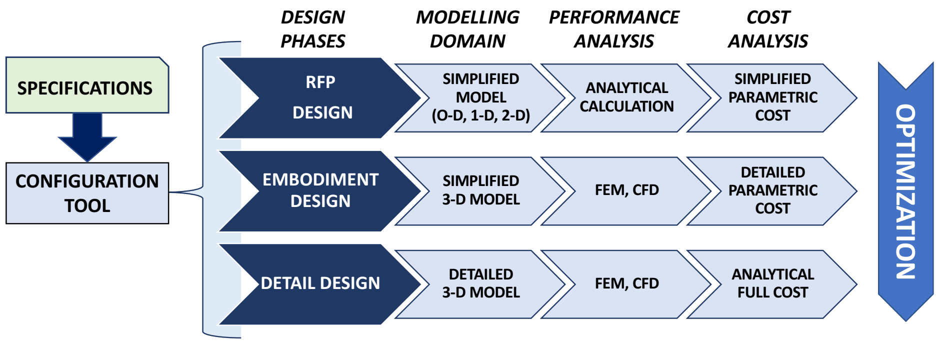


Figure 4.1: Illustration of proposed method.

4.1 Sequential optimization approach

The methodological approach is designed to support the design of modular products from the early design phase to the detailed design stage. Even though the case studies, that will be presented in the next chapters, are focused on oil and gas systems, the approach is also applicable to different types of ETO items. As discussed previously, the design of ETO products begins with the RFP phase. In this stage, engineers develop a project draft in 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, in accordance with what was described by Pahl et al. [44]: i) conceptual design, ii) embodiment design and iii) detail design (engineering).

Objective functions focus on performance enhancement and cost reduction. Performance enhancement is an important issue because it may impact on material costs, transport, and handling [62]. Cost reduction is another important issue related to the design of all kind of systems, as it directly increments the competitiveness and profits of an ETO producer [5]. Regarding the proposed design approach, MOO (Multi-Object Optimization) analysis is common to each design level; however, methods and tools used vary and are described in the following sections as highlighted in Fig. 4.1.

While Fig. 4.1 describes the design optimization approach, which is applied at each design level, the workflows illustrated in Fig. 4.2, Fig. 4.3 and Fig. 4.4 show interactions occurring between each optimization level during the design phases. The input of the proposed approach concerns specifications of the ETO product

to be engineered. Therefore, input data are related to geometrical dimensions, constraints, boundary conditions and standards and regulations to be applied. Boundary conditions and applied loading forces are the same for each level of the proposed design optimization.
As stated above, the proposed approach is focused on an MOO analysis for the design of modularized ETO products such as oil and gas systems. Such ETO products require the use of configuration tools to perform design activities [61, 32, 96], limiting efforts and costs involved in early design phases. The design methodology analyzed in this thesis considers a configuration process as highlighted in Fig. 4.1. The configuration process is designed to develop CAD models with related a 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., respectively 1-D/2-D, simplified 3-D and detailed 3-D solids for the conceptual, embodiment and detailed design phases).
The optimization process is designed to define the optimum configuration of design variables (e.g., height, thickness, length etc.) based on three different levels of geometrical detail. While the first optimization level is based on a 1-D/2-D model, the second one is based on a 3-D simplified model. Finally, the third level involves detail design where simulations and analysis are based on 3-D solid models. The first step aims to define the quantity of design variables that optimizes the systems. This result is further optimized in the second stage. During the second MOO stage, some design variables may be fixed based on the first stage. Therefore, the second stage of MOO refines the optimization defining the values for the remaining design variables. The third stage is focused on detail simulations and calculations used to release the engineered design. The following sections describe the design approach used in each MOO stage.

4.2 Product configuration

This section describes the operation of the product configuration tool that is how it interacts with the knowledge-base and the use-case design process. The goal of this tool is to guide the design engineer towards the modeling of the product that he/she wants to configure. It allows the parts selection and the boundary conditions definition to reproduce as faithfully as possible the real scenario. The parts can be selected from appropriate menus that show data necessary to describe

their technical characteristics. The generated output is sent to the simulation tool and it allows the reconstruction of the product's behavior.
The principal characteristic of the configuration tool is to facilitate and speed up the process of the scenario definition. In fact, all data could be directly managed in the simulation tool, but this would require the knowledge of programming language and longer times for the data entry. For this purpose, in the configuration tool, the user should find a user-friendly interface and he/she should have the possibility to display the information at different levels of detail. Furthermore, the configuration tool should offer the opportunity to use innovative features that perform the auto filling of some data. They are very useful when a user does not know some parameters or for fast simulations that do not require a high results accuracy (e.g. simulation for statistical evaluation, simplified simulation for inexperienced users). The configuration tool is a knowledge-based tool and it is linked with the knowledge gained during the processes of data research and elaboration where there were defined the rules that identify the links between the considered parameters. The configurator should possess a simple user interface that contains the parameters related to the product, the geographical area, the parts to configure and the standards and client's requests to follow. In an easy way, the user can define basic parameters that already allow defining an average design configuration. From these simple input data, the configuration tool generates an automatic compiling of the other sections in which all devices and related data involved in the user scenario are presented in detail. Before the simulation, the user can decide to modify personally each single parameter created or to leave those inserted automatically, but also to activate parts that were not selected.
Once the configuration phase is completed, it is possible to generate the use scenario through an output file readable by simulation tool. The list of information contained in the output file is summarized below:

- The selected parts and their technical specifications;
- The user habits and characteristics (e.g. how he/she uses such systems);
- The links between the selected parts (e.g. connections, interfaces, etc.);
- The external parameters;
- The simulation's horizon of time.

The Configuration tool is a typical configurator to define a preliminary system design, including the definition of a product design to be optimized. Generally, product configurators have been proved to be very effective systems to improve competitiveness of ETO companies. These tools are knowledge-based systems (KBSs) that "supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined" [54].

The Configuration tool provides design rules formalized from experts' interviews and past projects. The formalization can be reached through a knowledge classification and elicitation. The needed knowledge to design a product can be mainly classified in four categories: configuration, geometry, performance and normative. All these aspects equally contribute to the formulation of a preliminary design. The knowledge related to relations between the various systems comes from the designers past experience. This is a tacit knowledge and therefore it is difficult to be described analyzing best practices and rules.

The configuration domain of a system gathers all the information related to technical specifications, client requirements, cost targets, installation site, concept solutions etc. It contains rules for components design, configuration, and selection. These rules can be retrieved analyzing experts' practices and data.

The geometry knowledge concerns all the geometrical specifications and related design rules. These specifications are represented, considering for example an Oil & Gas plant, by information about the available plant footprint (that defines the maximum plant dimensions), equipment and components sizes and position of systems and obstacles in the plant. Design rules allows to check interference between the parts, to define connections between the various elements and to create a general arrangement of the plant. These rules aim to guarantee a configuration that allows the proper functioning of a system respecting the safety regulations. All the information elicited by engineers and technical workers experience have to be formalized into geometrical formulas and rules.

The knowledge about performance is a very important issue as it allows to provide an assessment about the quality of the reached design. Assessment is an integral part of design process, as it determines whether or not the aims of a project are being met. It affects decisions about all the design choices. Engineers need to know not only if the design requirements are achieved, but also how good is their solution to provide a more competitive bid. To evaluate system's performances, a mix of theoretical and empirical approaches can be exploited. This knowledge

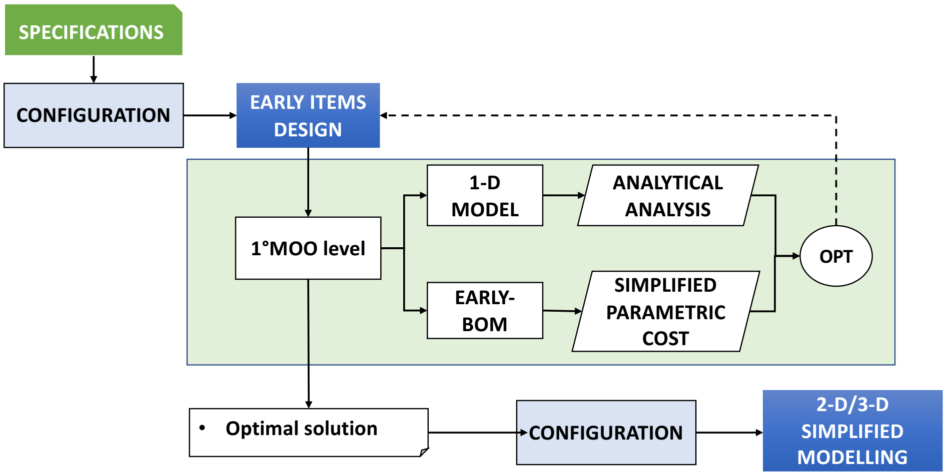


Figure 4.2: Illustration of I step of the proposed method.

can be formalized through formulas and corrective factors.
Norms and standards constitute the basis to engineer a new system able to guarantee a safe installation and functioning. Generally, this kind of knowledge is easily retrievable and formalizable. Indeed, the various regulations establish design criteria and constraints in a pure analytical way. However, a confrontation with experts have to be performed to provide a correct implementation of the design rules within the Configuration tool. This knowledge is binding, the other domains must adapt their indications to encounter the requests coming from technical standards.

4.3 Multi-objective optimization steps

4.3.1 I optimization level

The first design stage is concurrent with the RFP phase (Fig. 4.2). In this phase, a preliminary design should be developed and optimized. The proposed preliminary design method employs a 1-D/2-D model in which the product to be studied is described by a simplified model (Fig. 4.2).
This first optimization phase is focused on the analytical analysis of a 1-D/2-D model, which can be solved by applying mathematical equations. This simplified approach analyzes the product guaranteeing efficient calculation (faster than a 3-D analysis). For example, as it was be done for the case study presented in the next section, a MATLAB® calculation tool may be developed to solve the stress

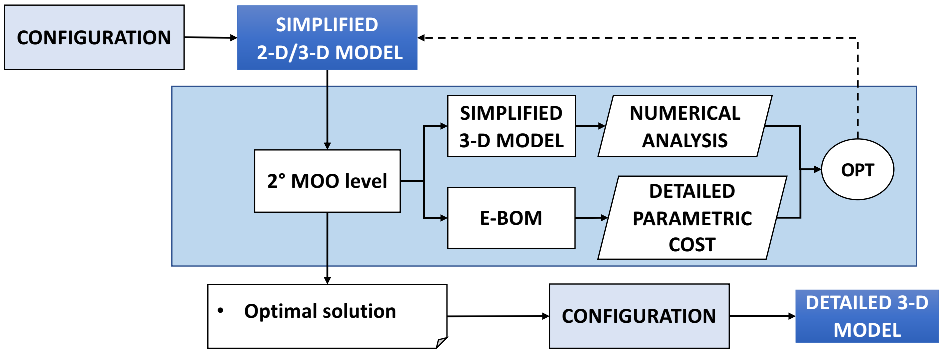


Figure 4.3: Illustration of II step of the proposed method.

state of a simplified 1-D model. This tool could perform a structural analysis based on an analytical approach (lumped parameters model).

The cost analysis approach related to this model is based on a simplified parametric approach that considers few parameters such as the number of items involved, parts dimensions and weights etc. At this level, a simplified parametric cost is calculated based only on the product BOM.

The proposed optimization analysis approach is performed using an optimization tool that describes the geometrical parameters of each item to achieve a configuration with a reduced cost and enhanced performance. The objective function is evaluated using the analytical model for performance assessments and the parametric model for cost evaluation. In a preliminary phase, the output is a simplified design of the product specifying the number of modular items to be involved and the main technical details of each item. The quantity of items and their dimensions 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. Some design variables can be defined in this phase, while others can be also 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 design variables. This is important in limiting computational time needed to simulate design solutions generated during the embodiment design stage.

4.3.2 II optimization level

The second stage of design focuses on the optimization of a simplified 3-D model (Fig. 4.3). An example of simplified modelling is the representation of a duct item by a shell entity such as a cylindrical surface, reinforcements and flanges can be

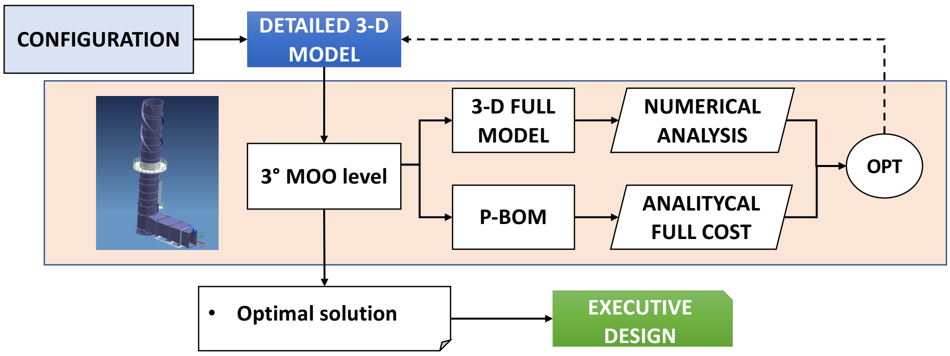


Figure 4.4: Illustration of III step of the proposed method.

modeled as planar surfaces. This second MOO stage occurs after the RFP phase and refers to a product's embodiment design. Performance analyses are based on numerical simulations that calculates resulting response of the simplified 3D model.

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 design variables can be simplified from the first stage to the second stage. From the second MOO stage an optimized value for each variable is determined to reduce costs and enhance product performance using a detailed parametric cost approach and numerical simulations.

Here manufacturing cost estimation follows a detailed parametric approach due to the availability of more detailed product-related information with related features. The values of design variables are defined by the product configurator. In this stage one can measure costs more specifically than before due to the availability of information allowing one to consider the manufacturing process of each component.

4.3.3 III optimization level

The third stage of the design of ETO products involves detailed design where the output is the executive project (Figure 4). 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 MOO. MOO focuses specific features of the 3-D full model to determine the executive design. For example, design optimization can be used in studies of temperature profiles and structural behaviors observed at specific points. Moreover, in this stage, engineers simulate the overall product via an FEM analysis. In this phase, FEM simulation differs from that executed in the second MOO stage, as it is based on a full 3-D geometry with a solid mesh. Therefore, the cost phase of detailed design is based on an analysis of a 3-D geometry related to the full assembly model of the product. The costing tool employed can read geometrical parameters of 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 final manufacturing costs.

4.4 Cost analysis

According to the presented literature review, four different cost estimation approaches are available. In reference to their characteristics, in the context of this thesis, a simplified parametric method for the first optimization stage in which the product is simplified with a 1-D/2-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 are proposed. 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 cost progression. Indeed, a standard cost breakdown that remains the same during different design stages is recommended for the monitoring of a product's cost history. Using this approach engineers can control 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. Cost items considered for the estimation of a system are as follows:

Material items the cost of raw materials, including commercial items (e.g., screws, nuts, pins, etc.) and customized parts (e.g., sheet metals, beams, supports, flanges, etc.);

Manufacturing items costs to obtain a final product from the material (e.g., lasers, oxyacetylene and saw cutting, bending, calendering, drilling, milling, etc.);

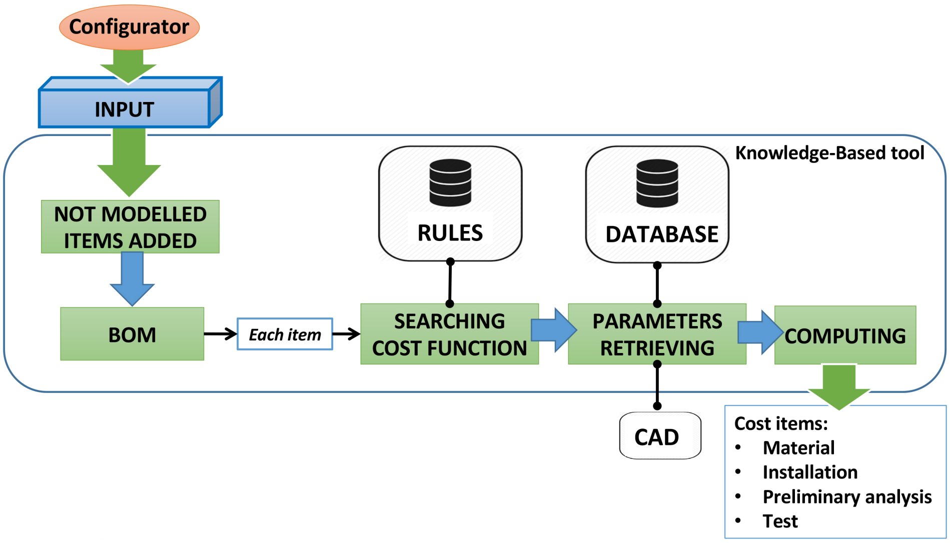


Figure 4.5: Illustration of parametric cost estimation.

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 semi-finished components;

Non-Destructive Testing (NDT) costs for controlling parts or assembly features, for example, checking weldings through the use of liquid penetrant technologies;

Assembly costs necessary to assemble each component based on the cost of positioning and welding parts together.

4.4.1 Parametric cost estimation

The simplified parametric cost models are based on configuration parameters used in the conceptual design phase (e.g., the diameter, thickness, material, length, number of items etc.). This cost analysis generates a value for an entire system 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 product due to a lack of available information (e.g., number of stiffeners, flange dimensions, etc.).
The raw material cost is mainly determined from the weights of parts, scraps and other components such as stiffeners and flanges. The manufacturing cost may

be determined from a reference table citing for example diameters, thicknesses, lengths and 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 diameters and lengths considered. This cost item is measured using the same approach applied to determine the manufacturing cost, as it is determined from a reference table. The NDT cost can be modeled as a percentage of the assembly cost, as it is mainly needed to test assembly features such as weldings. Logistics costs are shaped by the overall weight because they refer to the movement of components across the shop floor. The parametric method used to determine cost items is based on configuration features, 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 system. Cost calculation equations also consider additional parameters relative to manufacturing processes required to realize the components of a product. Each parameter is shaped by one or more variables. For instance, the time needed to drill a hole may be shaped by the hole diameter, depth and material used. For such an example, the drill time may be obtained by collecting and analyzing drill times determined from workshops, from the literature or from analytical cost estimation software tools.

Assembly operations involve, for example, welding the casing with stiffeners, flanges and relative stiffeners. Logistics costs relative to the transport of parts between production departments may be computed by multiplying the overall weight of a product by a unit cost specific to the workshop in which assembly is realized. NDT test costs used to control weldings may be seen as the product of the welding length and unit cost.

The parametric approach can be implemented in a knowledge-based tool containing a set of rules and algorithms for the cost calculation. Fig. 4.5 shows the implemented approach for the cost estimation of each component. The first step for calculating the cost consists in analyzing the input data (coming from the configuration tool) and adding those components not modelled by the configuration tool. This is required for getting the complete description of a system. The output of this first step is the Bill of Material. The second step consists in searching the cost function from a database of rules, which have to be implemented before at the time of the research. The third step consists in retrieving the calculation

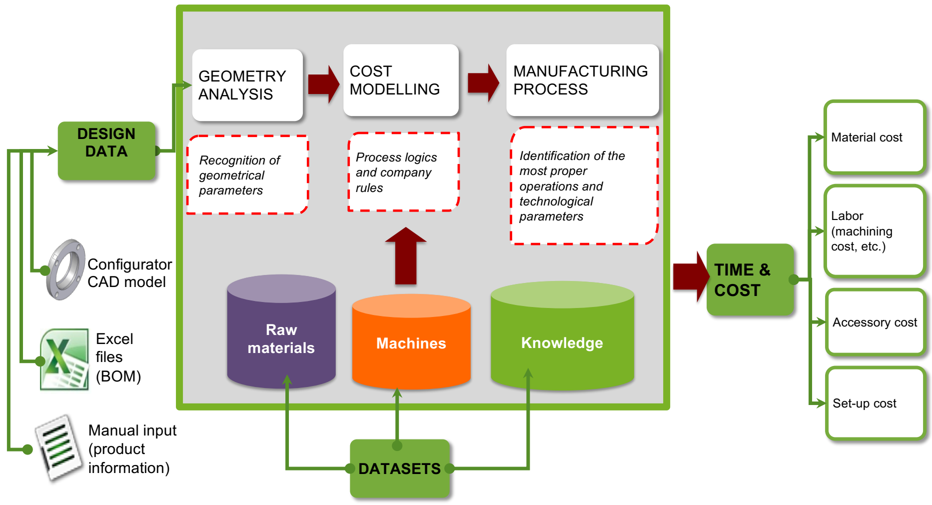


Figure 4.6: Illustration of analytical cost estimation.

parameters from the database and the CAD model generated by the configurator, which are the specific cost of the commercial items, the time for each operation (cutting, installation, etc.) etc. The fourth step is the computing phase, where each cost item is resolved for each component. In particular, Fig. 4.5 highlights the considered cost items.

4.4.2 Analytical cost estimation

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 use of commercial tools is suggested. Among tools available, the choice of the most suitable one should be made considering:

- the availability of manufacturing processes used to develop components;
- availability of a module for customizing cost models;
- the availability of 3-D feature recognition algorithms for automatically computing 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 a cost estimation tool to extract a Bill of Materials, characteristic dimensions, etc. The software program then identifies raw materials, manufacturing processes and related costs of each component. Once each component has been analyzed, the tool determines assembly operations (welding, NDT testing and logistics for a fabricated tube).
For 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 should be initially customized to manage commercial items available within a BoM (such components 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 of related parameters should be marginally customized to specify 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 has to be developed for collecting cost data according to the breakdown defined in the first optimization stage. In Fig. 4.6 is reported the process to achieve an analytical calculation by the software tool used in the case study.

4.5 Performance evaluation

Performance assessment is crucial to determine the best design configuration. As it was highlighted in the previous chapter, analytical calculations as well as numerical analysis are valid methods to assess performance of a system. In the proposed framework both numerical analysis and analytical calculations are employed.
Analytical calculations should be preferred in the first design level since the evaluation of the product performances using numerical analysis, due to the complexity of the numerical codes, requires a great deal of time to perform an evaluation. Additionally, when the problem domain is very large (e.g. heavy machinery, civil large structures, etc.) the time increases rapidly making the performance assessment not feasible within the timeframe requested by the customer in the RFP. Therefore, to simplify and accelerate the identification of the optimal product configuration and to increase the product quality reducing

the time-to-market (TMT), analytical calculations have been exploited to assess performance during the RFP. The accuracy of the results provided by this method is not high. However, in this phase, more than accuracy, results robustness is requested.
As the design progresses, the degree of accuracy required for the results grows. Therefore, to follow the request for a higher accuracy, numerical calculation is exploited during the embodiment and detail design phases. In these phases the time-related issues are partially solved since the research domain is restricted in the previous phase, less design configurations have to be assessed.
Analytical calculations as well as numerical simulations can be carried-out either implementing the relative procedure in built-in-house software tools or exploiting dedicated commercial tools.
The performance evaluation tools allow running the operating scenario defined in the configuration tool. They contain the virtual models of real system and they are able to reproduce its operation based on input parameters set in the previous phase. Their structure is designed to reproduce the conditions of the environment in which the system is located, so they consider the relationships that exist between system and how its operation is affected by the external environment and client preferences. The simulation tools are able to assess the performance of the product under different scenario. The simulation process involves an initial data import and recognition of products and systems that the user has selected in the configuration tool. Then, an iterative process begins performing the calculation in static or dynamic regime of the values relative to the selected scenario within the chosen horizon of time. After this procedure, the tool produces results report including performance assessments and the relative graphs.

4.6 Optimization procedure

The optimization process represents one of the main actors of the proposed framework as it allows to solve the multi-objective optimization problem in a simple and efficient way. In this thesis, the multi-objective approach has been chosen because considered more convenient and appropriate compared to the single-objective one. In fact, engineers, during the PDP, have to take into account, simultaneously, different criteria, such as performance, costs, reliability etc. Some of these objectives are conflicting.

The proposed optimization process includes three phases: optimization problem formulation, optimization, decision-making.
The formulation of the optimization problem is a key point. Indeed, an inadequate formulation typically leads to wrong conclusions. The first step is always to study and understand what the design problem is, examining deeply all the background project information. This examination should be performed from the perspective of optimization so that the following tasks could be easily managed. In defining the optimization problem, designers must choose: the objectives to achieve, the variables to investigate and the constrains to satisfy.
A clear and reasonable definition of the objectives of the analysis is a very crucial part of the all methodology as it drives the choice of the design variables and the identification of the constraints.
Once the objectives are soundly identified, it's necessary to proceed with the determination of the design (input) variables. The design variables are what the engineers can change to create a new design. Thicknesses, lengths, number of items are some examples. These variables are input for the simulation tool to calculate the output variables. The minimization or maximization of one or multiple output variables can define the optimization objectives.
In general, the response of a system may be affected by several parameters, but it is practically impossible to identify and study each minimum contribution. Therefore, in order to contain the costs (computational and of resources) and to make the analysis more precise, the main task of the designer is to identify and choose the variables that most affect the system's performance. This selection, that requires a certain grade of expertise in matter of mathematical and engineering science, can be performed after a sensitivity analysis [106] or can be derived from a comprehensive analysis of the system. To define design options two different kinds of variables are used: continuous and discrete. For example, considering a photovoltaic module, its peak power is a discrete variable (depending on the commercial availability) while the tilt angle could be a continuous variable.
Once the variables are chosen, it is necessary to proceed with the definition of their constraints, ranges and steps. Designers have to manage two different kind of constraints: box constraints (continuous variables) and selection constraints (discrete variables). Box constraints give the boundary values while selection constraints a predefined group of possible choices. To create a box constraint, engineers have to define the upper and lower limit of a continuous variable,

while, to define a selection constraint, they have to specify a set of alternative values for a discrete variable. Step is the minimum change that can affect design variable. Even if theoretically, the step can be as small as what the optimization is capable to accept, it's important to consider the reality and to choose a proper value. For example, to use 1 [mm] as step for the thickness of a duct insulation is totally unrealistic while a step of 10 [mm] looks like to be much more convenient. Moreover, the use of large steps allows to save CPU resources.
After the problem formulation definition, in order to go on with the optimization, it is necessary to select or create an optimization tool. On the market different kind of optimization programs are available: modeFRONTIER®, iSIGHT®, ModelCenter®, etc. All of these software provide an optimization environment that offers a seamless coupling with third party engineering tools, enables the automation of the design simulation process and facilitates analytic decision-making. They all allow through their interface to establish the optimization work flow in a straightforward manner.
Once the workflow is created, the next step is represented by the selection of the most suitable optimization technique or algorithm to solve the optimization problem. In literature many optimization algorithms are presented.
Once the selection of a proper algorithm is performed, it is necessary to set the search control parameters: start point, step size and stopping criteria. According to Nguyen et al. [72] there are a great number of stopping criteria (which are mostly dependent on the corresponding optimization algorithms), but the most used criteria are:

- maximum number of generations, iterations, step size reductions;
- maximum optimization time;
- acceptable objective function (the objective function is equal to or smaller than a user-specified threshold);
- objective function convergence (changes of objective functions are smaller than a user-specified threshold);
- maximum number of equal cost function evaluations;
- population convergence (or independent variables convergence);
- gene convergence (in GAs).

At this point, to run the optimization, it is necessary to establish a link between the simulation and the optimization tool. As described in the research studies this connection can be created in different ways.
After the identification of design and output variables, the determination of constraints, ranges and steps, the definition of the work flow (with simulation tool coupling), and the selection of the optimization algorithm and settings, the optimization is ready to run. The optimization tool will take the design variables and call for the simulation tool. The results of the simulation will be transferred to the optimization tool that will draw out the defined output variables. The optimization algorithm will generate a different combination of input variables and will examine the outputs. This loop will be automatically iterated until the objectives or one of the stopping criteria will be met.
During the optimization phase, it is important to monitor convergence of the optimization and to detect errors which could occur during the entire process. It is essential to underline that a convergent optimization process does not necessarily mean that the global minimum/maximum has been found.
The optimization approach is similar for each stage. The main difference is rooted in the number of parameters involved, in the different ranges for design variables and in the use of different tools to solve objective functions. In fact, while the first stage considers a small number of geometrical 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 geometry, manufacturing, and assembly. Each optimization process starts with the definition of an initial population as a first set of values for variable parameters. The evaluation process is based on the calculation of objectives, on the evaluation of fitness, and on rankings to add solutions to the Pareto dominance value. The Pareto dominance value provides excellent solutions that are non-dominated, meaning that no point is superior among 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 one to evaluate different optimal solutions. Generally, in the mechanical sector, the genetic algorithms - GAs are the most used optimization algorithms [28]. These algorithms are widely used because they use a smart multi-search elitism approach that preserves excellent solutions without spurring premature convergence to local-optimal frontiers [103]. These algorithms, based on the Darwin's evolutionary theory, starting from

a random population of individuals that evolves from generation to generation, it performs a heuristic search that favors the areas of the search space where it is most probable to find optimal solutions.
Passing from the first to the second and then to the third optimization level, the ranges of value for the design variables to be analyzed may be limited and some design variables can be even eliminated. Indeed, if in the previous level of optimization all the best solutions fall into a narrow portion of the investigated domain, then, in the subsequent optimization analyzes the variable variation ranges will be restricted to that specific portion. Moreover, a design variable can be neglected in the next optimization levels, if it is highlighted to have no influence in determining the optimal configuration.

4.7 Decision-making process

The last step of the optimization process is the decision-making process: the analyst has to assess the results in order to find the optimal design. Usually, in multi-objective optimization problems, there is no single global solution but a number (even infinite) of *Pareto optimal solutions* [31] which provide a trade-off among the objectives. Each solution, being different from the other, will tend to sacrifice one or more objective functions in order to have a better response in others. Therefore, the designer, identified the Pareto front, in order to find the best solution, has to bring the optimization problem to a single-objective one through the definition of a composite function given by the weighted sum of the various objective functions:

$$F_{ws}(\vec{x}) = \sum_{i=1}^{k} w_i f_i(\vec{x}) \tag{4.1}$$

where $w_i \in [0,1]$ are the weight factors assigned to each objective. The engineer has the task to select appropriate values for weight factors according to the priorities of every objective. Once the composite function has been properly defined, its minimization will provide the optimal solution. Most of the commercial optimization software are embedded with decision-making tools that drives the designer toward the identification of the best solution.

Chapter 5

Case study: Chimney

The presented approach has been validated through two real case studies, thanks to the collaboration with a leading company in the Oil & Gas sector. The case presented in this chapter concerning the design of a modular steel tower. Specifically, an oil and gas self-bearing chimney used to carry and discharge exhaust gases from a GT for power generation is designed (shown in Fig. 5.1).

Generally, the design of this type of structure is guided by the CICIND - the Model Code for Steel Chimneys (CICIND (Organization) 1999) [34], 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 and height greater than 15 meters. Other standards must also be followed to define loads and assessment criteria. Standards to be used depend on where structures have to be erected. For example, for US territory, loads to be applied are described in ASCE 7-05 standard (American Society of Civil Engineers 2006) [4] while ANSI/AISC 360-10 standard (American Institute of Steel Construction 2010) [3] provides assessment criteria. Similarly, for Australian territory designers must follow AS1170 (Australian Standard 2011) [10] and AS4100 (Australian Standard 1998) [9].

5.1 Chimney description

Chimneys are composed of shell elements referred to as *stacks*. These consist externally in cylinder-welded steel sheets and represent the structural part of the chimney. The CICIND standards cite Fe360, Fe430, Fe510 or equivalents as raw materials used for steel chimneys [34]. Stainless steels are used only on customer

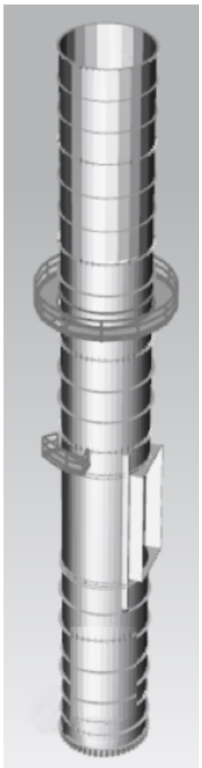
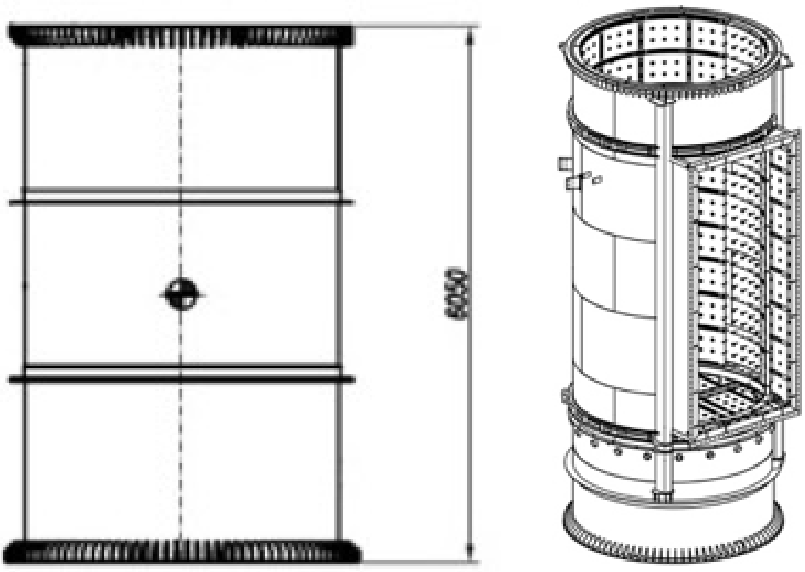


Figure 5.1: Geometry of the self-bearing chimney.

special request or in case of particular environmental conditions. Stacks are connected one another by flanges welded at the ends and are manufactured from welded shell plates of carbon steel. These chimneys are internally insulated with rock wool, or basalt wool, whose thickness generally varies between 100 mm and 150 mm. The insulation is kept in position through a system of floating panels (*internal cladding*) generally made of AISI409 and connected to the insulation with a series of pegs. The goal of the insulation is to guarantee a temperature of the outer casing of about 60 °C, in conditions of ambient temperature of 30 °C in the shade and with a wind of 1 $m\,s^{-1}$. However, this temperature is averaged on the external duct, indeed the distribution is not uniform since the pegs create a thermal bridge, where it can even reach 120 °C. The internal diameter of the stacks is defined by the so-called *gas path* and by necessary insulation levels. This is evaluated considering the type of machine, the outlet flue temperature, the outlet pressure, and imposing a speed of about 30 $m\,s^{-1}$ (35 $m\,s^{-1}$ max) for the exhaust gases. Considering the same typology of machine, the same diameter is generally used.



(a) (b)

Figure 5.2: a) Standard stack b) Stack base.

Stacks can be of different lengths and thicknesses and can have standard (commercial) or custom dimensions in accordance with design specifications. The standard component has a height of 6050 mm (shown in Fig. 5.2), derived by the commercial dimensions of metal sheets. However, it is possible to have components with lower height, by means of carpentry operations. Generally, the ducts at the upper and lower ends of the chimney have a non-standard height, as they are designed to respect the constraints about the total height. To limit vibrations and to stiffen the structure, stacks can include welded *L* shaped rings. The CICIND standards suggest that stiffeners should be positioned at a maximum distance of 9 times the outer diameter of the stack [34].

The most critical part of a chimney is the so-called *stack base* (shown in Fig. 5.2(b)), which serves as a point of connection to the horizontal duct and which includes a side opening (to allow the passage of gas) that weakens the structure. This connection is created by means of an anti-vibrating 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 bounded by the height of the horizontal duct. It includes an internal closure to drive exhaust gas to the upper part of a chimney. Ducts underneath the stack base do not require internal insulation.

On stacks located at the higher part of the chimney, it is possible to find aerodynamic stabilizers (shown in Fig. 5.1). The stabilizers are inserted in order to reduce the vibrations due to cross wind [34]. The chimney cross wind response is generated by the phenomenon of vortex shedding. It is known that when the wind flows around a circular body like a chimney, the boundary layer can be separated from the leeward side because of its excessive curvature. The wind separation leads to the periodic formation of alternating vortices, which stress the chimney with a periodic force transverse to the flow direction. The frequency of this stress can be assessed by the Strouhal number, equal to 0.2 for cylindrical bodies with undisturbed flow. This phenomenon is also known as Von Karman vortex street, and its occurrence depends on the Reynolds number, which is a function of chimney diameter and wind speed. The useful effect of three continuous helical fins has been demonstrated in many steel chimneys [90]. The radial width of the fins must be 10 % of the diameter, and the pitch should be five times the diameter of the chimney. These must be mounted on at least on a third of the total height. However, their presence generates a greater drag force than the wind, which is considered in structural analysis with a corrective coefficient. Aerodynamic stabilizers can not be used to reduce the effects of wind interference from chimneys or other nearby structures, in this case, damping devices mounted along the chimney must be used.
The CICIND standards describe the features of 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 of S355 steel or similar materials. The first step for the assembly is the construction of the concrete foundation with the anchor bolts, and then the fixing of the stack at the base with the bolts.
The chimney is erected by bolting the stacks on top of each other through the welded external flanges. The latter are reinforced by welding some trapezoidal elements called stiffeners, their number varies according to the diameter of the chimney and the height from the ground of the flanges. Generally, three stacks at the time are assembled on the ground, then they are lifted using lifting eyelets welded to the outer box or removable cruises. The eyelets are to be preferred because they are subjected to a less stringent regulation with respect to removable cruises. These chimneys are equipped with platforms and ladders to satisfy the maintenance operations and the control of exhaust gases. At the level of the main platform there is also a manual winch for lifting machinery.
During the preliminary design phase, system layouts and components are de-

Table 5.1: Main chimney design specifications and constraints.

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

fined to meet the customer's requirements. In this phase, different features such as inner chimney diameters or materials are addressed. Once the gas turbine is fixed, geometric and non-geometric 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 internal insulation levels.

In Tab. 5.1 specifications and design constraints for the chimney analyzed in this case study are reported.

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

5.2 Sequential design optimization framework

The methodological approach was applied to support the design of modular steel towers from the early design phase to the detailed design stage. Even though the presented case study is focused on chimneys for oil and gas systems, the approach can be easily applicable to different types of Engineering-to-Order products.

As discussed above, the design of ETO products begins with the RFP phase. In this stage, engineers develop a project draft in 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 preliminary design 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

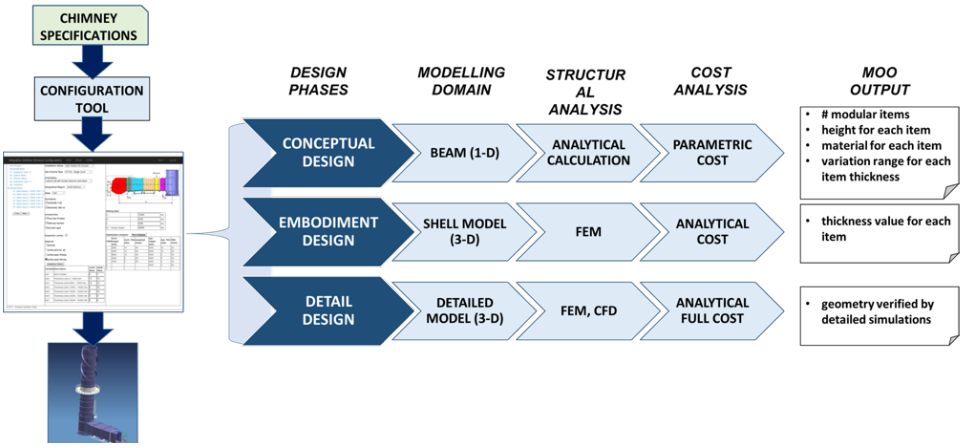


Figure 5.3: The proposed design methodology applied to the design of a modular steel tower.

an important issue because it impacts material costs, transport, and handling [62]. 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 [5]. Regarding the proposed design approach, MOO (Multi-Object Optimization) analysis is common to each design level; however, methods and tools used vary and are described in the following sections as highlighted in Fig. 5.3.

The input of the proposed workflow concerns specifications of the ETO product to be engineered. Therefore, input data are related to geometrical dimensions, constraints, gas turbine sizes, 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. Boundary conditions and applied loading forces are the same for each level of the proposed design optimization. Design loads are described in more detail in the following sections. Generally, loading conditions include the following: dead loads, live loads, wind load, seismic load, and operative pressure level.

As stated above, the proposed approach is focused on an 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 [61] [32], limiting efforts and costs involved in early design phases. The design methodology analyzed in this thesis considers a configuration process as highlighted in Fig. 5.3. The configuration process is designed to develop CAD models with related a bill of materials (BOM) used during the three stages of design optimization.

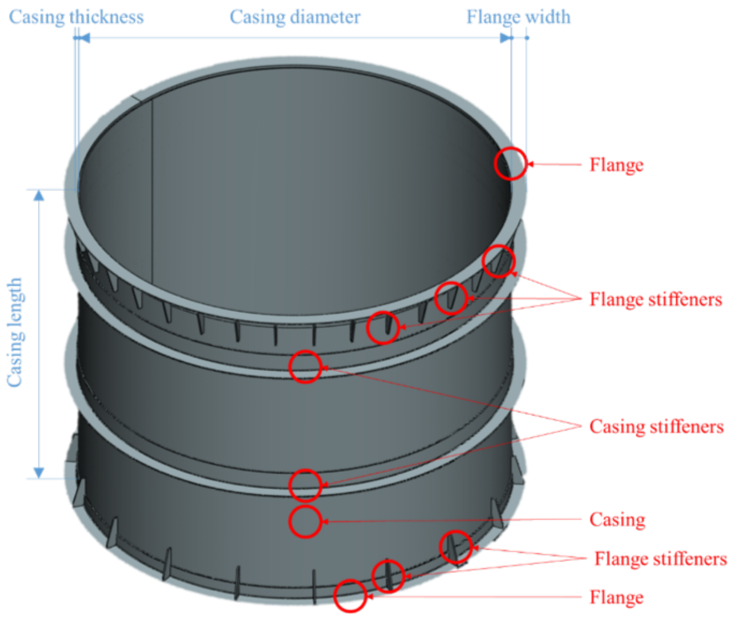


Figure 5.4: 3-D CAD model of a circular stack.

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., respectively 1-D and 3-D shells and detailed 3-D solids for the conceptual, embodiment and detailed design phases).

5.3 Chimney 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. The most important parameters considered for a duct are:

General parameters valid for every duct:

- **Inlet/outlet section shape** round, rectangular and square sections are available (tabulated value);
- **Section width** internal dimension of the section (i.e. diameter for round ducts, width for rectangular and square sections) (tabulated value);
- **Section height** internal dimension of the section (i.e. diameter for round ducts, height for rectangular and square sections) (tabulated value);

Length length of the duct (free value);

Thickness thickness of the sheet metal used for the construction of the duct (tabulated value);

Insulation thickness thickness of the insulating material (tabulated value);

Material construction material (tabulated value);

Flange dimension height of the flanges used for connecting two ducts (tabulated value);

Stiffening method method used for stiffening the duct (tabulated value).

Specific parameters only for specific product families:

Reduction factor value that determines the reduction between the inlet and outlet sections (valid for transition) (tabulated value);

Dimensions of the inlet section dimensions of the inlet duct connected to the chimney (valid for chimney stack base) (tabulated value).

It is worth noting that the ducts are parametric products, split in product families, and most of these parameters are tabulated (designer cannot select free values) and constrained each other. By way of example, in this thesis, a steel tower for GT chimneys is taken under consideration. The stacked tower consists of different shell elements; each element is composed of a fabricated circular tube (Fig. 5.4). 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 in shape and created from sheet metal.

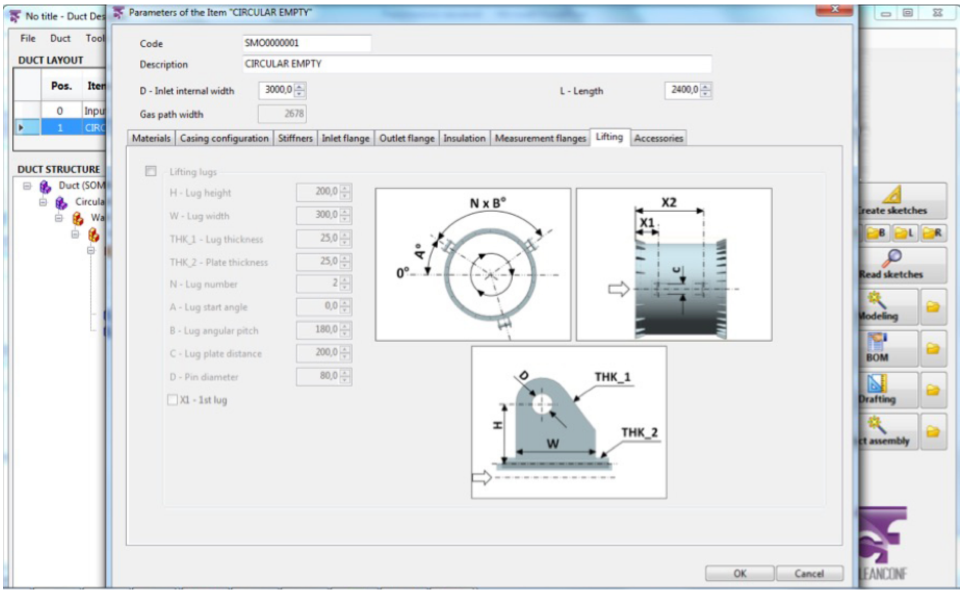


Figure 5.5: Screenshot of the implemented ducts configuration tool.

Characteristic features (dimensions, shapes and materials) of each component of a circular stack are determined according to configuration rules based on fundamental dimensions defined by a designer (Tab. 5.2). 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 fundamental dimensions, configuration rules allow one to determine all other dimensions.

A software tool has been developed providing a graphical interface and formalizing all the item object structure and configuration rules (the configuration rules can not be reported due to confidentiality problem). The system is linked to a modelling CAD kernel and a database where all the data are stored. The configuration tool was developed using the Microsoft VisualStudio.NET framework. Fig. 5.5 shows the windows-based user interface of the configuration tool. The tool is able to provide the complete list of parts (BOM), 3-D CAD models at various detail level, technical documentation (2-D drawings, manufacturing info, etc.), and all the geometrical and non-geometrical information needed for performance assessment.

Table 5.2: Characteristic features of a circular stack.

Parameter	Description	UoM	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	nput (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	-	=Integrer (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

5.4 Cost assessment

5.4.1 Parametric cost model

The simplified parametric cost models are based on configuration parameters used during the PDP (Tab. 5.2) (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. During the first design 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, flange dimensions, etc.). 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 casings, scraps and other components such as stiffeners and flanges:

$$\begin{aligned} MaterialCost = &\pi \cdot CasingDiameter \cdot CasingThickness \\ &\cdot CasingLength \cdot CasingMaterialDensity \\ &\cdot CasingMaterialUnitPrice \\ &\cdot \Big(1 + \frac{StiffenersFlangesWeightImpact}{100} \\ &+ \frac{CasingScrapeRate}{100}\Big) \end{aligned} \tag{5.1}$$

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 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 weldings:

$$NDTCost = AssemblyCost \cdot NDTCostPercentage \tag{5.2}$$

Logistics costs are shaped by the overall weight because they refer to the movement of components across the shop floor:

$$\begin{aligned} LogisticsCost = \Big(1 + &\frac{StiffenersFlangesWeightImpact}{100} \\ &+ \frac{CasingScrapeRate}{100}\Big) \\ &\cdot CasingWeight \cdot LogisticUnitCost \end{aligned} \tag{5.3}$$

The parametric method used to determine cost items is based on 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. Cost calculation equations also consider additional parameters relative to manufacturing processes required to realize the components of a stack. For each parameter, Tab. 5.3 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.

The casing consists of precut sheet metal (laser or oxyfuel cutting depending by the thickness and composition of material used) that is calendered and then welded to form a round tube. The raw material cost considers the cost required for cutting operations and scraps related to the cutting process. The scrap rate is a percentage based on the shape involved (sheet metals or beams). 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, length and diameter to achieve. The welding time is computed by dividing the welding length by the welding speed (as a function of welding dimensions, materials, geometries and types). Cost models for the other components (casing stiffeners, flanges and flange stiffeners) use similar equations.

Assembly operations involve welding the casing with stiffeners, flanges and relative stiffeners. Logistics 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 assembly is realized. NDT test costs used to control weldings are the product of the welding length and unit cost. Manufacturing cost models of each component are modeled according the equations reported in Tab. 5.4.

Table 5.3: Parameters used in cost calculation equations.

Parameter	Description	UoM	Source	Influencing parameters
CasingMaterialDensity	Density of the casing material	kg/m3	DB(Function)	CasingMaterial
CasingStiffenerMaterialDensity	Density of the casing stiffener material	kg/m3	DB(Function)	CasingStiffenerMaterial
FlangeMaterialDensity	Density of the flange material	kg/m3	DB(Function)	FlangeMaterial
FlangeStiffenerMaterialDensity	Density of the flange stiffener material	kg/m3	DB(Function)	FlangeStiffenerMaterial
CasingMaterialUnitPrice	Unit price of the casing material considering sheet metal cutting operations	€/kg	DB(Function)	CasingMaterial
CasingStiffenerUnitPrice	Unit price of the casing stiffener material considering sheet metal cutting operations	€/kg	DB(Function)	CasingStiffenerMaterial
FlangeMaterialUnitPrice	Unit price of the flange material considering saw cutting operations	€/kg	DB(Function)	FlangeMaterial

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FlangeStiffenerMaterialUnitPrice	Unit price of the flange stiffener material considering sheet metal cutting operations	€/kg	DB(Function)	FlangeStiffenerMaterial
CasingScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	DB(Function)	Shape
CasingStiffenerScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	DB(Function)	Diameter
StiffenersFlangesWeightImpact	Weight of flanges and stiffeners as a percentage of the casing weight	%	DB(Function)	Shape
FlangeScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	DB(Function)	Shape
FlangeStiffenerScrapRate	Percentage of scraps generated through sheet metal cutting operations	%	DB(Function)	Shape
SheetmetalCalenderingUnitTime	Time required to calendar sheet metal	Minutes	DB(Function)	Thickness Length Diameter

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BeamCalenderingUnitTime	Time required to calendar a beam	Minutes	DB(Function)	Thickness Length Diameter
WeldingSpeed	Manual welding speed	Mm/min	DB(Function)	Thickness Material Geometry (e.g.,butt weld, fillet weld, etc.) Welding type (e.g., continuous, intermittent, etc.)
DrilingUnitTime	Time required to drill a hole	Minutes	DB(Function)	Diameter Depth
SheetmetalCalenderingUnitCost	Unit cost of a sheet metal calendaring machine	€/hour	DB(Function)	Thickness Length Diameter
BeamCalenderingUnitCost	Unit cost of a beam calendaring machine	€/hour	DB(Function)	Thickness Length Diameter
WeldingUnitcost	Unit cost of a certified welder	€/hour	DB(Function)	Overall dimensions

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LogisticUnitCost	Unit cost of logistic activities executed on the shop floor	€/kg	DB(Function)	Workshop
NDTUnitCost	Unit cost of Non Destructive Testing	€/m	DB(Function)	Overall dimensions
NDTCostPercentage	Cost of Non Destructive Testing measured as a percentage of the assembly cost	%	DB(Function)	Constant
DrillingUnitCost	Unit cost of a drilling machine	€/hour	DB(Function)	Overall dimensions

Table 5.3: Parameters used in cost calculation equations.

Table 5.4: Parametric cost model equations for cylindrical stack.

Component	Cost model
Casing	$CasingWeight = (CasingDiameter \cdot \pi \cdot CasingLength \cdot CasingThickness) \cdot CasingMaterialDensity$ $CasingMaterialCost = CasingWeight \cdot (1 + CasingScrapeRate/100) \cdot CasingMaterialUnitPrice$ $CasingCalenderingCost = SheetmetalCalenderingUnitTime \cdot SheetmetalCalenderingUnitCost$ $CasingWeldingCost = CasingLength/WeldingSpeed \cdot WeldingUnitCost$ $CasingManufacturingCost = CasingWeldingCost + CasingCalenderingCost$ $CasingManufacturingCost = CasingWeldingCost + CasingCalenderingCost$
Casing stiffener	$CasingStiffenersWeight = (CasingStiffnerHeight + CasingStiffenerWidth - CasingStiffnerThickness) \cdot CasingStiffenerThickness \cdot \pi \cdot CasingDiameter \cdot CasingStiffenerMaterialDensity$ $CasingStiffenerMaterialCost = CasingStiffenerWeight \cdot (1 + CasingStiffenerScrapeRate/100) \cdot CasingStiffenerMaterialUnitPrice$ $CasingStiffenerCalenderingCost = BeamCalenderingUnitTime \cdot BeamCalenderingUnitCost$ $CasingStiffenerWeldingCost = (2 \cdot (CasingStiffenerHeight + CasingStiffenerWidht))/WSpeed \cdot WeldingUnitCost$ $CasingStiffenerManufacturingCost = CasingStiffenerCalenderingCost + CasingStiffenerWeldingCost$

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Flange	$FlangeWeight = (FlangeWidth + FlangeHeight - FlangeThickness) \cdot FlangeThickness \cdot \pi \cdot CasingDiameter \cdot FlangeMaterialDensity$ $FlangesMaterialCost = FlangesWeight \cdot (1 + FlangesScrapeRate/100) \cdot FlangeMaterialUnitPrice$ $FlangesCalenderingCost = BeamCalenderingUnitTime \cdot BeamCalenderingUnitCost$ $FlangesDrillingCost = DrillingUnitTime \cdot FlangeHolesQuantity \cdot DrillingUnitCost$ $FlangeWeldingCost = (2 \cdot (FlangeHeight + FlangeWidht))/WeldingSpeed \cdot WeldingUnitCost$ $FlangesManufCost = FlangesCalenderingCost + FlangesWeldCost + FlangeDrillCost$
Flange stiffener	$FlangeStiffenerWeight = ((FlangeStiffenerWidth + FlangeStiffenerHeight))/2 \cdot FlangeStiffenerThickness \cdot FlangeStiffenerMaterialDensity$ $FlangeStiffenersMaterialCost = FlangeStiffenerWeight \cdot (1 + FlangeStiffenerScrapeRate/100) \cdot FlangeStiffenerMaterialUnitPrice$
Fabricated tube	$CaseStiffWeld = (CasingDiameter \cdot \pi \cdot 2 \cdot CaseStiffQuantity)/WeldingSpeed \cdot WeldingUnitCost$ $FlangeStiffenersWelding = ((FlangeStiffenerWidth + FlangeStiffenerHeight) \cdot 2 \cdot FlangeStiffenersQuantity)/WeldingSpeed \cdot WeldingUnitCost$ $FlangeWelding = (CasingDiameter \cdot \pi \cdot 2 \cdot FlangesQuantity)/WeldingSpeed \cdot WeldingUnitCost$ $Logistic = (CaseWeight + CaseStiffWeight + FlangesWeight + FlangeStiffWeight) \cdot LogUCost$ $NDT = TotWeldingLength \cdot NDTUnitCost$

Table 5.4: Parameters used in cost calculation equations.

5.4.2 Analytical cost model

The cost estimation method used in the third optimization stage involves analytically evaluating the manufacturing process from a 3-D CAD model. As it was highlighted in the previous chapter, several software tools can be used for this purpose and the use of commercial tools is suggested. Among tools available, LeanCOST® by Hyperlean srl® has been choose as the most suitable for the analysis to be carried-out. LeanCOST® is a commercial cost estimation tool that adopt an analytical approach. It has the great capability to be directly integrated with the most used CAD systems. Retrieving in an automatic way all the geometrical and not-geometrical information from the CAD model and thanks to a feature recognition engine it is able to achieve a product quotation. Thanks to this automation, it is able to speed-up the cost evaluation process. Moreover, it offers the advantage that can be used by engineers not skilled in manufacturing processes. Indeed, the software considers automatically each elementary operation required to create a product (a sheet metal, a beam, a prismatic part, etc.) and the relative assembly operations (welding, tackling, manual assembly, etc.). The cost models database of this tool is quite wide but, however, limited. Not all the possible manufacturing technologies are implemented. Nevertheless, for the analyzed case study the required processes are available. The tool was preliminary customized in order to manage the commercial items available within a BoM (such components should not require a manufacturing process). A further customization was required for managing the general attributes (i.e. surface coatings and materials) in order to automatically define the related manufacturing process.

5.5 Performance assessment

This section describes the models created to analyze the mechanical performance of the chimney taken into consideration. In accordance with the proposed framework, at first an analytical model has been developed, and then subsequently, two three-dimensional models (simplified and detailed). For the creation of both these models, reference is made to a job already carried out in the United States of America. During the initial phase of the project, all the documents related to climatic data, client's specifications, and regulations to be considered are available.
Before proceeding with the construction of the model, it is important to have

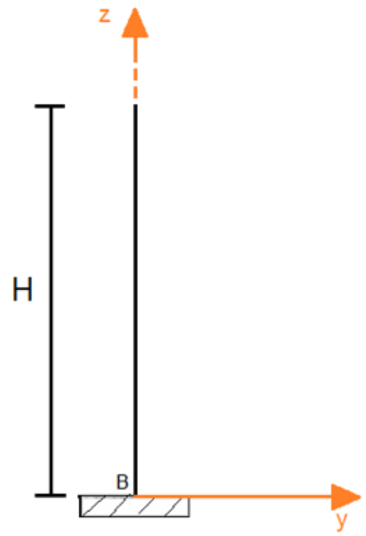


Figure 5.6: Approximation of the self-bearing chimney as a De-Saint Venant's beam fixed at one end.

a clear idea about chimney geometry (height, diameter, platform height, axis height of the horizontal duct etc.), the machine used in the plant (determines the gas path and the dimensions of the stack-base) and the structural materials with which the stacks can be manufactured. All these data will be used as input for both the 1D modeling and the subsequent 3D modelings.

5.5.1 Analytical model

A self-supporting chimney of a power plant has some peculiar aspects. First of all, the structural components of the chimney are represented by welded cylindrical steel sheets, which are bolted among each other through flanges. Secondly, they are rigidly grounded by means of a series of anchor bolts arranged radially on the base circumference and fixed to the concrete foundation. Another characteristic component is the connection with the horizontal exhaust duct, usually performed through an anti-vibration joint.

On the basis of these characteristics, it was decided to approximate the chimney as a De-Saint Venant's beam fixed at one end (Fig. 5.6), with an annular section of variable thickness from stack to stack. The degree of approximation of this one-dimensional modeling is high, but acceptable for the purpose of this first design phase.

The chimney is subdivided in its constituent elements, i.e. the number of stacks from which it will be formed and their height (based on the geometric constraints imposed by the customer and the gas turbine) are indicated.
In Fig. 5.2 a standard stack with a height of 6050 mm is shown. This parameter depends on the size of the commercial sheet metal sheets, whose smaller side is of 6050 mm. Obviously, minor lengths can be achieved by cutting the sheets in the workshop. However, when it is possible, it is preferred to use steel sheets as they are, in order to avoid additional costs and any production of scraps.
Typically, the constraints imposed on the geometry are the following:

- The type of turbine imposes a fixed external diameter for the chimney, calculated according to the maximum mass flow and the outlet temperature of the machine. The kind of turbine constrains the so-called gas path. The tile and insulation dimensions are also fixed in the base section that connects to the horizontal duct (stack-base), to meet certain safety temperature requirements on external surfaces. Therefore, the external diameter of the stack-base is fixed, and this determines the external diameter of the whole chimney. Indeed, any changes in thickness of the sheets or insulation are absorbed with an internal step of the ducts.
- The type of turbine binds the other geometric characteristics of the stack-base. The dimensions of the lateral opening and the lower and upper distance from the horizontal axis of the exhaust duct are known.
- The total height of the chimney is defined by the customer.
- The positioning of the machine imposes the height of the horizontal axis of the duct, and therefore, of the stack-base.

Fig. 5.7 shows the chimney with the imposed geometrical constraints. On the basis of these constraints the number of standard sections above and below the stack-base can be defined. The stack at the ground and the one on the terminal part of the chimney will be those components that will adjust their height according to the total height. The number of standard stacks below the stack-base can be calculated as:

$$N\_stacks\_below\_SB = INT\left(\frac{H_{ground}}{6050}\right) + 1 \tag{5.4}$$

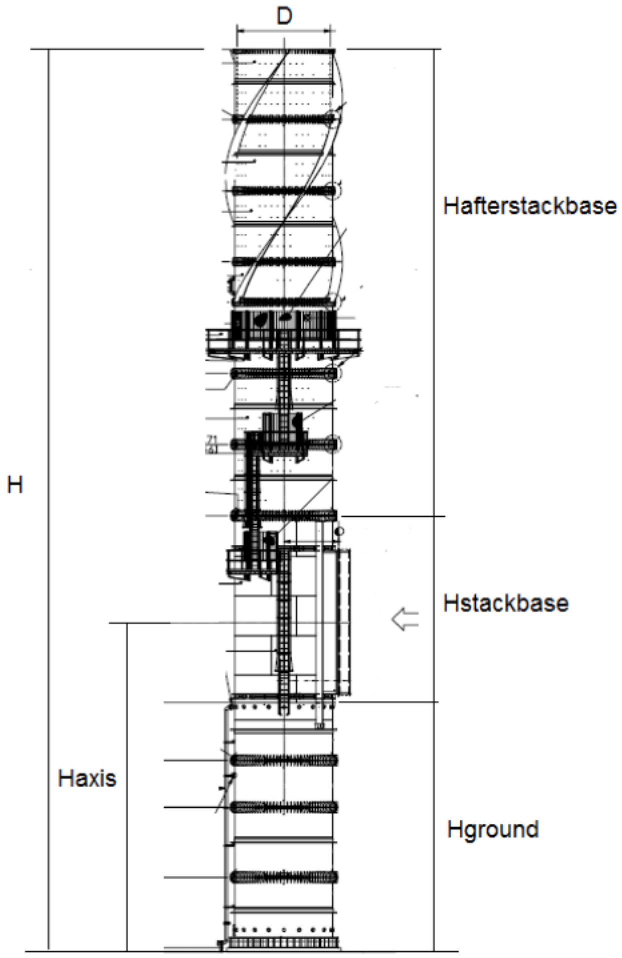


Figure 5.7: Technical representation of the investigated self-bearing with its geometrical constraints.

where SB is the stack-base, the INT function rounds a number down to the nearest integer, the term +1 is added to consider the section of variable height when present. Indeed, it is possible that the stack at the base is the stack-base itself. In the same way the number of standard stacks above the stack-base:

$$N\_stacks\_above\_SB = INT\left(\frac{H_{over}}{6050}\right) + 1 \quad (5.5)$$

in this case the +1 term refers to the terminal variable stack.

In the case in which the height of the base section is too small, so that it is not possible to make connections with the other stacks, it is convenient to divide the height of the base and of the section above it into two distinct sections of

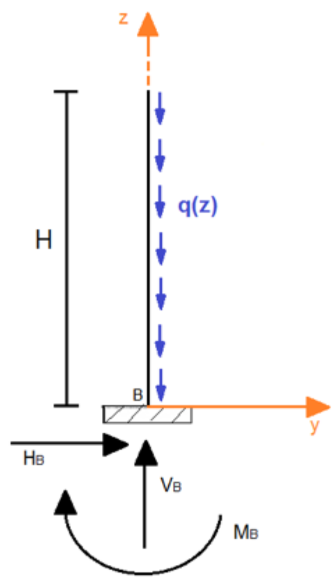


Figure 5.8: Diagram of the fixed beam with application of dead loads.

adequate height, for example by applying to each one half of the total height.
The analyzed chimney is located in the USA, therefore, the ASCE standards have been considered for load applications. In particular, the ASCE/SEI 7-05 has been examined [4] . The prescribed loads have been applied individually. The results for each load condition are then added following the load combinations defined by the ASCE standard. The beam is computed by nodes, i.e. the resolutive formulas are applied to a pre-established number of points located at specific heights of the beam. Five different kind of loads have been analyzed: dead loads, live loads, wind load, seismic load and internal pressure.

Dead loads

The first analyzed loads are the dead loads. Dead load are static forces that are relatively constant for an extended time. They have been modeled as a distributed load $q(z)$ along the beam (Fig. 5.8). The value of the distributed load q was derived from the sum of two contributions. The first contribution, q_s, is the weight relative to structural steel. The weight of each section varies as function of the thickness, so the value q_s, in $\mathrm{N\,m^{-1}}$, is obtained from the average weight per meter of height, computed for each node of the beam, i.e.:

$$q_s = \frac{\sum_{i=1}^{n} \Delta q_i}{n} = \frac{\sum_{i=1}^{n} \rho g (z_i - z_{i-1}) \frac{\pi(D^2-(D-2s_i)^2)}{4}}{n} \tag{5.6}$$

where Δq_i is the weight of the steel calculated between node$i$ and node $i-1$ in $\mathrm{N\,m^{-1}}$, ρ is the density of steel in $\mathrm{kg/m^3}$, g is gravity acceleration 9.81 $\mathrm{m/s^2}$, D is the external diameter of the stack in m, s_i is the thickness of the $i-th$ node in m, n is the total number of computational nodes. In this way, a single value is uniformly applied over the whole beam, which takes into account the variation in thickness along the height.
The second contribution, instead, is given by the weight of all the elements and the accessories that have not been considered in the simplified model, due to the approximation and the lack of information. This contribution was calculated by analyzing the data of chimneys previously produced by the company to determine an average weight per meter of height for each standard stack. By averaging the number of chimney sections, a constant value q_a is applied to the beam. Thus, the final value q is equal to the sum of q_s and q_a.
Subsequently, to solve the structural problem, it is necessary to compute the reactions and the internal actions. In this case, the calculation is very simple because the load is only vertical, therefore there is only a vertical reaction in the opposite direction to gravity, V_B, equal to:

$$V_B = q * H \tag{5.7}$$

and there is only one internal action, the normal stress:

$$N(z) = q * z - V_B \tag{5.8}$$

In Fig. 5.9 is reported the typical diagram of normal stress along the beam subjected to dead loads.

Live loads

Live loads are typically unstable (temporary and of sort duration) or moving loads. The only live load applied to the structure is that related to maintenance operations, in which checks are carried out on the exhaust gases, with the aid of special equipment. The outlets for the exhaust gas are positioned at fixed heights with respect to the horizontal ducts. These outlets can be reached through a horizontal platform that has the task of supporting the weight of machines and people. In the analytical model, the load is applied as a concentrated force L at the point of the beam that corresponds to the platform installation height (Fig. 5.10).

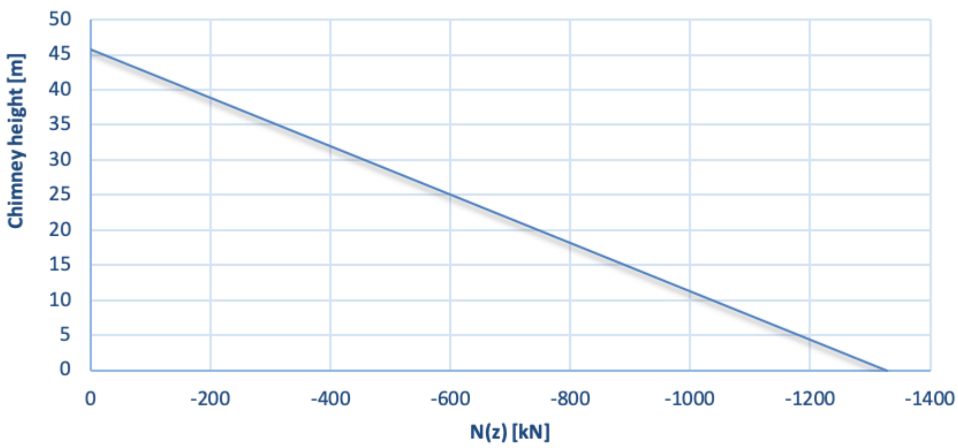


Figure 5.9: Typical diagram of normal stress along the beam subjected to dead loads.

This force includes the total weight of the platform, given by the contribution of the grids, 0.49 kN/m^2, and the handrails, 0.22 kN m^{-1}, and the design maintenance load, 4.79 kN/m^2, not applied to the whole platform, as unrealistic from the operational point of view, but only to a twelfth of the walkable area. In this way the structure is easily solved:

$$V-B = L = 0.49 * A_p + 0.22 * P_{ext} + 4.79 * \frac{1}{12} * A_p \tag{5.9}$$

$$N(z) = \begin{cases} -V_B, & \text{if } z \leq H_p \\ 0, & \text{otherwise} \end{cases} \tag{5.10}$$

where A_p is the walkable surface of the platform, calculated as the area of a circular crown, P_{ext} is its outer perimeter, $N(z)$ the axial force, H_p the height of the platform.
As can be seen from the formulas and from Fig. 5.11, the axial force has a jump in correspondence with the concentrated force.

Wind load

Wind load is a very important load to take into consideration when a civil structure is designed. The ASCE standard defines the procedure to calculate the wind pressure upon the structure [4]. The pressure value, expressed as function of the height, refers to a load on the projected surface of the structure in the wind direction. To apply this load to the beam, it was converted into a linear load,

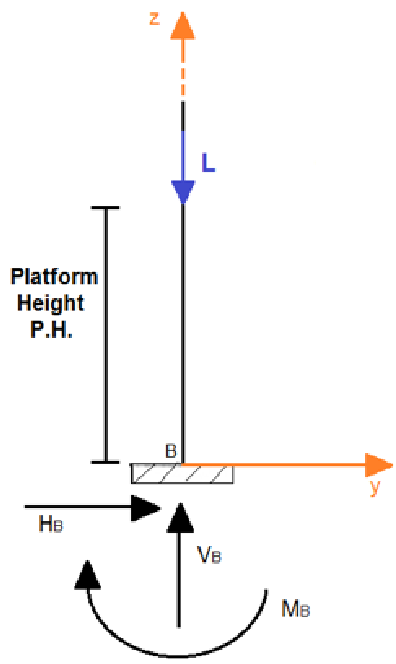


Figure 5.10: Diagram of the fixed beam with application of live loads.

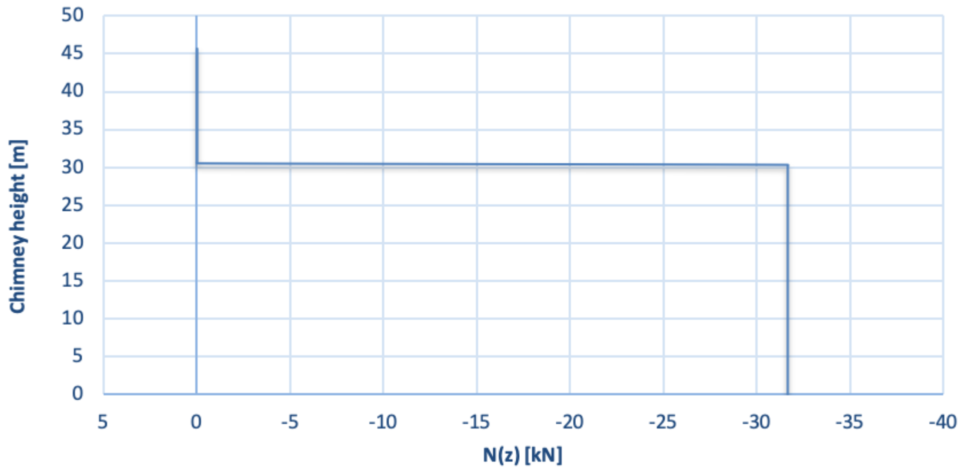


Figure 5.11: Diagram of the fixed beam with application of live loads.

variable along the chimney height, dividing the pressure by the external diameter D of the chimney. Given the symmetry of the analytical model, each direction of application of the load is equivalent to one another: the -Y direction was chosen. In assessing the wind load, the presence of helical strakes was considered, i.e. the aerodynamic stabilizers that reduce the effects due to the vortex shedding. As

Table 5.5: Wind load calculation values according to ASCE/SEI 7-05 [4].

Coefficient	Simbol	Value	UoM
Basic Wind Speed	V	81.81	m/s
Wind Directionality Factor	K_d	0.95	-
mportance Factor	I	1.15	-
Exposure Category		C	
Velocity Pressure	K_z	$2.01(\frac{4.6}{z_g})^{\frac{2}{\alpha}}$ for z<4.6 m	-
Exposure Category		$2.01(\frac{z}{z_g})^{\frac{2}{\alpha}}$ for $4,6m \leq z \leq z_g$	
Terrain Exposure Constant	α	9.5	-
Terrain Exposure Constant	z_g	274.32	m
Topographic Factor	K_{zt}	1	-
Gust Effect Factor	G	0.85	-
Enclosure Classification		Enclosed Building	
Internal Pressure Coefficient	Gc_{pi}	± 0.18	-
Force Coefficient	C_f	$1.2\ for z \leq 2/3H$	-
		$1.4\ for z > 2/3H$	-
Velocity Pressure	q_z	$0.613 * K_z * K_{zt} * K_d * I * V^2$	N/m^2
Design Wind Load	p	$q_z * G * C_f$	N/m^2

precautionary measure, they were immediately included in the model, as they increase the drag force and, consequently, the wind pressure value calculated according to the regulations. However, the need for the helical strakes will have to be verified later. Their extension corresponds to the last third of the total height of the chimney. Tab. 5.5 summarizes the main parameters for the wind load calculations.

In this case, the resolution of the problem is more complex. The wind load is divided into three contributions (Fig. 5.12): the first, $p1$, is constant up to 4.6 m, the second, $p2(z)$, is variable according to the function defined by ASCE 7-05 [4] and goes from 4.6 m to the height where the helical strakes begin; the third, $p3(z)$, is variable along the extension of the helical strakes with the same function defined for $p2(z)$, but with a modified force coefficient C_f.

For the calculation of the reactions, the following integral formulations have been considered to assess the wind load contributions:

$$Q_2 = \int_{L_1}^{L_1+L_2} p_2(z)\delta z = \frac{cost}{\frac{2}{\alpha}+1} * \left[(L_1+L_2)^{\frac{2}{\alpha}+1} - L_1^{\frac{2}{\alpha}+1}\right] \tag{5.11}$$

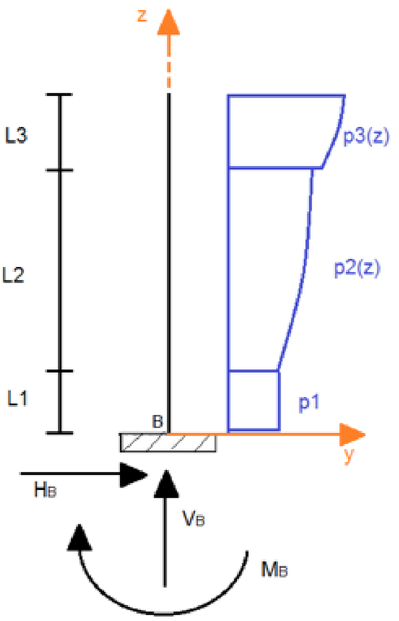


Figure 5.12: Diagram of the fixed beam with application of wind load.

$$Q_3 = \int_{L_1+L_2}^{L_1+L_2+L_3} p_3(z)\delta z = \frac{cost_1}{\frac{2}{\alpha}+1} * \left[(L_1+L_2+L_3)^{\frac{2}{\alpha}+1} - (L_1+L_2)^{\frac{2}{\alpha}+1}\right] \quad (5.12)$$

$$M_2 = \int_{L_1}^{L_1+L_2} z * p_2(z)\delta z = \frac{cost}{\frac{2}{\alpha}+1} * \left[(L_1+L_2)^{\frac{2}{\alpha}+1} - L_1^{\frac{2}{\alpha}+1}\right] \quad (5.13)$$

$$M_3 = \int_{L_1+L_2}^{L_1+L_2+L_3} z * p_3(z)\delta z = \frac{cost_1}{\frac{2}{\alpha}+1} * \left[(L_1+L_2+L_3)^{\frac{2}{\alpha}+1} - (L_1+L_2)^{\frac{2}{\alpha}+1}\right] \quad (5.14)$$

where:

$$cost = 0.613 * K_{zt} * K_d * I * V^2 * 2.01 * \left(\frac{1}{z_g}\right)^{\frac{2}{\alpha}} * G * 1.2 \quad (5.15)$$

$$cost_1 = 0.613 * K_{zt} * K_d * I * V^2 * 2.01 * \left(\frac{1}{z_g}\right)^{\frac{2}{\alpha}} * G * 1.4 \quad (5.16)$$

are two constants that differ only by the value of the force coefficient: 1.2 for the section without helical strakes and 1.4 for the section with helical strakes; Q_2

is the resulting force transmitted by $p2(z)$, Q_3 is the resulting force transmitted by $p3(z)$, M_2 is the resulting moment generated by $p2(z)$, M_3 is the resulting moment generated by $p3(z)$. The reactions due to wind load can be expressed as:

$$\begin{cases} V_B = 0 \\ H_B = p_1 L_1 + Q_2 + Q_3 \\ M_B = p_1 \frac{L_1^2}{2} + M_2 + M_3 \end{cases} \tag{5.17}$$

From the reactions it is possible to calculate the internal forces. The shear force $T(z)$ can be described as:

$$\begin{cases} T(z) = p_1 * z - H_B & \text{for } 0 \leq z \leq 4.6m \\ T(z) = p_1 * z - H_B + Q_2(z) & \text{for } 4.6 \leq z \leq 32.9m \\ T(z) = p_1 * z - H_B + Q_2(z) + Q_3(z) & \text{for } z > 32.9m \end{cases} \tag{5.18}$$

where:

$$\begin{cases} Q_2(z) = \int_{L_1}^{z} p_2(z)\delta z \\ Q_3(z) = \int_{L_1+L_2}^{z} p_3(z)\delta z \end{cases} \tag{5.19}$$

To simplify the implementation of the bending moment calculation procedure, the wind action was approximated to the sum of trapezoidal elements:

$$\begin{cases} M(z) = p_1 * \frac{z^2}{2} - H_B * z + M_B & \text{for } 0 \leq z \leq 4.6m \\ M(z_j) = p_1 * L_1 * \left(z - \frac{L_1}{2}\right) - H_B * z + M_B + M_{wj} & \text{for } z > 4.6m \end{cases} \tag{5.20}$$

M_{wj} is the moment generated by the wind pressure $p2(z)$ and $p3(z)$ up to the z_j quote, considered as a summation of trapezoidal elements with a thickness Δz. The number of trapezoidal elements n_j is equal to the height of the chimney 45 meters minus 4.6 meters (the height on which $p1$ is applied) divided by Δz. The action of each of these trapezoidal elements is decomposed into a constant and a linear load:

$$\begin{cases} M_{w_{j,i}} = p(z_{i-1})\Delta z\left(z_j - \left(\frac{\delta z}{2} + z_{i-1}\right)\right) + \frac{p(z_i)-p(z_{i-1})}{2}\Delta z\left(z_j - \left(\frac{2}{3}\Delta z + z_{i-1}\right)\right) \\ M_{w_j} = \sum_{i=1}^{n_j} M_{w_{j,i}} \end{cases} \tag{5.21}$$

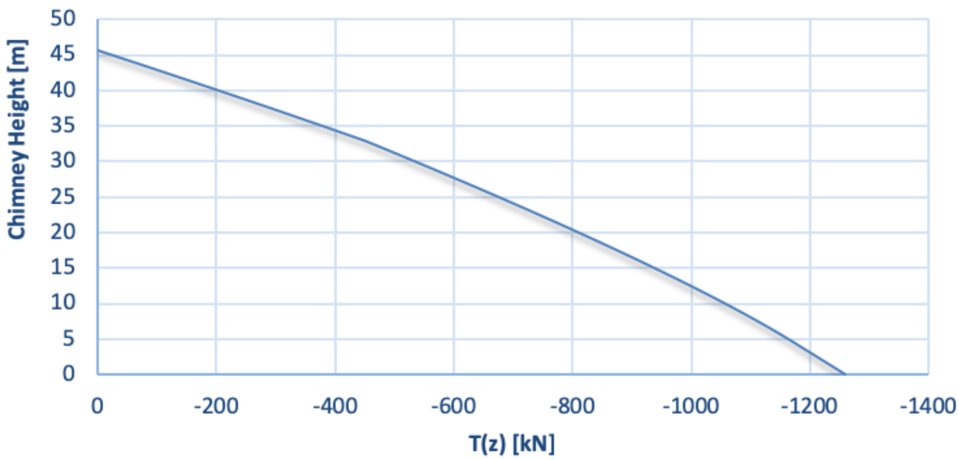


Figure 5.13: The shear force diagram of the chimney under wind load.

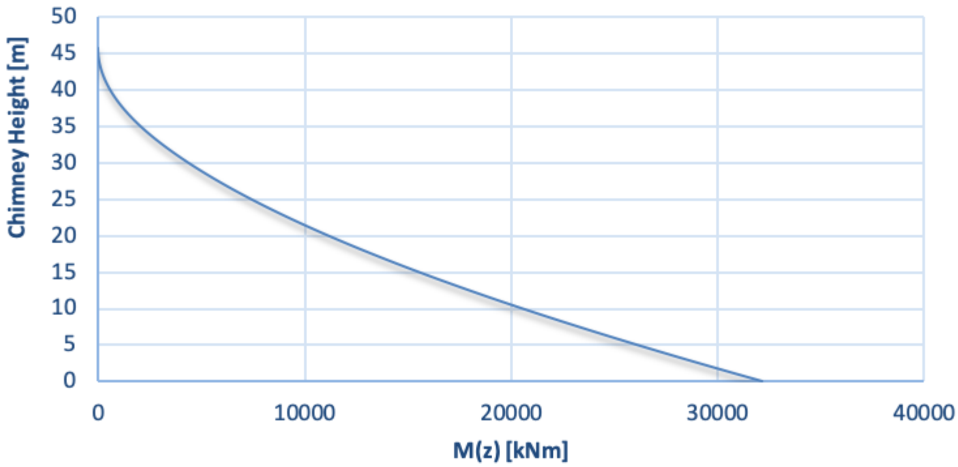


Figure 5.14: The bending moment diagram of the chimney under wind load.

Fig. 5.13 shows the graphs of the shear force while Fig. 5.14 the diagram of the bending moment. As would be expected, there are no clear jumps in the internal actions, and their values cancel out at the farthest end of the beam, while they are maximum at the joint.

Seismic loads

The seismic loads are analyzed applying the *static equivalent procedure* described in ASCE 7-05 [4]. In Tab. 5.6 are reported the seismic data for the case of interest. The items with unit of measure g are a fraction of the gravity acceleration.
The vertical load, being a function of dead loads, is considered as distributed load

Table 5.6: Calculation values for the seismic load according to ASC/SEI 7-05 [4].

Coefficient	Value	UoM	Description
S_s	0.106	g	Mapped Spectral Response Acceleration at Short Periods
S_1	0.054	g	Mapped Spectral Response Acceleration at a Period 1s
$S.C$	E	-	Site Class
S_{MS}	0.265	g	Spectral Response Acceleration at Short Periods
S_{M1}	0.190	g	Spectral Response Acceleration at a Period 1s
S_{DS}	0.177	g	Design Response Acceleration at Short Periods
S_{D1}	0.127	g	Design Spectral Response Acceleration at a Period 1s
T_0	0.143	s	
T_S	0.717	s	
T_L	12	s	Long-period transition period
I	1.25	-	Importance factor
$S.D.C.$	B	-	Seismic Design Category
R	3	-	Response Modification Coefficient
Ω_0	2	-	Over-strength Factor
C_d	2.5	-	Deflection Amplification Factor

along the structure, while the horizontal action is modeled as a concentrated force applied to the barycenter of the chimney (Fig. 5.15). Since the weight force generated by all the elements is considered uniformly distributed over the whole structure, the element that varies the position of the barycenter is the thickness of the steel sheets. Then, the barycenter of the chimney was calculated as:

$$Z_G = \frac{\sum_{i=1}^{n} m_i * z_i}{\sum_{i=1} n m_i} \tag{5.22}$$

where m_i is the mass for each section between two computational nodes, z_i the ground distance of the center of gravity of the i-th element, n is the number of nodes.

The rheonomic constraints can thus be calculated:

$$\begin{cases} V_B = E - V * H \\ H_B = E_H \\ M_B = E_H * Z_G \end{cases} \tag{5.23}$$

then the internal forces can be inferred:

$$\begin{cases} N(z) = E_V * z - V_B & \\ T(z) = 0 & \text{for } z > Z_G \\ T(z) = -H_B & \text{for } z \leq Z_G \\ M(z) = 0 & \text{for } z > Z_G \\ M(z) = M_B - H_B * z & \text{for } z \leq Z_G \end{cases} \tag{5.24}$$

Internal pressure

The last acting load on the chimney is the internal pressure. This can be calculated applying the operating pressure at the exit of the machine, 5 kN/m^2, to the entire exhaust duct. It is known that this pressure does not occur in the real world, but it is taken into consideration as a precautionary measure. In this case, the stresses are calculated using the Mariotte's formulas and only the circumferential tension

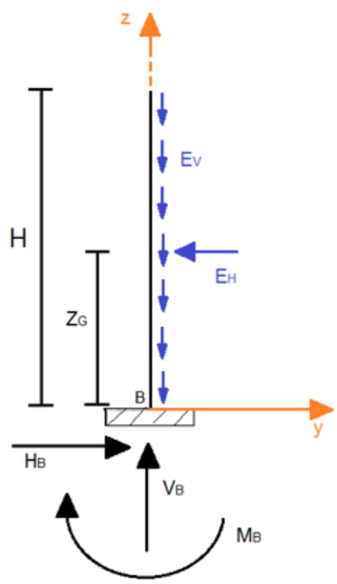


Figure 5.15: Diagram of the fixed beam with application of seismic loads.

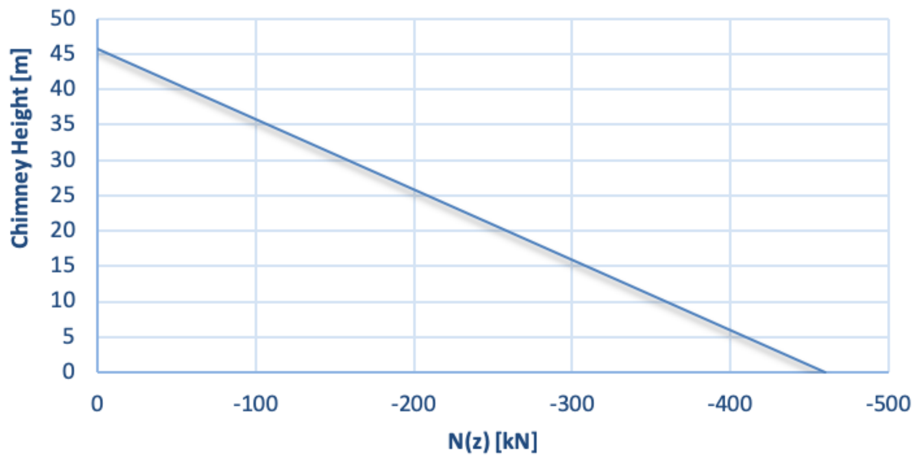


Figure 5.16: The normal force diagram of the chimney under seismic load.

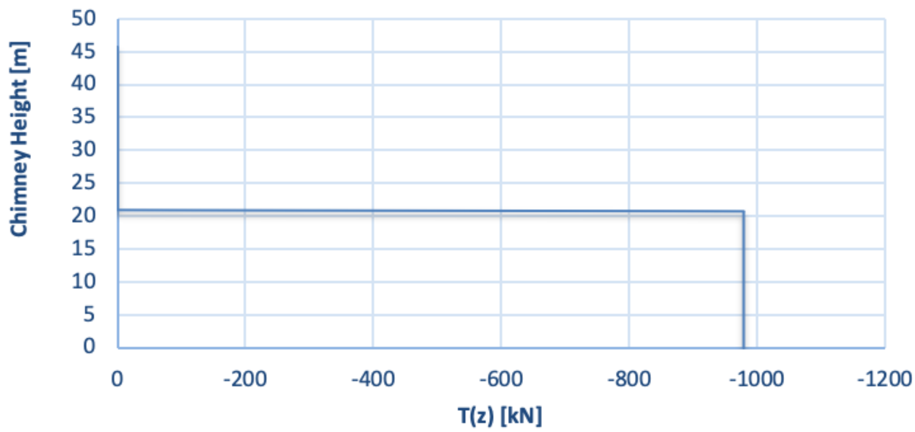


Figure 5.17: The shear force diagram of the chimney under seismic load.

is considered, whereas the axial tension is neglected due to the vertical extension of the chimney. The overpressure case was also evaluated, considering a value of 9 kN/m^2. The circumferential sigma can be calculated as:

$$\sigma_c = \frac{p * D}{2 * s} \tag{5.25}$$

Load combinations

After calculating the internal forces due to the individual loads, these are summed following the load combinations indicated by the regulations [4]. Below are the combinations related to the *strength design*, with the related corrective factors:

1. 1.4 (Dead Loads + Operative Pressure)

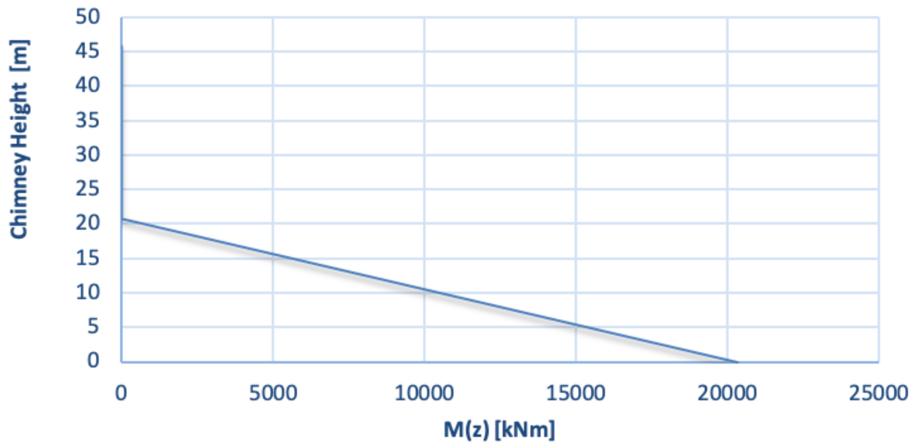


Figure 5.18: The bending moment diagram of the chimney under seismic load.

2. 1.2 (Dead Loads + Operative Pressure) + 1,6 Live Loads
3. 1.2 Dead Loads + 0,8 Wind Loads
4. 1.2 Dead Loads + 0,5 Live Loads + 1,6 Wind Loads
5. (1.2 + 0.2 SDS) Dead Loads + Live Loads + Earthquake Horizontal
6. 0.9 Dead Loads + 1,6 Wind Loads
7. (0.9 - 0.2 SDS) Dead Loads + Earthquake Horizontal

These are the combinations related to the *allowable stress design*:

1. Dead Loads + Operative Pressure
2. Dead Loads + Operative Pressure + Live Loads
3. Dead Loads + Operative Pressure + Wind Loads
4. (1 + 0.14 SDS) Dead Loads + Operative Pressure + 0.7 Earthquake Horizontal
5. Dead Loads + Operative Pressure + 0,75 Wind Loads +0.75 Live Loads
6. (1 + 0.105 SDS) Dead Loads + Operative Pressure + 0.525 Earthquake Horizontal + 0.75 Live Loads
7. 0,6 Dead Loads + Wind Loads
8. (0.6 + 0.14 SDS) Dead Loads + 0.7 Earthquake Horizontal

Once the internal actions have been summed, the various tensions can be calculated for each load combination:

$$\begin{cases} \sigma_{z,N} = \frac{N}{A} \\ \sigma_{z,M,max} = \frac{M_x}{I_x} y_{max} \\ \tau_{yz,max} = \frac{T_y S_X^*}{I_x b} \end{cases} \tag{5.26}$$

where $\sigma_{z,N}$ is the axial tension due to normal stress, $\sigma_{z,M,max}$ is the maximum value of axial tension generated by the bending moment (in this case it is calculated with respect to x, because the forces of shear generate a moment in the x direction) while $\tau_{yz,max}$ is the maximum shear tension, the latter is considered (as a precautionary measure) at the same point of the compression action, even if it is not present. In general, when both $\sigma_{z,N}$ and $\sigma_{z,M,max}$ act simultaneously in a single combination, the two values are summed together to form a single axial stress, which will correspond to the stress state of a point at the end of the section. Moreover, when it is needed, the circumferential tension is recalculated, multiplying it by the appropriate corrective factor. Once all the tensional state is known, the Von Mises ideal tension is evaluated. This is the parameter that will be compared with the admissible sigma value. The latter was calculated using the coefficients indicated by the ANSI/AISC 360-10 standard [3], both for strength design and for the allowable stress design. Regarding the first verification criterion, the beam has to satisfy this inequality:

$$\sigma_{id,VM} \leq \sigma adm = \phi \sigma_{yield} \tag{5.27}$$

where σ_{yield} is the minimum yield stress of the material, Φ is the resistance factor defined according to the ANSI/AISC 360-10 equal to 0.9 [3]. The second verification criteria can be expressed as:

$$\sigma_{id,VM} \leq \sigma adm = \frac{\sigma_{yield}}{\Omega} \tag{5.28}$$

where Ω is the safety factor, defined by the ANSI/AISC 360-10 equal to 1.67 [3]. The verification of these criteria is carried out for all the load combinations, at each beam calculation node. Both methods are evaluated.
Moreover, as a further verification, the calculation method for elements subjected to compression and bending is applied, as suggested by the ANSI/AISC 360-10 standard [3]. Also in this case, the verification method is computed for both

methods, and will be considered the most cautionary. Finally, the elastic stability check is assessed for each load combination.

5.5.2 Numerical model

The second and third level of design focuses on 3D analyses. While the optimization-objectives are the same of the previous level, tools and input data used for the evaluation processes are different. Indeed, during the second level, the structural response is evaluated using a 3-D FEM solver.
To perform a FEM analysis three main steps should be performed:

Pre-processing definition of the finite element problem to be simulated starting from the physical problem:

- CAD model simplification
- Discretization (mesh) of the geometric model to create a finite elements equivalent model
- Definition of the material properties
- Application of loads
- Applications of constraints

Processing resolution of the finite element problem, considering all the defined data in the pre-processing phase. Identification of nodal displacements.

Post-processing calculation and visualization of information related to results such as deformation, tensions, etc.

In the embodiment and detailed design phases two different kind of numerical analysis have been performed: static and dynamic. The optimization of the chimney has been reached only considering the static behavior of the system, no dynamic considerations have been taken into account. The modal analysis has been performed only on the optimal configuration as a check. Into dynamic analysis, sufficient modes shall be included to ensure that at least 90 % of the mass of the structure is participating for the direction under consideration. Further, all modes with a participating mass greater than 5% shall be considered. The vortex forces on the stack could cause ovalling resonance. The ovalling vibrations can be expected if the frequency of the vortices coincides with an ovalling frequency of the shell. Generally, a lined stack is more resistant to ovalling because the lining contributes to increase the damping for the elastic ring, and ovalling may not be considered for lined chimneys. Anyway, also the ovalling is checked.

Static analysis

The linear static analysis consists into the solution of the following system of equations:

$$\bar{K} \cdot \vec{u} = \vec{F} \tag{5.29}$$

where $\bar{K}$ is the stiffness matrix, u is the vector of joint's displacements and F represents the applied loads. The hypothesis at the base of the method are that the applied loads are not a function of time or displacement, the behavior of material is indefinitely elastic, and the second order effects are negligible (geometric linearity).
The vector F can be seen as a linear combination of the forces which are due to the singles load conditions, as follows:

$$\vec{R}_i = \sum_{j=1}^{N_{LC}} \alpha_{ij} \cdot \vec{F}_j \tag{5.30}$$

If $\vec{u}_j$ is the vector of displacements which is associated to the load condition $\vec{F}_j$, it can be easily demonstrated that the overall structural response $\vec{V}_i$ for the loads combination $\vec{R}$ is given by:

$$\vec{V}_i = \sum_{j=1}^{N_{LC}} \alpha_{ij} \cdot \vec{u}_j \tag{5.31}$$

The stiffness matrix $\bar{K}$ is symmetric and defined positive, and to solve the system, the Cholesky's algorithm can be used, as follows:

$$\bar{K} = \bar{L} \cdot \bar{L}^T \tag{5.32}$$

$$\bar{L} \cdot \bar{L}^T \cdot \vec{u}_j = \vec{F}_j \tag{5.33}$$

The system is solved by applying two substitutions; y is obtained by solving the system $\bar{L} \cdot \vec{y} = \vec{F}_j$ and then, $\vec{u}_j$ is calculated by $\bar{L}^T \cdot \vec{u}_j = \vec{y}$. Once the field of displacements $\vec{u}_j$ is known for each structural joint and for every load combination, the state of stress is obtained consequently.

Modal dynamic analysis

A dynamic linear analysis, by the modal response spectrum method, shall be considered the usual way to define the design seismic forces and it is carried out by following three basic steps: determination of the main structural modes (modal analysis), calculation of the effects of seismic action, which is represented by the response spectrum, and then combination of the effects that are related to each mode. The modal analysis consists into the solution of the equations which describe the displacement of structure, that is considered indefinitely elastic, under free vibration conditions (without any external forcing factor), and into the determination of the deformed shapes, which are the natural modes of the building.
The modal shapes are an intrinsic characteristic of the construction, because they are determined in absence of external forces, and are defined by a period of vibration (T) that is associated with a damping factor ζ that is equal to 5% for steel structures.
The modal analysis is based on the factorization of the overall structural dynamic response into the sum of contributions of each modal shape: a system with n degrees of freedom ($nd.o.f.$) is transformed into n systems, everyone with a single degree of freedom ($s.d.o.f.$). The structural response, in terms of deformed shape and then of stress state, is obtained by an opportune combination of all the significant modes.
The single modes of a structural system become progressively less significant with the decreasing of their own period $T = 2\pi/\omega$ or, in the same way, with the increasing of their frequency ω . Depending on the seismic forces that act on structure, some modes will have a most important role than others in the composition of the resulting deformed configuration.
Each vibration mode is characterized by a participation coefficient that decreases with the period, and represents the portion of total mass (excited mass) which is involved into dynamic oscillation. When its value becomes too low, the effects on whole structure of the correspondent mode, in terms of displacements and stresses, are negligible.
In a structure which is sufficiently symmetric and regular, in relation to distribution of mass and stiffness, the first modes have a prevalent importance than the remaining.
The design standards prescribe that, in order to determinate with sufficient accuracy the effects of seismic action on structure, all modes which have a partic-

ipating mass greater than 5% and a number of modes capable to activate at least the 90% of total mass shall be included in the dynamic analysis.
When the seismic event occurs, the maximum effects on structure aren't reached at the same instant for each single mode, because everyone is characterized by a different own period. For this reason, the overall stresses cannot be obtained by a simple sum of every mode's effects, but through probabilistic rules which consider this temporal delay. In accordance with the design code a Complete Quadratic Combination (CQC) shall be used. Its effect is to give values which are as higher as the periods are closer to each other.

$$E = \Big(\sum_j \sum_i \rho_{ij} \cdot E_i \cdot E_j\Big)^{0,5} \tag{5.34}$$

where E represents the overall effects of seismic action for the direction under consideration, E_{ij} are the values of the effects which are related respectively to modes i and j and ρ_{ij} is the correlation coefficient between modes$i$ and j:

$$\rho_{ij} = \frac{8 \cdot \epsilon^2 \beta_{ij}^{\frac{3}{2}}}{(1+\beta_{ij})[(1-\beta_{ij})^2 + 4 \cdot \epsilon^2 \cdot \beta_{ij}]} \tag{5.35}$$

where ϵ is the viscous damping ratio, that is assumed equal to 5% and β_{ij} is the ratio between the periods of every couple of modes i and j.
Referring to the combination of the components of seismic action, the maximum values E, which are obtained separately along each direction, shall be combined as follows: the overall action, for the direction under consideration (e.g. E_x), have to be added to 30% of the components that act orthogonally (e.g. $E_x + 0.3 \cdot E_y + 0.3 \cdot E_z$) with rotation of combination coefficients. The vertical component E_z shall be taken into account only if necessary. Moreover, the effects due to gravitational loads D and L have to be added to seismic action E.
In order to take into account both the spatial variability of seismic motion, that any uncertainties in the location of structural center of gravity, the standards prescribe that an additional eccentricity shall be assigned to its position in relation to the one which derives from the calculation.
In absence of more accurate determinations, this eccentricity, for each direction, shall not be considered less than 5% of the side of the structure which is measured perpendicular to the direction of application of seismic force. This eccentricity causes additional torsional effects that shall be considered in the dynamic analysis.

Simplified numerical model

The modeling of a 3D geometry can be carried out choosing among three different modeling strategies: shell, plane, solid. For the 3D simplified analysis the shell element has been chosen, as it is able to withstand both forces and moments with a limited resource consumption. Among the shell elements more behaviors can be distinguished:

Membrane resists only to loads in the plane or normal moments to the plane.

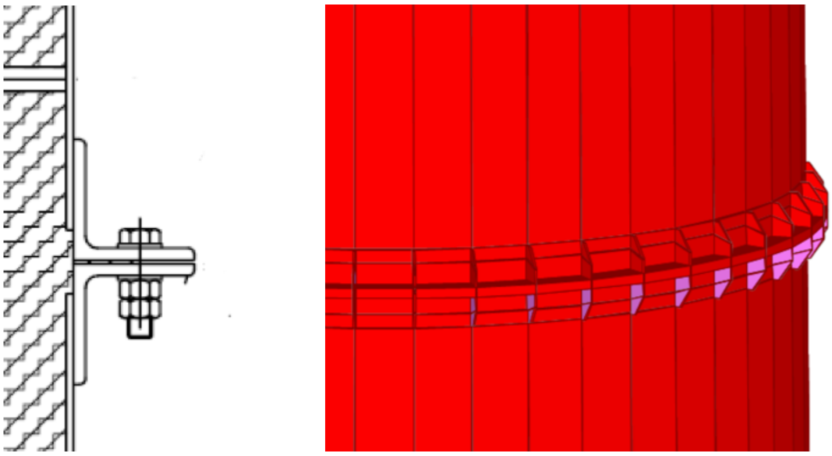
Plate supports only shear forces or moments in the plane.

Shell includes the behavior as membrane and plate.

The shell behavior was adopted for all the geometry. The 3D model of the chimney analyzed during the second design phase is a simplified model. Indeed, to speed-up the design and optimization process, some simplifications have been applied:

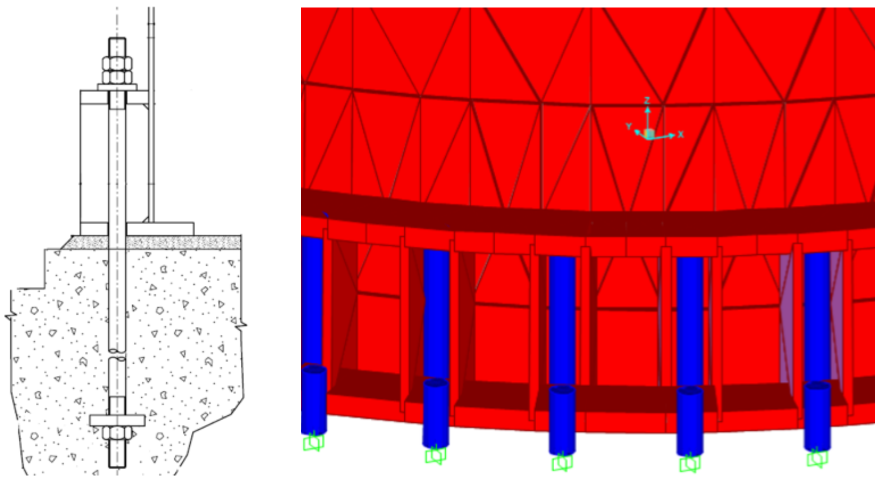
- The connection between one stack and the next is usually realized bolting two flanges. In the model this kind of connection has been neglected. Two stacks are rigidly connected through a flange of thickness equal to the sum of the two real flanges (Fig. 5.19).
- The ground connection by means of the anchor bolts is modeled with rods of circular cross-section, connected at one end to the support plate and, at the other end, to the ground. As result, the bolt is not considered (Fig. 5.20).
- L-shaped reinforcement elements are not modeled as externally welded to the duct section but are considered as an unicum.
- Only the structural elements of the chimney are modeled. The accessory elements (e.g. tiles, rungs, insulator, etc.), which make up the internal part of the duct, are neglected; only their weight is considered.

Once the geometric model has been completed, the loads and constraints must be applied. As mentioned previously, the structure is fixed to the concrete foundation by means of anchor bolts, which have been configured as cylindrical section rods. At the base of these rods a fixed constraint has been applied to the ground, to simulate the anchorage to the foundation. Moreover, to simulate that the structure rests on the ground on the base surface, high stiffness springs which act



(a) (b)

Figure 5.19: Simplification of the bolted connection: a) real connection, b) simplified connection.



(a) (b)

Figure 5.20: Simplification of the ground connection: a) real connection, b) simplified connection.

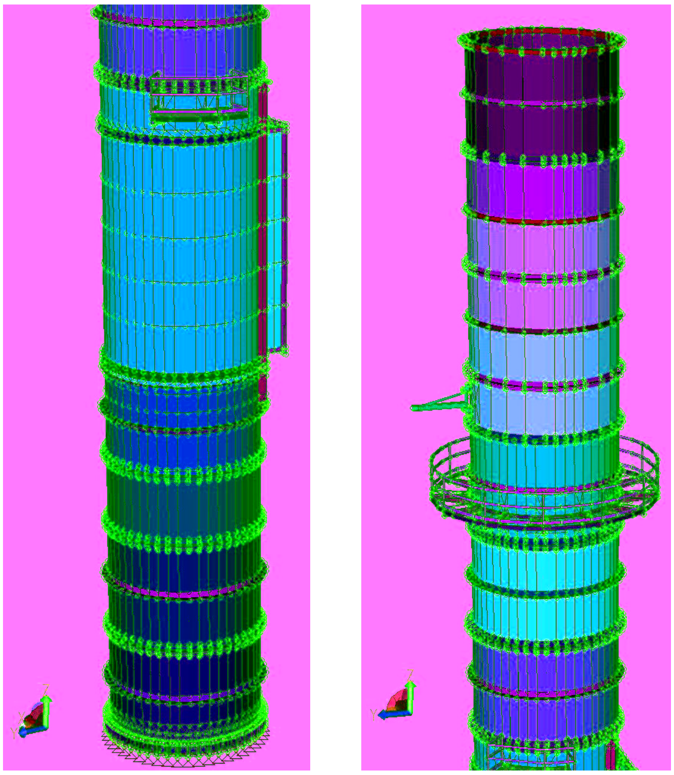


Figure 5.21: 3D view of the FE analysis model.

only in compression have been applied to the elements which constitute the base. A simple support would have over-constrained the structure by also absorbing the forces due to bending and shearing. The loads to be applied to the 3D model are defined by the ASCE/SEI 7-05 regulation. These loads have been described in the previous section for the 1-D model.
The numerical analysis during the second design level was carried out exploiting the SAP2000® as FEM tool. In Fig. 5.21 is reported 3D view of the FE analysis model. The following sketches, from the FEM model, provide an idea of the overall geometry of the analyzed chimney. Note that the aerodynamic stabilizers are not introduced into the analysis model, but their effect is considered in terms of increasing of the wind drag force. The force coefficient (C_f) over the upper 1/3 of the height is assumed equal to 1.4 instead of the value 1.2 which is used for the circular hollow sections [34].

Full numerical model

During the detailed design phase, a 3-D full modeling strategy is exploited to perform all the necessary analysis. The developed model is a full 3-D geometry with a solid tetrahedral mesh. In particular, all the details are introduced and only few simplifications are made. For example, the bolted connection among the stacks is still neglected also in this analysis phase. Indeed, it is without any sense performing the design check of all the bolted flanges that connect every stack's section by means of a FEM solver. This kind of verification can be carried out in a simple way through analytical calculations. Also anchor bolts and stiffener's weldings can be assessed in an analytical way.
The boundary conditions and the loads acting on the chimney have been modeled in the same way of the simplified 3d model. In this case a different FEM solver is used, the Ansys® suite is exploited.
A solid strategy is also used to perform optimization on specific components of the chimney such as for example insulation, rain hood, flanges etc.

5.6 Multi-objective optimization

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 analysis 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 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 MOO refines the optimization defining the thickness of each duct. The third stage is focused on detail simulations and calculations used to release the engineered design. Further information is available in Tab. 5.6. Moreover, the following section describes the design approach used in each MOO stage.

Table 5.7: 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's 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

5.6.1 I optimization level

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. The maximum number of variable segments, in which the beam can be divided, is calculated considering the possible minimum height for the stacks. The height for the stack-base is fixed at 9500 mm. Therefore, the maximum number of stacks is 18. Each item is solved based on the characteristics of a tubular shell element. 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 can be used: Fe360, Fe430, and Fe510.
This chimney is designed for use on US territory, and for this reason ASCE/SEI 7-05 (American Society of Civil Engineers 2006) and ANSI/AISC 360-10 (American Institute of Steel Construction 2010) standards were respectively used to define loads and assessment criteria. Moreover, the CICIND was used for the definition of strength criteria. These standards describe different load cases to be considered during structural verification: dead loads, live loads, wind load, seismic load and internal pressure levels. More specifically, 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 depend 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 (American Society of Civil Engineers 2006) are schematically reported in Fig. 5.22.
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 previously described. For the same MATLAB® script, a parametric cost model is used to estimate the cost of the chimney.
Parameters that can be optimized in this design phase (as reported in Tab. 5.6) 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 the following values were considered: 8, 10, 12, 15, and 18 [mm]. The height of each shell element is analyzed as a stepwise variable with a step of 500

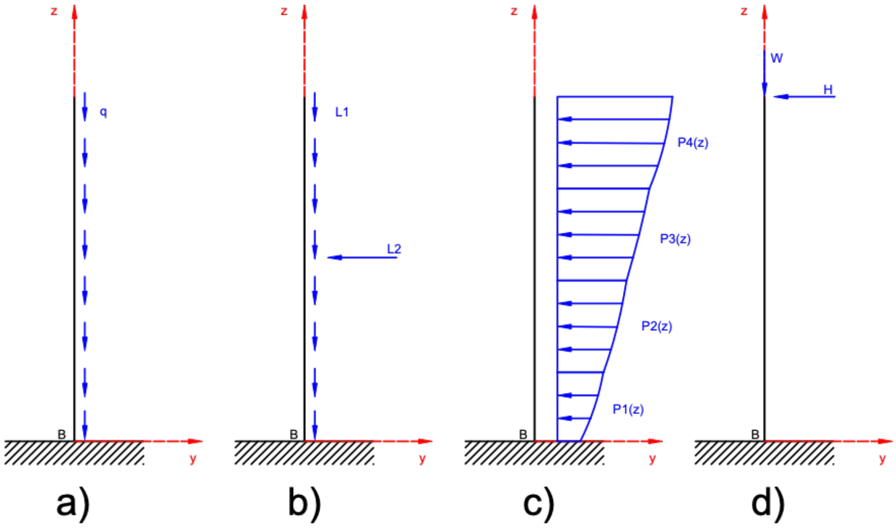


Figure 5.22: Scheme of load conditions prescribed by the ASCE/SEI 7-05: a) dead load, b) live load, c) wind load, d) seismic load.

mm ranging from 2000 to 7000 mm and 0 mm to account for different number of stacks. 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 related material costs.
The objective is to minimize costs and weights. Generally, the minimization of weights does not necessarily reduce cost. For example, the use of lightweight materials can increase acquisition costs. However, weight reduction is crucial to facilitating 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, Genetic Algorithms and Response Surface Methodologies to solve multi-objective and multi-disciplinary 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 per-

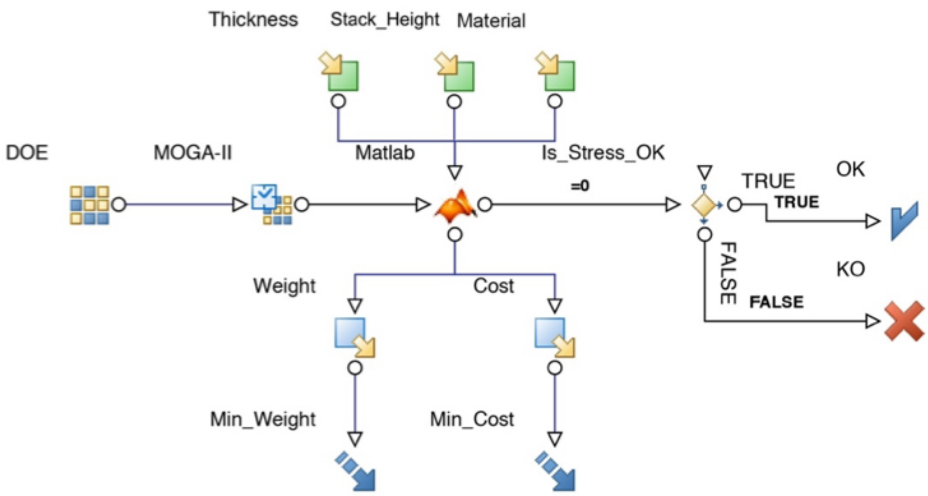


Figure 5.23: Workflow of the first MOO stage.

form a structural-cost optimization. The developed optimization workflow is reported in Fig. 5.23.
To limit the problem domain, thicknesses must not increase with 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, thickness levels tend to decrease in homogenizing internal stress placed on stacks.

5.6.2 II optimization level

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 developed configuration tool shown in Fig. 5.5. The 3-D shell model is a simplified model that includes only relevant components for the required level of detail. 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.
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. Structural stress and displacement values are verified in accordance with Ultimate Limit State and Serviceability Limit State methods.
The parametric cost estimation method is based on formalized rules described

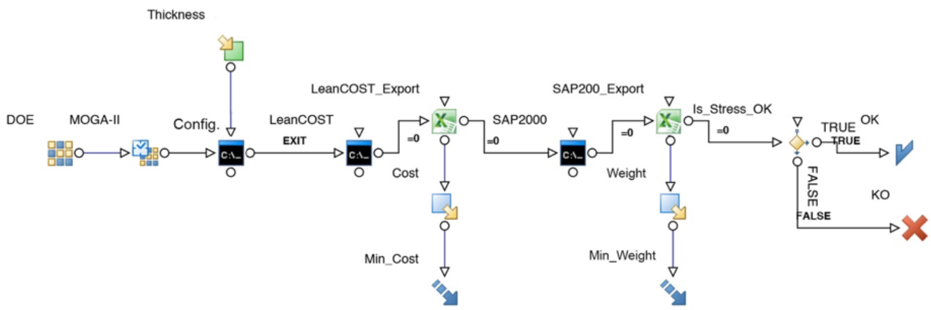


Figure 5.24: Workflow of the second MOO stage.

in the parametric cost model section.
The optimization process is similar to that of the first level. The modeFRONTIER® tool is used for cost-performance optimization using the MOGA-II algorithm. However, SAP2000® cannot be directly interfaced with modeFRONTIER®. For this reason, a dedicated VB (Visual Basic) scripts was created to launch the FEM solver. The optimization workflow defined under the modeFRONTIER® framework is reported in Fig. 5.24. In the second MOO stage 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 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.

5.6.3 III optimization level

In this stage, a detailed 3-D CAD model is generated. 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 and flange deflection values are analyzed by means of a FEM model with a solid tetrahedral mesh.

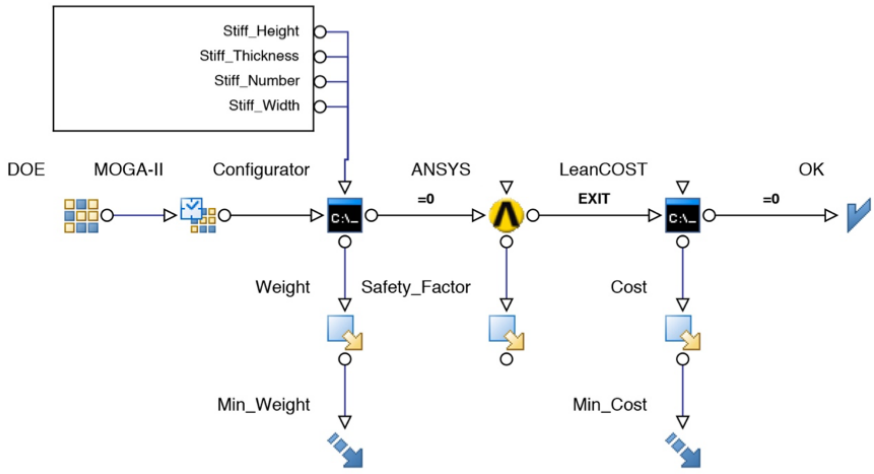


Figure 5.25: Workflow of the third stage of MOO.

As an example, the optimization of stiffeners supporting flanges is reported. Stiffeners are trapezoidal elements welded on flanges to reinforce connections between two consecutively stacked elements (reported in Fig. 5.19). The aim of the optimization method is to reduce the quantity and dimensions of stiffeners involved while minimizing material and manufacturing costs and weights.

Another example of optimization that can be carried out during the detailed design phase is finding the optimal distance between the rain hood (shown in Fig. 5.29(a)) and the outlet section. The goals of the optimization are to minimize the exhaust gas velocity at the outlet of the chimney minimizing, at the same time, the distance between the rain hood and the outlet section. The outlet velocity have to be less than 35 $\mathrm{m\,s^{-1}}$ due to noise issues.

ANSYS® suite 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.

The modeFRONTIER® platform was also used for the third stage of MOO (Fig. 5.25). However, the optimization loop involves only specific aspects without affecting some of the results of the second optimization process.

The workflow is completed with the phase called as *final items design*. This phase regards the engineer's review after the third MOO (III-MOO). In fact, the result of the multiobjective optimization with two objectives is often a Pareto frontier. A task of the engineer is the selection of the best point from the Pareto frontier. After this phase, the product structure is completely defined.

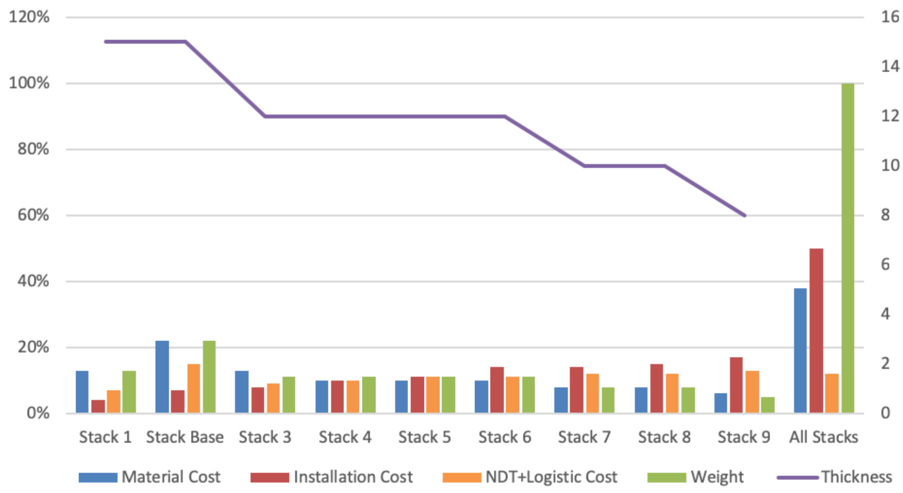


Figure 5.26: Results of the first optimization stage: 8 stacked items with different thicknesses (mm), weights (%) and costs (%).

5.7 Results and discussion

5.7.1 I optimization level results

Fig. 5.26 presents a report generated from the first MOO process. For data confidentiality reasons, costs and weight are reported as percentages of total values. The optimization, based on 475 different configurations, shows that the one with eight stacks is the least expensive to employ. Installation costs, as shown in Fig. 5.26, increase with chimney height due to an increased labor cost with an increase in height. The resulting configuration also illustrates levels of structural performance required based on normative checks, which are defined as boundary conditions in the analytical model. Other costs are representative of Non-Destructive Testing (NDT) and logistical costs.
Using this simplified method, many configurations can be easily evaluated. The identified optimal solution represents a starting point of the second optimization stage. The approach used for the selection of an optimal solution involves adopting the cheapest configuration passing stress tests with a ratio of 0.85 (equivalent stress level per maximum value allowed) for each duct segment.

5.7.2 II optimization level results

The results of the second MOO process are reported in Fig. 5.27, which describes the optimal configuration obtained from the proposed optimization process. It

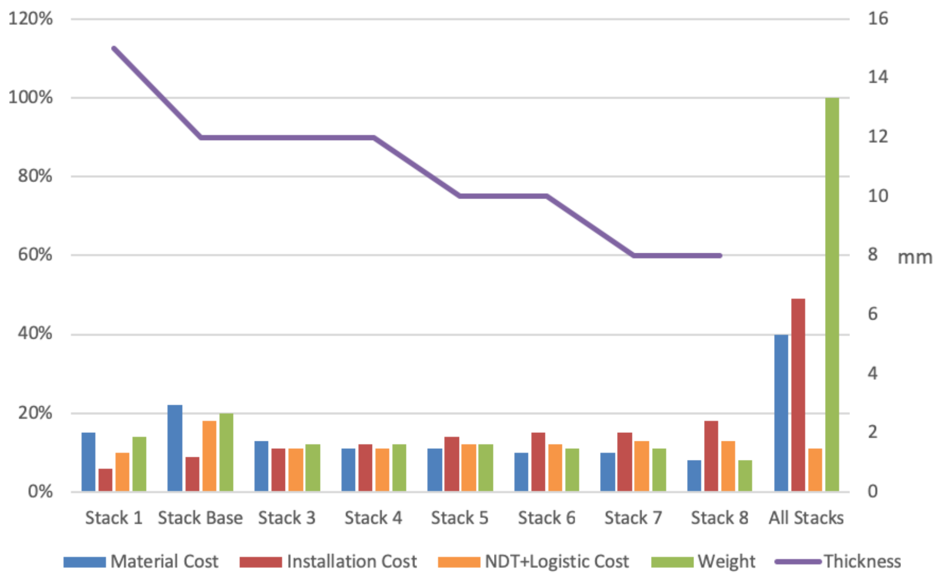


Figure 5.27: Results of the second optimization stage: 8 stacked items of different thicknesses (mm), weights (%) and costs (%).

was found that thicknesses decrease 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.

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 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 is attributable to the restriction of the problem domain resulting from the first stage. Moreover, a detailed parametric approach was applied for product cost calculations. From the 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.

5.7.3 III optimization level results

The last stage involves the optimization of specific chimney components. Two example are reported, the optimization of stiffeners that support the flanges and the rain hood distance are described.

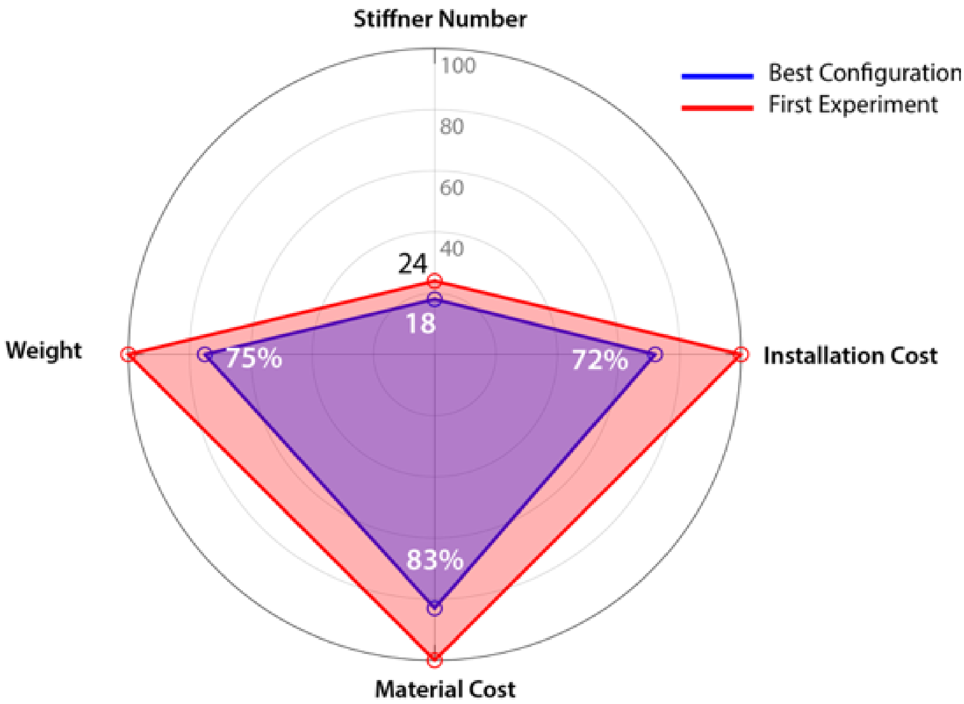
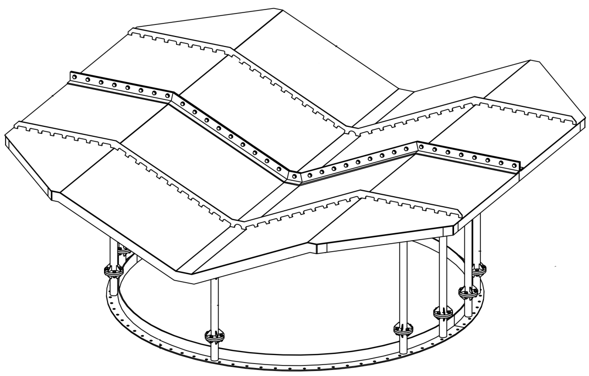


Figure 5.28: Comparison of the as-is rain hood and the best configuration.

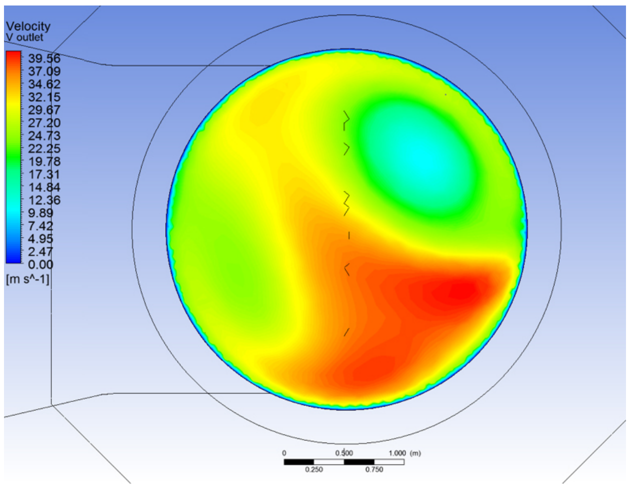
For the connection of the stack base to the third stack, 24 equidistant stiffeners with a mass of 1.2 kg were simulated. After 35 simulations were automatically performed using the optimization software, an optimal solution was identified. The optimization analysis was performed using a GA method and using Ansys Workbench® as an FEM numerical solver. A comparison between the as-is case and best configuration is shown in Fig. 5.28.
The optimization of the rain hood was carried-out by means of fluid-dynamic analyses. In this case a CFD solver has been used. Fig. 5.29 shows the technical draw of the investigated rain hood and the as-is velocity profile reached on the outlet section and the optimal one. The optimal distance between the chimney outlet section and the lower point of the rain hood is of 1332 mm.

5.8 Optimal configuration and AS-IS model

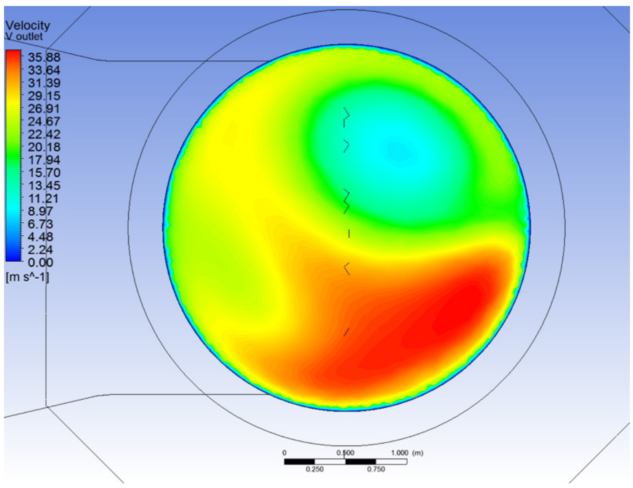
The case study presented in this chapter is a real chimney installed in US soil. Therefore, it is very interesting confronting the configuration reached by means of the use of the proposed framework and the one really built. Object of the comparison are the thickness and the number of the stacks, the total mass and



(a)



(b)



(c)

Figure 5.29: 3D CFD analysis of the chimney's rain hood:
a) rain hood technical draw,
b) as-is rain hood distance,
c) optimal rain hood distance.

Table 5.8: Confrontation between the real case and the one reached with the proposed framework.

Real case			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
Stack 7	10	29.1	Stack 7	8	40
Stack 8	8	32.7	Stack 8	8	45.7
Stack 9	8	34.7			
Stack 10	6	38.3			
Stack 11	6	41.9			
Stack 12	6	45.7			

the total cost of the chimney. Tab. 5.8 shows the stacks thickness values of the two models and the maximum height from the ground of each stack.
The number of stacks in the as-is case is greater than the new model. This is due to the fact that it was implemented as design rules to prefer, when possible, the use of the standard stacks of 6.05 meters.
It is interesting to note that in the real case the stack at the base of the chimney has a thickness significantly bigger than the one adopted in the optimal case. In general, in the real chimney, stacks with greater thickness have been always installed.
Every stack is connected to the other by means of bolted flanges. In the real case, the presence of a greater number of stacks determines a higher number of flanges. However, since the stacks adopted in the real case have a lower height, there is a lower necessity to use reinforcing rings (typically a standard stack has two reinforcing rings).
In conclusion, an important reduction of the mass and the 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 %.

5.9 Optimization design time

Since the introductory chapter, it has been highlighted how time is a key factor in the world of engineered-to-order products. The request for proposal phase must be rather quick, as a too long response time could have a negative effect on the possibility of winning the bid. Based on the case study analyzed above, it was tried to be estimated the execution time of the optimization process. Tab. 5.9 shows the main steps of the method described in this thesis. Each of these has been assigned with a value in minutes for completion. It was considered a design engineer who works in the Oil & Gas sector, which already has design experience, who is able to use the software and tools proposed by this study and which has all the documents and regulations necessary to proceed with the design.

Table 5.9: Design optimization time estimation

Method phases	**min**
Study of documentations	45
Model ideation	60
1D model creation	45
1D optimization	60
Simplified 3D model creation	120
Loads application on the simplified 3D model	30
Simplified 3D optimization	500
3D full model creation	210
Loads application on the full 3D model	50
Full 3D optimization	610
Results analysis	60
Total	1790

The time related to the initial process of study of the model, conception and creation of the simplified model, is considered constant. It generally does not change as the size of the chimney changes. The design of the 3D models and the assignment of loads may instead be faster if the chimney is of reduced height. These are hypothesized values and may vary depending on the user. This estimation was reached tanks to discussions with senior engineers working in the Oil & Gas sector.

On the contrary, the times related to 1D and 3D optimization are real data obtained from the optimization processes conducted with modeFRONTIER®. The

value shown in Tab. 5.9 is an average value of the different optimization analysis. This value can be influenced by the computational performance and the utilization rate of the computer where the analysis is running. For example, using software that requires a high value of RAM leads to a dilatation of the time needed for the optimization. It is possible to note how the optimization of the 3D model is slower than the 1D model of about 9 times. The resolution of an FEM model is much more expensive from a computational and time point of view than the resolution of a model implemented in MatLab. This difference is also due to the exporting process of the data coming from the SAP2000®. Indeed, the number of data to be exported and processed is of the order of hundreds of thousands. The optimization process is an automatic process, so the designers are able to employ the saved time in other business activities.
Moreover, it is possible to assume that the total optimization time varies as a function of the height of the chimney. Indeed, the number of stacks that compose the chimney, and thus the number of design variables to be optimized, varies with its height.

Chapter 6

Case study: Air Filtration System

The validity of the proposed framework was further assessed through another case study. An air filtration system AFS used to carry ambient air to a gas turbine was analyzed. This case study will be described discussing only the difference with reference to the chimney case. This description will be used to draw some considerations about the proposed framework rather than describing again all the design steps.

6.1 Filter house description

Gas turbines - GTs are turbo-machines largely used in various industrial sectors. They are widely employed in power generation plants. GT consume a large volume of ambient air during in-service condition. For this reason, the quality of air incoming the system is essential to the overall performance and longevity of a gas turbine. A filtration mechanism is usually employed to regulate the quality of ambient air by removing contaminants. Inadequate filtration system can lead to inlet pressure drop, reduction in output power and overall GT efficiency.
For high-powered turbines, the filter system consists of hundreds of single filters. Therefore, to achieve the best performance, a carefully design is needed. Specifically, is essential to maintain flow conditions at a minimum pressure loss adopting the best suited solution for the operational environment. Optimum use of filters can significantly reduce their costs and maintenance, and maintain the GT output power for an acceptable period. Studies have shown that, for large power generating plants, a slight enhancement in the system filtration efficiency can result in sensibly higher performance [35].

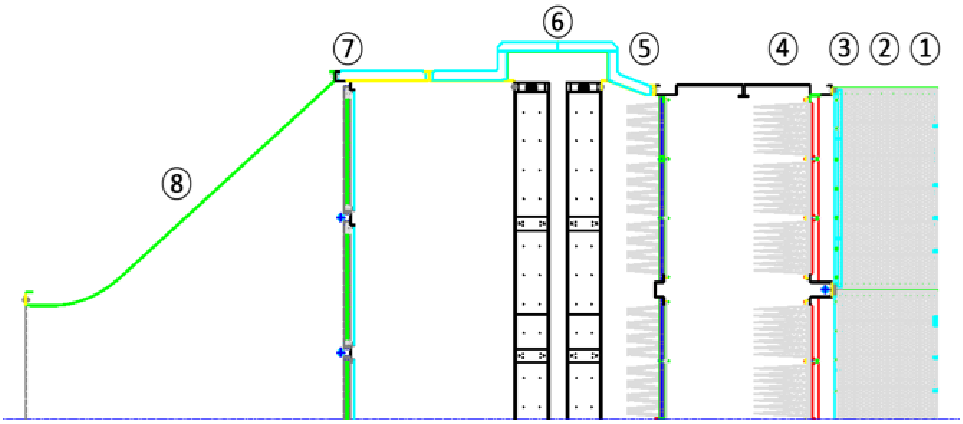


Figure 6.1: Geometry of the investigated air filtration system with its components: 1) weather hood, 2) droplet catchers, 3) bird net, 4 & 5) the filtering stages, 6) inlet air cooling system, 7) demisters, 8) transition section.

Gas turbines are requested to successfully operate under various environmental conditions: rural areas, industrial zones, polar regions, deserts, off-shore etc. Desert regions with high dust concentration and coastal regions with high humidity and airborne salt, produce two of the extreme conditions that have to be taken into account when selecting and designing the most appropriate Air Filtration System. Even in relatively clean environments, a gas turbine may ingest hundreds of kilograms of foreign matter each year. Whether or not this will cause a problem depends on the amount of this material, its physical properties, and its chemical composition. Poor air quality may lead to compressor fouling or compressor erosion as well as corrosion and cooling passages blockage in the hot parts of the gas turbine. Limit as much as possible this amount it is therefore of great importance. This is directly linked to the removal efficiency of the installed filter elements. It is anyway to notice the importance of properly selected additional components (e.g. mist elimination stages) in the overall performance of the Air Filtration System. The filter house analyzed in this thesis consists of the components as reported in Fig. 6.1. At the entry, a weather hood (1) equipped with droplet catchers (2) avoids entry of water inside the filtration system. A bird net (3) is present to prevent entrance of birds and insects. After these, the filtering stages (4-5) of gradually decreasing pore size are equipped. These are followed by an inlet air cooling system (6) to increase GT power output. Finally, a transition section (8) is fitted according to geometrical and layout constraints. At the transition inlet, demisters (7) are present to eliminate condensate from air.

The design of a filter house has as main aim the geometry optimization of the system in order to minimize the air pressure drop. It is extremely important to investigate air flow characteristics such as static pressure, temperature and velocity since they have a direct influence on GT performance. However, this kind of analysis is not a trivial task due to the high complexity of the flow in the air intake system. The local pressure losses are caused by the fluid flowing through the various components (ducts, filters, chiller coils, mist eliminators etc.) which change/influence flow direction. It is impossible to understand a priori the effects of a geometrical modification on the flow field. The use of numerical simulation allows this kind of investigation and enables engineers to propose design changes to improve flow distribution. Cost is another important driver in the design of these systems, and it is directly related to size and efficiency of the system.

6.2 Sequential optimization problem

The proposed framework, as it was more times highlighted, is intended to support the design phases of customized products from the RfP phase till the detailed design. To confirm the validation of the approach, reached thanks to the chimney case study, a filter house is analyzed.
In this specific case, objective functions concern the optimization of the fluid-dynamic characteristics and cost reduction. In particular, minimum pressure losses are searched. Minimization of pressure losses is an important issue since it impacts on GT efficiency. Moreover, the compressor that feeds ambient air into the GT will have to win a lower prevalence.
In Fig. 6.2 the design optimization approach, which is applied at each design level, is described. It is interesting to note as, at the conceptual design phase, a 2D modelling strategy has been used instead of a 1D one. Moreover, the performance assessment has been reached through numerical simulation also during the first design phase. It is important to underline that 2D virtual analyses allow to speed-up, in the same way, the design process. It is obvious that solving a 2D model rather than a 1D model is more time-consuming, nonetheless, the achieved benefits are concrete.
This optimization was performed to assure the meeting of the following design criteria and constraints:

- The velocity through the chiller coil section should be uniform and low

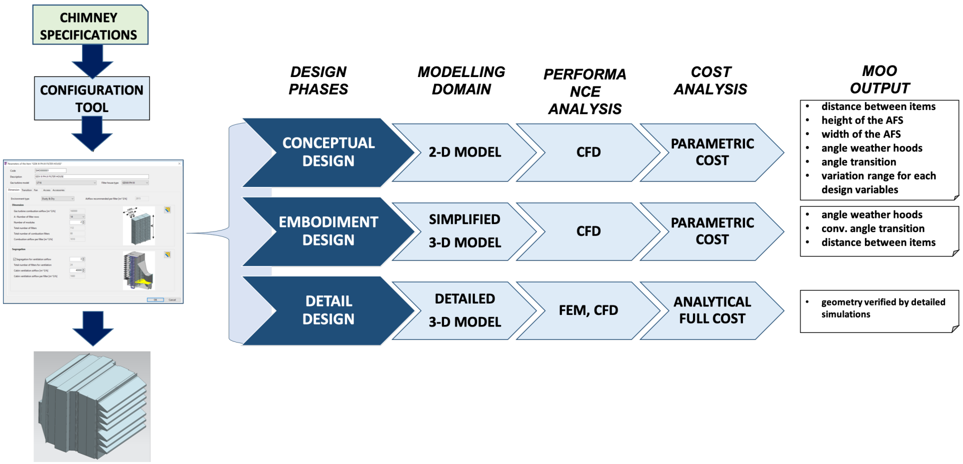


Figure 6.2: Sequential optimization approach of the air filtration system - AFS.

enough to prevent excessive condensed water from being carried downstream.

- The average velocity through the chiller coils should be a maximum of $2.7\ \mathrm{m\,s^{-1}}$ at the ISO design condition. There shall be no artificial flow redistribution devices, such as perforated plate, used within the flow path to meet this velocity requirement. The average velocity is calculated by taking the volumetric flow rate through each coil and dividing by the available face area of the chiller coils.

- The velocity distribution should not vary greater than 20 % as defined in ASHRAE 2000 Systems and Equipment Chapter S21.

- Velocity should be uniform 40 mm from the face of the chiller coils to ensure uniform exiting temperature distribution.

- Precaution shall be taken to assure that the localized high velocities leaving the filter elements shall not result in localized high velocities entering the chiller coil section.

- The inlet filter house shall have a sufficient transition section downstream of the chiller coil section to assure there are no localized high velocities resulting from the airflow transitioning into the inlet ducting.

- The air filtration system should have the minimum cost.

The optimization engine has reached the best configuration modifying the filter house geometry. In particular, the following design variables have been defined: distances between the various items, height and width of the AFS, angle of the weather hoods and convergence angle of the transition duct. The number of filters is determined as a function of the design air mass flow rate. Therefore, this quantity constrains the dimensions of the AFS. Height and width must be such allowing the insertion of all the needed filters. Discrete values are considered for height (7635-10685 mm with 610 mm as step) and width (5490-8540 mm with 610 mm as step). The distances between the components are treated as discrete variable (500 mm as steps). For the transition section, three different angles are considered, i.e. square to square: 35°, 40° and 45° convergence. In the same way, three angles for the weather hood are analyzed: 20°, 30° and 45°. Wide passage sections and great distances between the components allow to reach low speeds and a uniform flow field. However, this implicates higher costs. Therefore, a proper trade-off between these conflicting goals must be achieved. Also this optimization problem is based on the Pareto dominance concept.

6.3 Product configuration

The knowledge-based approach has been also used in this case study for the developed configuration tool. As for the chimney case study, the configuration domain of a filter house gathers all the information related to technical specifications, client requirements, cost targets, installation site, concept solutions etc. It contains rules for components design, configuration, and selection. These rules have been retrieved analyzing experts' practices and data.
Six different categories of configuration attributes can be identified: plant type (power plant, process plant, compression plant), fuel type (natural gas, liquid fuel such as kerosene), installation type (on-shore, off-shore), environment (desert inland, desert coastal, tropical, urban, industrial, rural countryside, coastal, platform, artic), transportation type (sea, road, lifting), machine number and components.
The environmental conditions are the main driver in the selection and configuration of the most suitable filter house. In Fig. 6.3 is reported, as example, one design rule implemented in the configuration tool. Due confidentiality problems no further design rules can be presented.
The geometrical parametrization of the air filtration system concerns only the

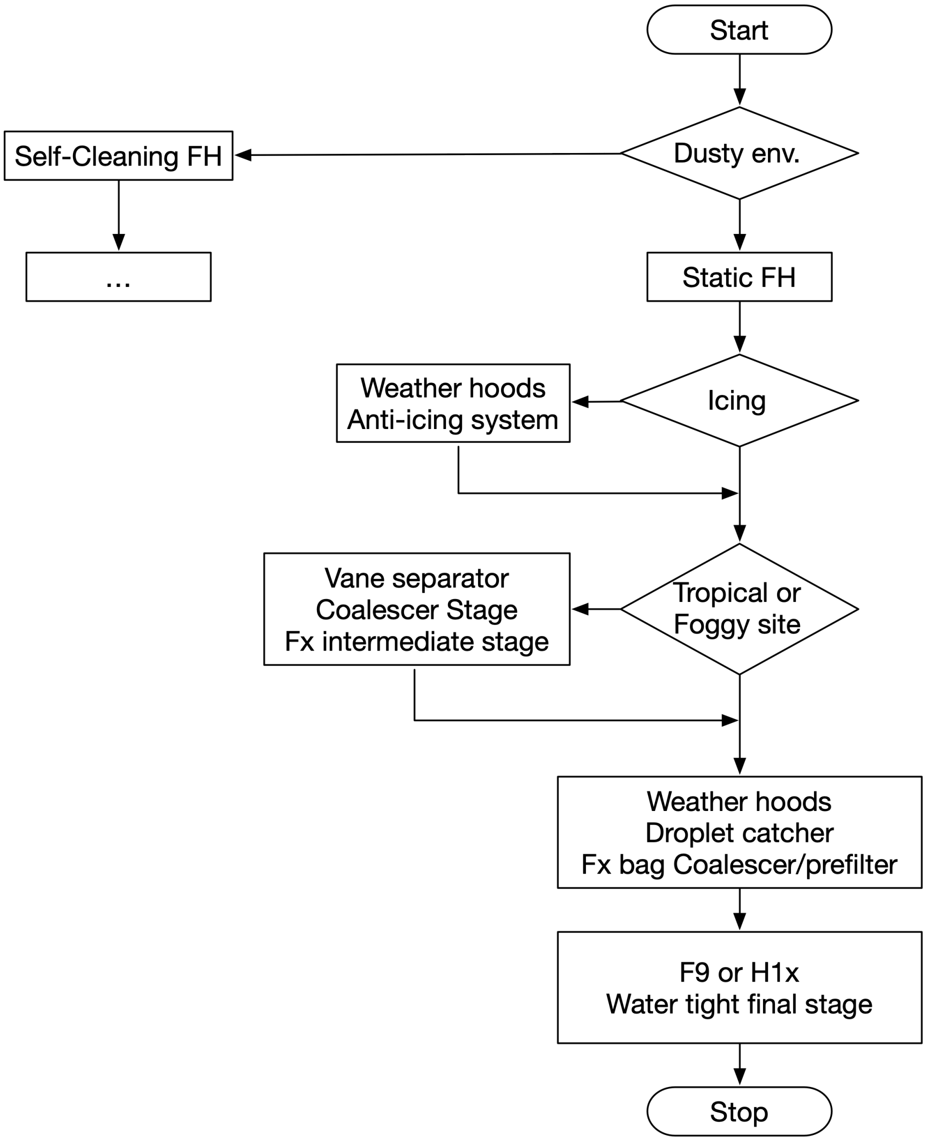


Figure 6.3: Implemented design rule for the selection of a filter house.

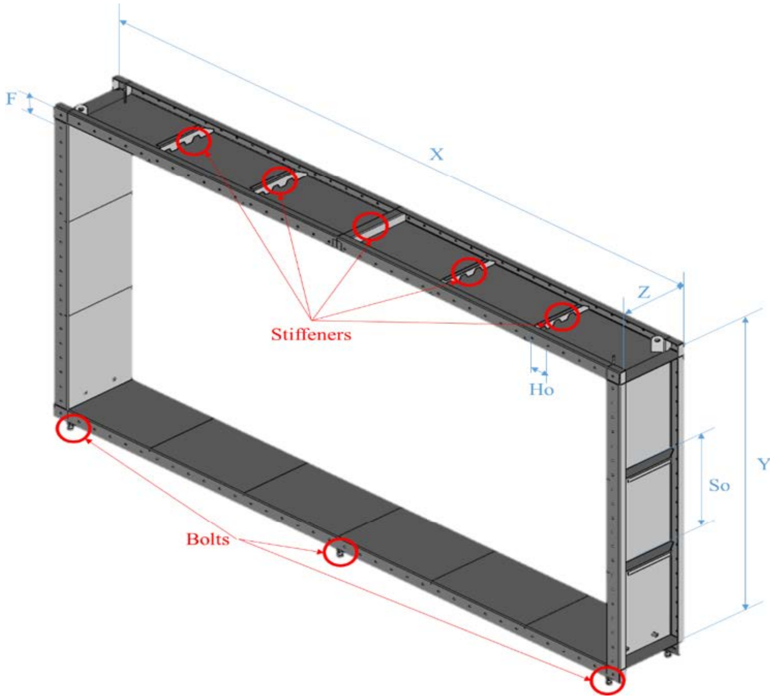


Figure 6.4: Rectangular uninsulated duct.

casing (i.e. the sheet metal parts), all the other items are commercial products with parametric but standardized characteristics. The most important parameters considered for the casing are almost the same described in the previous case study. The air filtration system consists mainly of rectangular ducts. In Fig. 6.4 is reported the parametrization for a rectangular uninsulated duct. The transition duct can be modeled in a similar way considering a supplementary parameter: the angles between the inlet and outlet sections.

6.4 Cost estimation

In the chimney case study, a parametric cost model was developed in case of circular stack. However, that model can not be used to achieve a quotation for an air filtration system. Indeed, in this case mainly rectangular items have to be quoted. Therefore, a further parametric model has been developed. In Tab. 6.2 the developed cost model for rectangular uninsulated duct is reported.
Tab. 6.2 uses the following nomenclature:

- S_r: scrap rate due by nesting problems of the sheet metal (10 % for a

Table 6.1: Parametric cost model for a rectangular uninsulated duct.

Cost item	**Parametric cost formulas**
Material	Material Cost = External case + Stiffening + Commercial items External case = $(2 \cdot X + 2 \cdot Y) \cdot (Z + 3 \cdot F) \cdot T_h \cdot \rho \cdot (1 + S_r/100) \cdot C_m$ Stiffening = $(2 \cdot X + 2 \cdot Y)/(S_o) \cdot Z \cdot F \cdot 2 \cdot T_h \cdot \rho \cdot (1 + (S_r/100)) \cdot C_m$ Commercial items = $C_c \cdot X$
Manufacturing	Construction cost = cutting+bending+welding Cutting = $\{[(2 \cdot X + 2 \cdot Z + 6 \cdot F) + (X/H_o \cdot H_d \cdot \pi)] \cdot 2 + [(2 \cdot Y + 2 \cdot Z + 6 \cdot F) + (Y/H_o \cdot H_d \cdot \pi)] \cdot 2\} \cdot C_c$ Bending = $(16 \cdot T_b + ((2 \cdot X + 2 \cdot Y))/S_o \cdot Tb) \cdot C_b$ Welding = $[((2 \cdot X + 2 \cdot Y))/S_o \cdot 2 \cdot Z + 8 \cdot W] \cdot C_w$
Logistics	Logistics = (External case weight+Stiffening weight) $\cdot C_l$
Assembly	Assembly = $(X + Y)/H_o \cdot 2 \cdot C_s$ + (External case weight+Stiffening weight) $\cdot C_p$
NDT	NDT = Total welding length · NDT unit cost

rectangular shape) [%];

- S_o: offset between the stiffeners (1000 mm for a rectangular shape) [mm];
- ρ: material density [kg/m^3];
- C_m: unitary cost of the raw material [€/m]. It depends by the material;
- C_c: unitary cost of the commercial items (nuts). [€/m] empirical formula.
- H_o: offset between the holes of the flange (generally 150 mm) [mm];
- H_d: diameter of the holes of the flange [mm]
- C_c: unitary cost for the cutting operation [€/m]. It depends by the thickness.
- C_b: unitary cost for bending [€/h]. It depends by the dimensions of the section.
- C_w: unitary cost for welding [€/m]. It depends by the thickness.
- C_l: unitary cost for logistics [€/kg]
- C_s: cost for apply a bolt [€/bolt];

- C_p: Cost for positioning the duct [€/kg].

The parametric cost model and the relative parameters (unitary cost values, configuration rules and standard parameters) have been implemented within Microsoft® Excel® in order to automate the calculation.
The analytical cost estimation method, used for the third optimization level, is based on detailed cost models and feature recognition algorithms for automatically recognizing a manufacturing process from a 3D CAD model. The virtual models managed by the CAD system contain information such as the Bill of Material (BoM), shape, dimensions, tolerances, roughens and general parameters (e.g. heat treatment, coatings, etc.) that drives the manufacturing process. Also for this work, LeanCOST® by Hyperlean srl® has been adopted managing manufacturing and process planning rules.

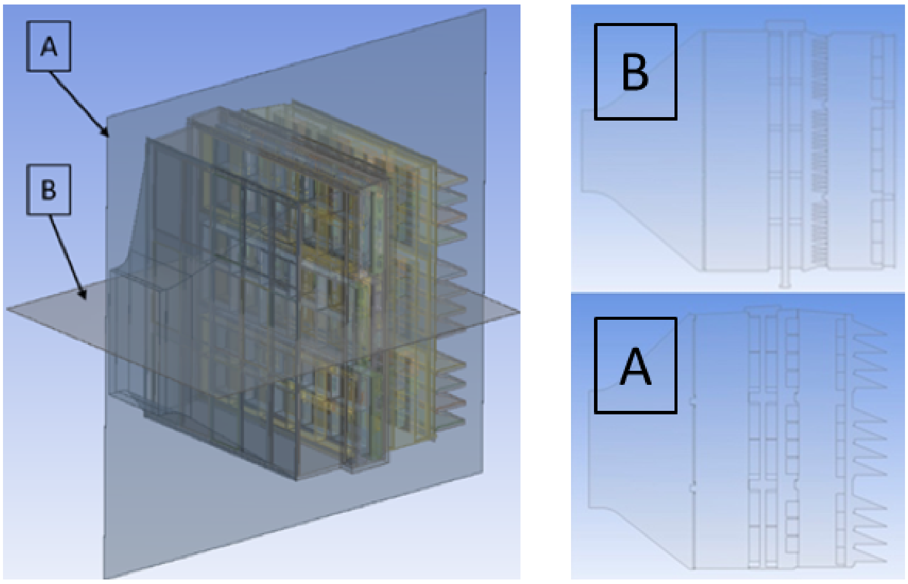
6.5 Performance assessment

In the chimney case study, the performance, during the RfP phase, was assessed solving a 1-D model through analytical calculations. However, in this case, it is not possible investigate the fuild-dynamic of the filter house by means of a 1-D model. Therefore, to speed-up the design process during the preliminary design phase, it was necessary to think to a different modelling strategy.
In literature, various methods have been proposed to reduce computational resources and speed-up the simulation process. The hypothesis of bi-dimensional flow represents one of the most used strategy in different industrial cases. It can be applied when some dimensions could be supposed as equivalent to each other. Nevertheless often, 2D simulations can catch the qualitative trend of a phenomena but they are not able to provide accurate results when quantitative considerations are needed.
Much research in recent years has focused on establishing the results accuracy of a 2D problem representation with respect to a 3D one. As example, Clegg and Kreft [35] studied results discrepancies between 3D and 2D models of microbial biofilms, finding quantitative, but not qualitative, differences between the approaches. Pashchenko [82] represented a micro-cylindrical combustor with a 2D planar, 2D axisymmetric and 3D meshes, establishing quantitative distinctness for the temperature field but almost no deviation for the pressure one. Li et al. [64] assessed dissimilarity between the two approaches in case of circulating fluidized bed risers, recommending 2D simulations only for qualitative consider-

ations and 3D for predictive simulations.
The aim of this case study is to show as it was possible to optimize filter houses integrating in a unique framework 3D and 2D simulations. 2D simulation are exploited to speed-up the design process reducing computational time and resources. Analyzing the geometry of the filter house, it was possible to conclude that to achieve all the necessary design considerations two section should be analyzed (shown in Fig. 6.5(b)). It is evident how the accuracy of 2D models have to be assessed through the confrontation with validated 3D simulations. In literature, no research studies addressing this issue can be found.

6.5.1 Numerical simulation

Ansys Fluent® was used as CFD simulation tool for the analysis of the thermo-fluidynamic behavior of the filter house. The system considered in this study is installed in India with an ambient air temperature of 35 °C. The investigated GT, at the ISO design condition, has a power output of 32 kW, an air flow rate of 417000 m^3/h and a ventilation air flow of 71500 m^3/h.
The geometry of the air treatment system was created thanks to the use of the configuration tool. For the 3D model, as the filtering house was symmetric, the geometry was simplified considering only half part of it (Fig. 6.5(a) shows the full geometry). Instead, for the 2D model, the lateral and top sections passing across the middle planes were analyzed (Fig. 6.5(b)).
The components considered by this study are: housing ducts, 120 M6 filters, 110 F9 filters, 2 chiller coils stages, droplet catchers, demisters and bird nets. The M6 and F9 filters are found, respectively, at the first and second stage of the filtration system. The M6 filter traps coarse particles while the F9 filter is capable of filtering fine particles. The heat absorbed by the first and second chilling stage is, respectively, of 1127 kW and 923 kW.
Polyhedral elements were used to mesh the 3D geometry while the 2D geometries were discretized with triangular elements. A grid independency check was performed both for bi-dimensional and three-dimensional modelling. It was found that for the 3D geometry extending the cells count above 12085756 does not significantly influence final results; for the 2D geometry increasing the cells number above 201294, for the lateral section, and 197045, for the top section, does not produce a significant effect on results. The average orthogonal quality was of 0.91, for the 3D mesh, and 0.95, for the 2D meshes.



(a) (b)

Figure 6.5: a) 3D model of the filter house, b) 2D top and lateral section model.

Boundary conditions

The boundary conditions considered in this analysis was defined as follow:

- static pressure at inlet = 0 Pa (ambient pressure),
- air temperature at inlet = 35 °C,
- static pressure at outlet = -440 Pa,
- static pressure at ventilation outlet = -270 Pa,
- turbulence medium intensity = 5%,
- filters pressure loss modeled as porous media,
- chiller coils heat exchange modeled as heat sink,
- all the filter house walls are treated as adiabatic walls.

The fluid passing through the system was modeled as saturated air. In Tab. 6.2 are reported the fluid properties.

Table 6.2: Saturated air properties.

Fluid properties SATURETED AIR				
Temp [°C]	*Density [kg/m3]*	*Viscosity [kg/(ms)]*	*Thermal conductivity [W/(mK)]*	*Specific heat capacity [J/(kgK)]*
15	*1.217*	*1.78E-05*	*0.0251*	*1015.5*
20	*1.194*	*1.80E-05*	*0.02542*	*1017.52*
25	*1.171*	*1.81E-05*	*0.02572*	*1021.39*
30	*1.148*	*1.82E-05*	*0.02601*	*1027.78*
35	*1.124*	*1.83E-05*	*0.02626*	*1036.96*
40	*1.1*	*1.84E-05*	*0.02649*	*1049.01*

Filters pressure loss

The pressure losses through the filtration stages were modeled as porous media in ANSYS Fluent®. The superficial velocity porous formulation was used. This kind of formulation generally gives a well representation of the pressure drop across a porous component. Porous media are taken into account adding a momentum source term, composed by a viscous loss term and an inertial loss term, to the standard flow equations. This momentum source term S_i for a simple homogeneous porous media can be described as:

$$S_i = -\Big(\frac{\mu}{\alpha} v_i + C - i\frac{1}{2}\rho |v| v_i\Big) \tag{6.1}$$

Where α is the permeability, C_2 is the inertial resistance factor, ρ the density, v the velocity and μ the dynamic viscosity.

Numerical approach

The numerical simulation was performed assuming a steady-state turbulent flow. The adopted general governing equations of mass, momentum and energy conservation were:

$$\begin{cases} \text{Continuity equation:} & \frac{\partial}{\partial x_i}(\rho u_i) = 0 \\ \text{Momentum equation:} & \frac{\partial}{\partial x_i}(\rho u_i u_k) = \frac{\partial}{\partial x_i}\big(\mu \frac{\partial u_k}{\partial x_i}\big) - \frac{\partial p}{\partial x_k} \\ \text{Energy equation:} & \frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\big(\frac{k}{c_p}\frac{\partial T}{\partial x_i}\big) - \frac{\partial p}{\partial x_k} \end{cases} \tag{6.2}$$

where u is the velocity, x the direction, ρ the density, μ the dynamic viscosity,

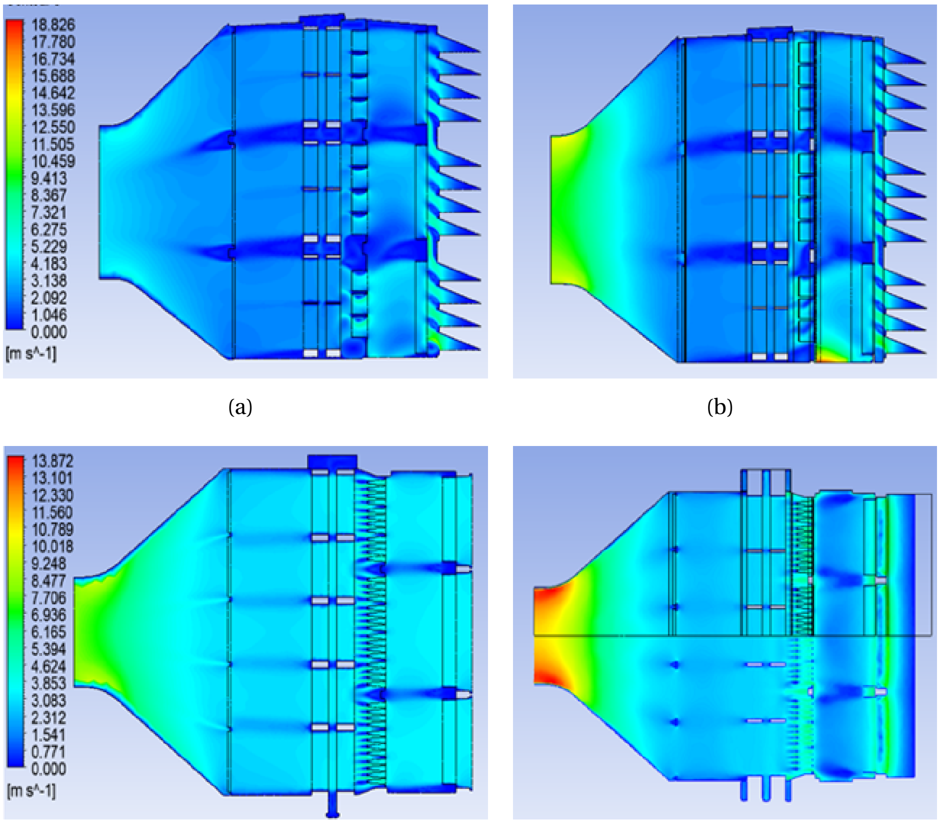
p the pressure, T the temperature, C_p the heat capacity at constant pressure and k the fluid thermal conductivity.
The shear-stress transport (SST) $k-\omega$ viscous model was adopted to take into account turbulence. Transport equations for SST $k-\omega$ model are:

$$\begin{cases} \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_k}\left(\Gamma_k \frac{\partial k}{\partial x_k}\right) + \tilde{G_k} - Y_k + S_k \\ \frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_k}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_k}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \end{cases} \tag{6.3}$$

where $\tilde{G_k}$ represents the generation of turbulence kinetic energy due to mean velocity gradients, G_ω the generation of ω, Γ_k and Γ_ω the effective diffusivity of k and ω, Y_k and Y_ω the dissipation of k and ω due to turbulence, D_ω the cross-diffusion term and S_k and S_ω are user-defined source terms.
The governing equations were solved by the COUPLED algorithm. Second-order upwind scheme was chosen for the discretization of the convection terms of each governing equation and pseudo-transient approach was enabled for the 3D numerical simulation. Type of initialization was hybrid. The convergence criteria, both for the 3D and 2D model, were posed at the tolerance of 10^{-4} for momentum and continuity and at 10^{-6} for energy.
It is important to underline that every numerical simulation should be validated by experimental tests. For the chimney case study, the validation was not necessary since there is an extensive literature about the assessment of mechanical performance of steel structure by De Saint Venant's theory and FEM method. Contrary, in this case the goodness of the results provided by these numerical models has been assessed by benchmark testing for the 3D model. Velocity, pressure and temperature have been measured in separated experiments. The comparison shows a good agreement between virtual results and real data coming from physical experiments and analytical calculations. The field of pressure, velocity and temperature are properly reconstructed with an average error less than 5%.

6.5.2 Validation of 2D modelling strategy

The presented design optimization framework proposes to speed-up the design phases by means of simplified models during the first phases and 3D full model for the last stage. A 2D modelling strategy has been proposed for the RfP phase. The accuracy of this strategy needs to be validated. Therefore, a confrontation between the results of 2D and 3D simulations was carried-out.



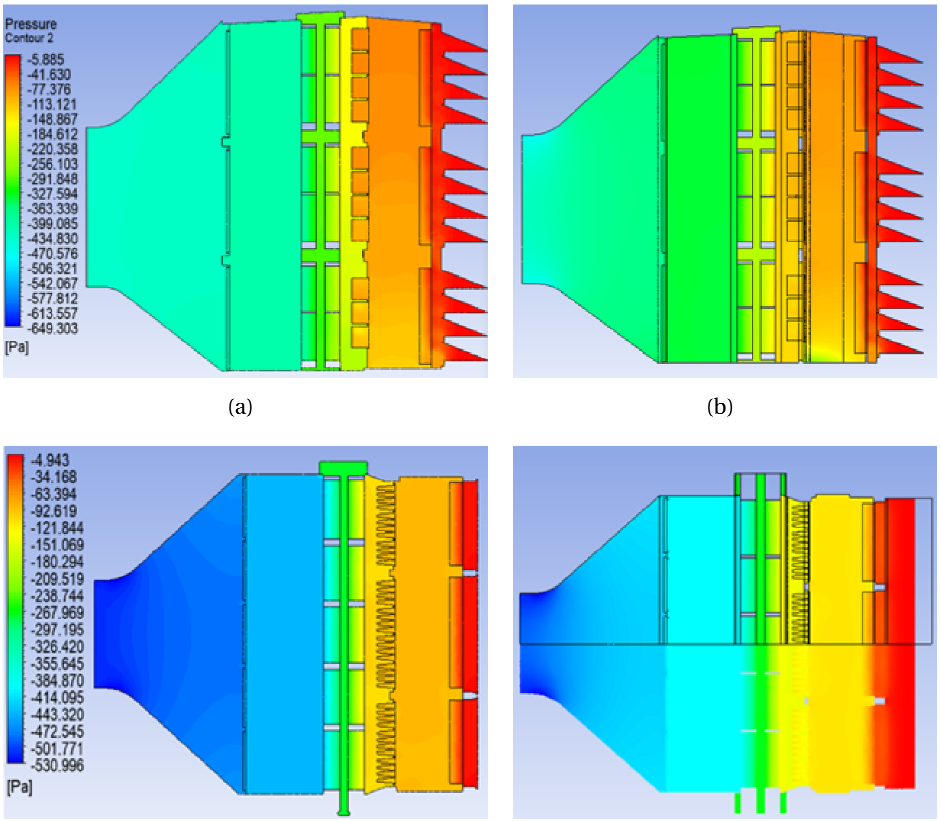
(a) (b) (c) (d)

Figure 6.6: Trend of velocity: a) A section of the 2D model, b) A section of the 3D model, c) B section of the 2D model, d) B section of the 3D model.

The 2D models simulate the two middle sections (section A and section B) described in Fig. 6.5(b). Analyzing the results, it is possible to observe the following considerations.

By assessing the velocity results (Fig. 6.6), it is possible to note that the 2D model can reproduce correctly the velocity trend in both analyzed planes. The velocity profiles between the passage of different filtering stages, air cooling system and demister are the same. The major discrepancies can be noted in the transition zone. In this zone, the 2D model it is not able to correctly reproduce velocity profile, due to the double variation of section in the two considered planes. The average error on the outlet section is around 25 % but the average error considering the all model is about 5 %.

By analyzing Fig. 6.7, it is possible to verify that the pressure profile between the 2D and 3D models is similar, because the flow field is correctly reconstructed.



(a) (b) (c) (d)

Figure 6.7: Trend of pressure: a) A section of the 2D model, b) A section of the 3D model, c) B section of the 2D model, d) B section of the 3D model.

The pressure average value is correctly reproduced in terms of profile trend and value, the average error is of 3 %.

The temperatures comparison of the 2D and 3D models shows a similar trend between two modeling strategies (as shown in Fig. 6.8). In both models the same temperature variation is observed in the passage between the chillers. The latter was simulated as porous jump in which have been set the value of pressure loss and thermal power. In this application the chillers have the function to decrease the incoming air temperature, so the value of thermal power is negative. Unlike the velocity and pressure trends, the temperature profile appears to be consistent for both models also in the transition zone. At the outlet section, the average temperature presents a difference greater than 5 % and the average error on the all model is 3 %.

An interesting conclusion can be drawn about the use of a 2D modelling strategy.

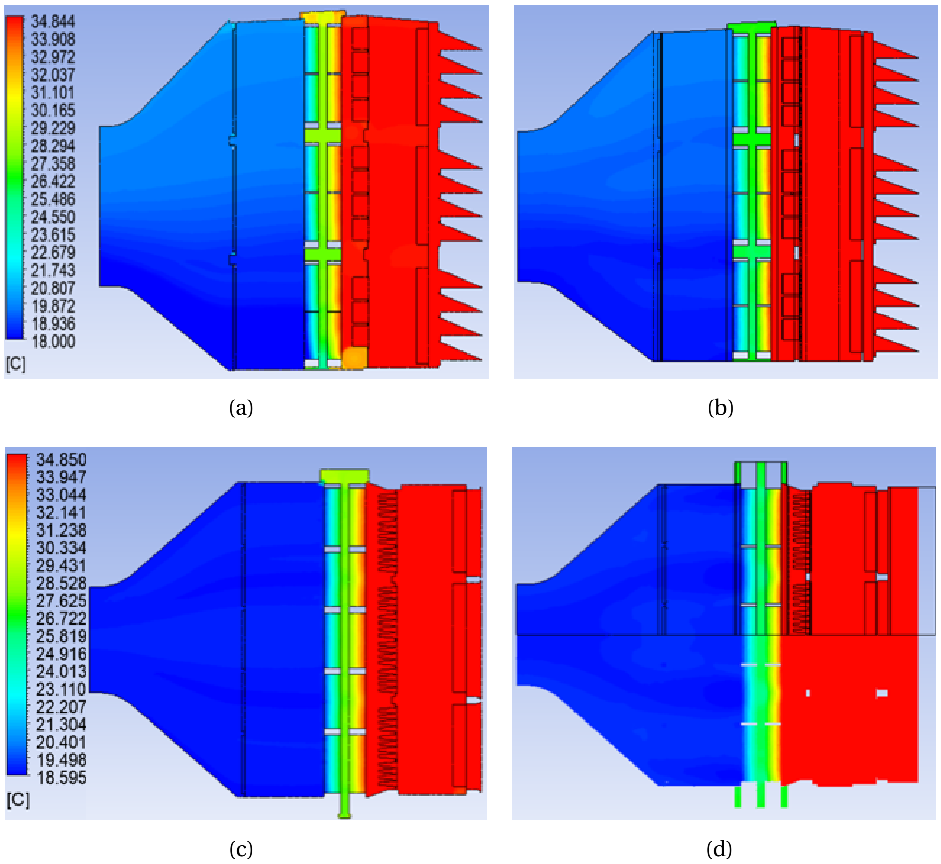


Figure 6.8: Trend of temperature: a) A section of the 2D model, b) A section of the 3D model, c) B section of the 2D model, d) B section of the 3D model.

Generally, the bi-dimensional approach is intended to speed-up the simulation process losing in results accuracy. However, in this specific case, through this approach it has been also possible simulating specific areas or zone of the model without any simplification. In the analyzed filter house, due to the high geometric dimensions and complexity of the details, the geometry of the M6 filters has been simplified as a parallelepiped in the 3D model, locally losing their geometric characteristics. Also in the last phase of the design process where a full 3D model is used, the real geometry of the filter was neglected due to computational issues. With 2D models the real geometry can be considered, simulating accurately their influence upon the field of motion, pressure and temperature during the fluid passage. In Fig. 6.9 is showed the velocity field considering the real M6 filter geometry.

It can be concluded that the 2D modelling strategy can be exploited to draw the

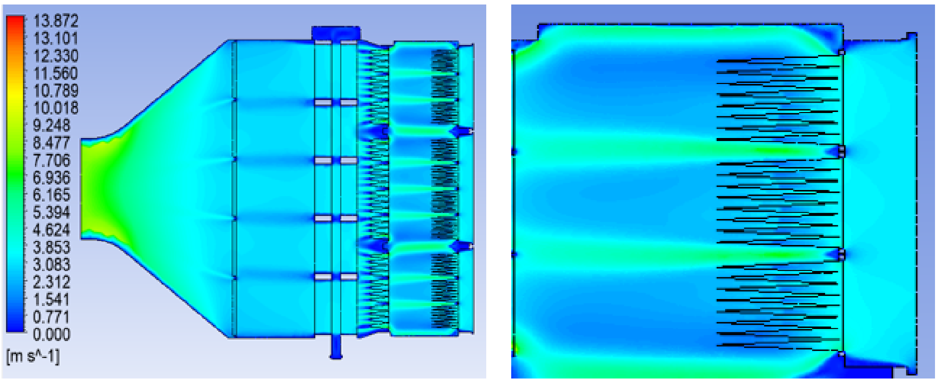


Figure 6.9: Trend of velocity on the B section considering the real M6 geometry

necessary design conclusions during the RfP phase. The results show a good correspondence between the models, with a deviation less than 5 % for each section.
The pre-processing time, when using a 2D modeling strategy, doubles compared to the 3D one. Indeed, in order to have a complete characterization of the system, it is necessary to simulate two different sections of the filter house and then performing twice the setting operations of the model (pre-processing). On the contrary, the use of 2D models allowed to reduce calculation time by 90 %.

6.5.3 Simplified and full 3D model

The second and third level of design focuses on 3D analyses. Simplified analysis for the second level and detailed for the third stage. The optimization-objectives are the same of the previous level while the tools are different. Indeed, the flow field is solved by a 3D CFD solver. Moreover, during the detailed design, also 3D FEM analysis are conducted. To produce an executive design even the mechanical strength have to be assessed.
The phase of the 3-D modelling concerns the definition of the complete geometrical structure of the product. However, the simplified 3D model continues to neglect some auxiliary components. Contrary, the detailed 3D one considers all the parts. Thus, components such as ladders and pipes are analyzed only during the III-MOO phase.
The computational resources to solve these 3D models are high. In particular, almost 24 hours of calculation is necessary to reach the convergence criteria for the simplified 3D simulation and 28 hours for the 3D full model. This calculation

time refers to the use of a workstation with 12 core (2.7 GHz) and 64 GB of RAM.

6.6 Optimization procedure

The definition of a three-levels approach for the design optimization of ETO products aims to provide tools and methods to support the typical project phases. The genetic algorithms method is common for each proposed level of optimization. A MOGA-II solver has been used due to the efficiency of this algorithm for multi-objective optimization. In fact, MOGA means Multi-Objective Genetic Algorithm and it uses a smart multi-search elitism, which can preserve some excellent solutions without bringing premature convergence to local-optimal frontiers. This algorithm is DOE (Design of Experiment) based and requires a maximum number of generations. The definition of a DOE table is applicable in the design-context for ETO systems. Indeed, several products, classified in specific product families, are parametrized with specific rules. This means that most of the parameters can assume only discrete values. Beside the product parametrization, designers, for respecting the design constraints (e.g. AFS length), can customize several product attributes (e.g. AFS height and width).
One of the main goals of the proposed framework is to enhance the product time-to-market. However, the AFS optimization, due to the high computational time required by the 3D simulations, is time consuming. Therefore, to solve this big and critical issue a different optimization procedure has been adopted. A virtual experimental campaign according to a Space Filler DOE strategy is carried-out. Then, the DoE results have been used to create the response surfaces. The polynomial SVD algorithm has been chosen to determine the correlation between design variables and objectives. Thus, the optimal configuration has been reached by the MOGA-II algorithm exploring a meta-model, saving lots of design time. Indeed, the optimization on response surfaces is rapid (few minutes). The time saving is estimated in -80 % if compared to a traditional optimization procedure.

6.7 Results and discussion

The presented approach has been used to redesign an existing AFS. In Fig. 6.10 is shown the achieved optimal configuration. Due to confidentiality problems the geometrical quotation can not be reported. The results presented in Fig. 6.6, 6.7

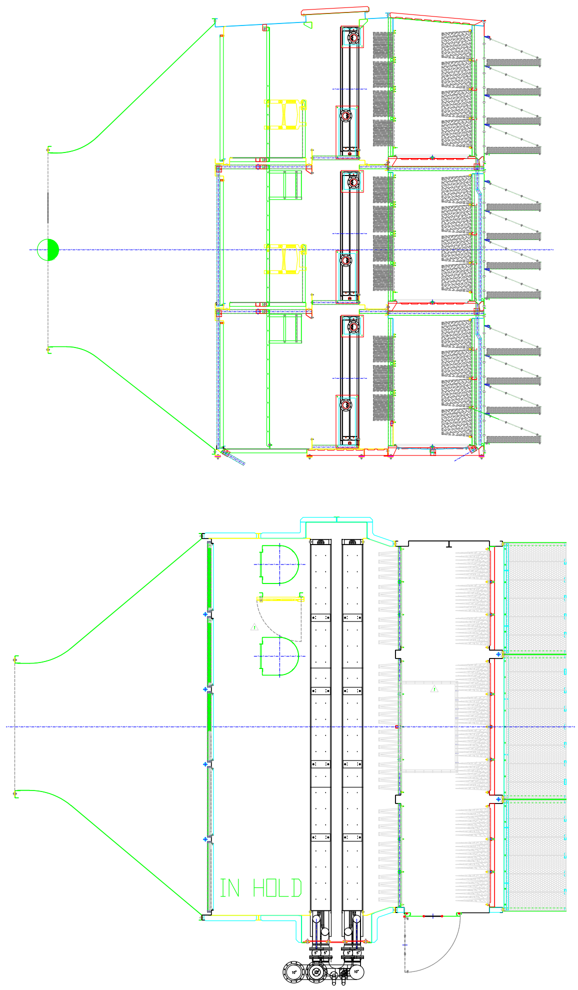
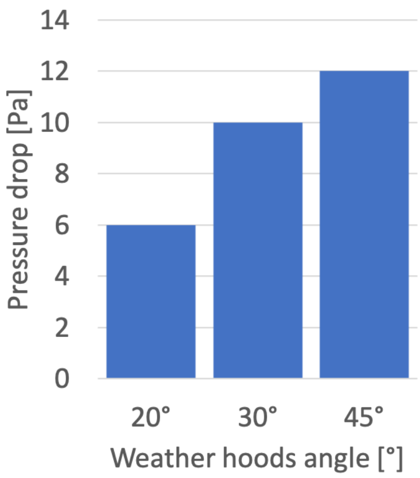


Figure 6.10: Optimal configuration for the air filtration system.

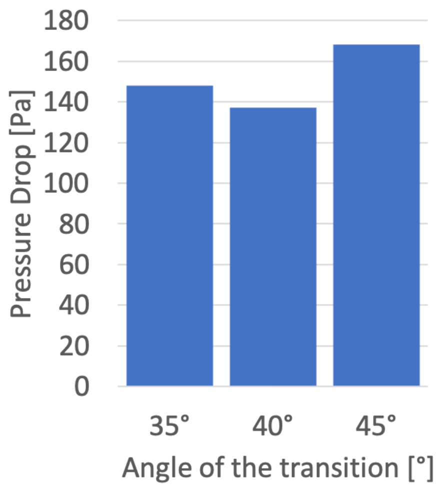
and 6.8 are referred to the optimal configuration.

From the calculations for the weather hood with the bird screen, it can be seen that minimum pressure drop is obtained for weather hood angle of 20° (as shown in Fig. 6.11(a)). From the calculations for transition section, it can be seen that minimum pressure drop is obtained for transition angle of 40° (as shown in Fig. 6.11(b)).

The achieved results have been compared with the AFS designed with the traditional approach. In particular, in Fig. 6.12 the confrontation between the velocity (at the inlet section of the first chiller coils) of the real case (Fig. 6.12(a)) and the optimal configuration (Fig. 6.12(b)) is shown. It is possible to conclude that all the design criteria have been met and enhanced performance have been reached.



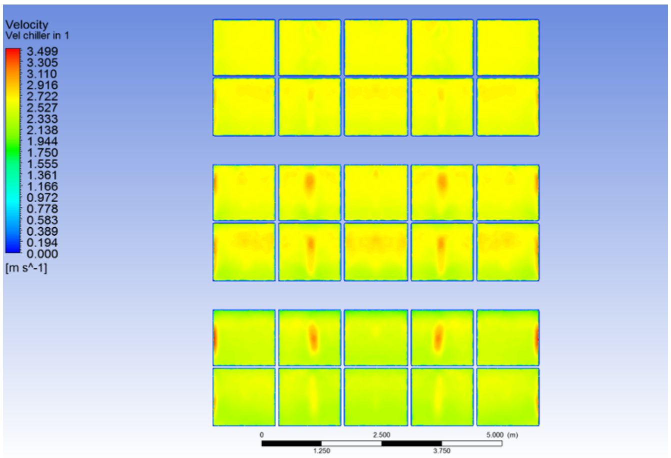
(a)



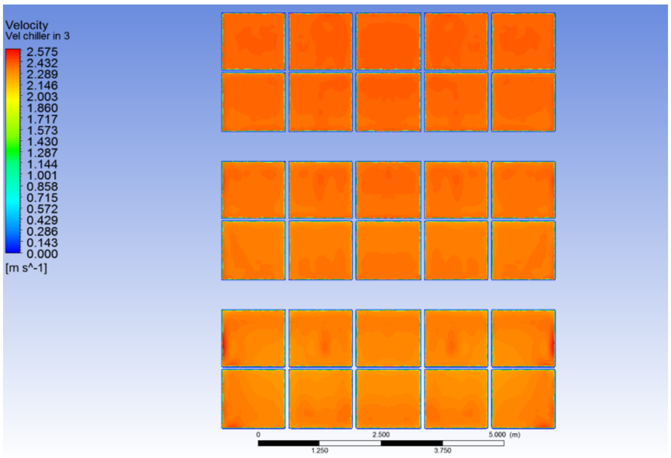
(b)

Figure 6.11: Pressure drop: a) weather hoods, b) transition duct.

The use of the mentioned approach was able to identify the optimal solution, saving 8 % of total cost and 10 % of total pressure loss, compared to the real case. The automation of this methodology allows to save engineers employment time necessary for the optimization processes. In fact, the traditional design approach (trial and error) requires high interaction with the designers while, in the proposed one, it is automatically performed by the optimization tool. Therefore, designers are able to employ the saved time in other business activities.
Thanks to this case study, it was possible to demonstrate that the presented framework is applicable during the design of different products. The methods and tools are flexible enough to be exploited in several engineering contexts. The accuracy of the reached results and the readiness to respond allow to achieve a great competitive advantage.



(a)



(b)

Figure 6.12: Confrontation between the velocity (at the inlet section of the first chiller coils) of the real case (a) and the optimal configuration (b).

Chapter 7

Conclusions and future works

The major contribution of this research work has been to develop a sequential and multi-objective optimization framework for supporting the design of Engineer-to-Order products. The aim is to help engineers in the designing of products and in reducing manufacturing and installation costs while meeting performances requirements.

The proposed method is based on three stages of optimization. The first involves preliminary design whereby companies receive a request for proposal (RfP). At this point, little information about the order is available, and limited time is available to formulate an offer (a few weeks). Thus, parametric cost models and simplified 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 3D 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 numerical 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.

A list of the main outcomes reached with the developed design optimization frameworks (methods and tools) are listed as follow:

- reaching an optimal design configuration
- designing more high-performance, cost-effective, and efficient products
- reduce errors
- avoiding scraps and reworks

- accommodating for more customization
- increasing the company's win rates
- achieving a competitive advantage through faster design and more cost-effective products
- decreasing the occurrence of damages liquidation
- managing in a simpler way engineering change requests

The relevant outcome of the proposed work has been the definition of a design optimization framework to deal with the current challenges of Engineering-to-Order products. In this research effort, two different case studies demonstrate the strength and the robustness of the proposed design method through the application of the related method.
In particular, the approach 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 soil and is 45 m tall. Its inner diameter is roughly 5 m and gas temperatures reach 440 °C. To validate the proposed method, a comparison between the typical design process and that based on the proposed method was carried out. For cost estimations, a company may propose an offer around 7 % cheaper than that already made. Once an order is made, a company can save around 10 % on costs while remaining within structural constraints using the presented method. Regarding time considerations, a company is able to speed-up all the phases of the product development process.
Though this 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. To demonstrate this, the proposed sequential MOO process was also used for the development of an air filtration system. Thanks to this second case study a concrete validation of the developed framework was reached.
Experimentations reveal that the use of this design process leads to relevant improvements in the product performance, cost and design time. Furthermore, the framework enable even less experienced engineers to reach optimal design solutions.
It is important to underline how the proposed approach can be used starting from the early activities of the PDP. This is absolutely fundamental in order to

reduce the time and the cost of the design process, enhancing, at the same time, product quality.
For sure, further improvements are needed to increase the quality of obtained results. These results shall be supported by the application of the proposed approach on other different industrial fields.
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 models validation, uncertainty management, optimization problem formulation and optimization algorithms as well as efficient 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? What should be the aspects that drive the design becoming constraining? 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 estimated costs resulting when using parametric cost models and especially during the first design stage.
Finally, other design objectives should be considered. For example, a Life Cycle Assessment analysis could be added to the proposed optimization workflow as another development. Indeed, environmental considerations have been becoming always more important to produce competitive products [26].

Bibliography

[1] Russell L. Ackoff. From Data to Wisdom. *Journal of Applied Systems Analysis*, 16:3–9, 1989.

[2] Maryam Alavi and Dorothy Leidner. Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues. *MIS Quarterly*, 25(1):107–136, 2001.

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

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

[5] Aicha Amrani, Salah Zouggar, Marc Zolghadri, and Philippe Girard. Supporting framework to improve Engineer-To-Order product lead-times. *IFAC Proceedings Volumes*, 43(17):102–107, 2010.

[6] P.E Anderson, David M. *Design for manufacturability: optimizing cost, quality, and time to market.* Lafayette, Calif.: CIM Press, 1990.

[7] M.C. Andrade, R.C. Pessanha Filho, A.M. Espozel, L.O.A. Maia, and R.Y. Qassim. Activity-based costing for production learning. *International Journal of Production Economics*, 62:175–180, 1999.

[8] Samuel André, Fredrik Elgh, Joel Johansson, and Roland Stolt. The design platform–a coherent platform description of heterogeneous design assets for suppliers of highly customised systems. *Journal of Engineering Design*, 28(10-12):599–626, dec 2017.

[9] Australian Standard. AS 4100 - 1998: Steel structures designs. Technical report, 1998.

[10] Australian Standard. AS1170 - 2011: Structural design actions. Technical report, 2011.

[11] Amir Sajjad Bahman and Francesco Iannuzzo. 8 - Computer-aided engineering simulations. In Katsuaki B T Wide Bandgap Power Semiconductor Packaging Suganuma, editor, *Woodhead Publishing Series in Electronic and Optical Materials*, pages 199–223. Woodhead Publishing, 2018.

[12] Manuel Barraza, Edén Bojórquez, Eduardo Fernández-González, and Alfredo Reyes-Salazar. Multi-objective optimization of structural steel buildings under earthquake loads using NSGA-II and PSO. *KSCE Journal of Civil Engineering*, 21(2):488–500, 2017.

[13] J. Becker and M. Prischmann. Supporting the design process with neural network complex application of cooperating neural networks and its implementation. *Journal of Information Scienceand Technology*, 3:79–95, 1993.

[14] Ashok D. Belegundu and Tirupathi R. Chandrupatla. *OPTIMIZATION CONCEPTS AND APPLICATIONS IN ENGINEERING*. Cambridge university press, 2nd editio edition, 1999.

[15] George E. P. Box and Norman R. Draper. *Response Surfaces, Mixtures, and Ridge Analyses*. John Wiley & Sons, Inc., Hoboken, NJ, USA, mar 2007.

[16] George E. P. Box, J. Stuart Hunter, and William G. Hunter. *Statistics for Experimenters: Design, Innovation, and Discovery*. Wiley, 2nd editio edition, 2005.

[17] Antoine Brière-Côté, Louis Rivest, and Alain Desrochers. Adaptive generic product structure modelling for design reuse in engineer-to-order products. *Computers in Industry*, 61(1):53–65, 2010.

[18] Jim Brown. Driving Engineer-to-Order Differentiation and Profitability. Technical report, Tech-Clarity, 2016.

[19] D Bruno, P Lonetti, and A Pascuzzo. An optimization model for the design of network arch bridges. *Computers & Structures*, 170:13–25, jul 2016.

[20] Hendri D.S. Budiono, Gandjar Kiswanto, and Tresna P. Soemardi. Estimation During the Early Design Phase Related To the. *International Journal of Technology*, 2:183–192, 2014.

[21] F. Caron. Large Engineering Projects: The Oil and Gas Case. In *Managing the Continuum: Certainty, Uncertainty, Unpredictability in Large Engineering Projects*, pages 11–14. Springer, Milano, 2013.

[22] F Caron and A Fiore. 'Engineer to order' companies: how to integrate manufacturing and innovative processes. *International Journal of Project Management*, 13(5):313–319, 1995.

[23] Vincenzo Castorani, Paolo Cicconi, Marco Mandolini, Alessio Vita, and Michele Germani. A method for the cost optimization of industrial electrical routings. *Computer-Aided Design and Applications*, 15(5):747–756, mar 2018.

[24] Vincenzo Castorani, Daniele Landi, and Michele Germani. Determination of the Optimal Configuration of Energy Recovery Ventilator through Virtual Prototyping and DoE Techniques. *Procedia CIRP*, 50:52–57, 2016.

[25] Vincenzo Castorani, Daniele Landi, Marco Mandolini, and Michele Germani. Design Optimization of Customizable Centrifugal Industrial Blowers for Gas Turbine Power Plants. *Computer-Aided Design and Applications*, page In Press, 2019.

[26] Vincenzo Castorani, Marta Rossi, Michele Germani, Marco Mandolini, and Alessio Vita. Life Cycle Assessment of Home Smart Objects: Kitchen Hood Cases. *Procedia CIRP*, 69(May):499–504, 2018.

[27] Vincenzo Castorani, Alessio Vita, Marco Mandolini, and Michele Germani. A CAD-based Method for Multi-objectives Optimization of Mechanical Products. In *Proceedings of CAD'16*, volume 1, pages 168–172, 2016.

[28] Vincenzo Castorani, Alessio Vita, Marco Mandolini, and Michele Germani. A CAD-based Method for Multi-objectives Optimization of Mechanical Products. *Computer-Aided Design and Applications*, 1(5):168–172, 2017.

[29] M Cederfeldt and F Elgh. Design Automation in SMEs-Current State, Potential, Need and Requirements. In *Proceedings ICED 05, the 15th International*

Conference on Engineering Design, Melbourne, Australia, 15.-18.08.2005, pages 1–15, Melbourne, 2005.

[30] Senthil K. Chandrasegaran, Karthik Ramani, Ram D. Sriram, Imré Horváth, Alain Bernard, Ramy F. Harik, and Wei Gao. The evolution, challenges, and future of knowledge representation in product design systems. *CAD Computer Aided Design*, 45(2):204–228, 2013.

[31] Altannar Chinchuluun, Panos M. Pardalos, Athanasios Migdalas, and Leonidas Pitsoulis, editors. *PARETO OPTIMALITY , GAME THEORY AND EQUILIBRIA*. Springer, New York, NY, 2008.

[32] P. Cicconi, V. Castorani, M. Germani, M. Mandolini, and A. Vita. A multi-objective and multi-level design optimization method for oil & gas ducts. In *Proceedings of the ASME Design Engineering Technical Conference*, volume 2B-2017, 2017.

[33] Paolo Cicconi, Michele Germani, Sergio Bondi, Alessandro Zuliani, and Emanuele Cagnacci. A Design Methodology to Support the Optimization of Steel Structures. *Procedia CIRP*, 50:58–64, 2016.

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

[35] Carlo Coltri. Innovative Technologies for Gas Turbine Air Filtration. Technical Report April, 2013.

[36] Veronica Czitrom. One-Factor-at a Tim Versus Designed Experiments. *The American Statistician*, 53(2):126–131, 1999.

[37] Luiza Daschievici, Daniela Ghelase, and Alexandru Epureanu. Modeling and estimation of the product time and cost in manufacturing system-market relationship. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 8(4):277–282, 2014.

[38] Aldo Duchi, Filippo Tamburini, Daniele Parisi, Omid Maghazei, and Paul Schönsleben. From ETO to Mass Customization: A Two-Horizon ETO Enabling Process. In *Managing Complexity*, pages 99–113. Springer, Cham, 2017.

[39] P. Duverlie and J. M. Castelain. Cost estimation during design step: Parametric method versus case based reasoning method. *International Journal of Advanced Manufacturing Technology*, 15(12):895–906, dec 1999.

[40] Klaus Ehrlenspiel, Alfons Kiewert, and Udo Lindemann. *Cost-Efficient Design*. Springer, iv edition edition, 1998.

[41] M El Semelawy, A O Nassef, and A A El Damatty. Design of Prestressed Concrete Flat Slab Using Modern Heuristic Optimization Techniques. *Expert Syst. Appl.*, 39(5):5758–5766, apr 2012.

[42] M. Farshchin, C.V. Camp, and M. Maniat. Multi-class teaching–learning-based optimization for truss design with frequency constraints. *Engineering Structures*, 106:355–369, 2016.

[43] Cipriano Forza and Fabrizio Salvador. *Product Information Management for Mass Customization*. Palgrave Macmillan, New York, 2006.

[44] K.H. Grote G. Pahl, W. Beitz, J. Feldhusen. *Engineering Design : A systematic approach*. Springer, 2004.

[45] Saeed Gholizadeh and Amir Baghchevan. Multi-objective seismic design optimization of steel frames by a chaotic meta-heuristic algorithm. *Engineering with Computers*, 33(4):1045–1060, oct 2017.

[46] I. Giagkiozis and P. J. Fleming. Methods for multi-objective optimization: An analysis. *Information Sciences*, 2015.

[47] David E Goldberg. *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1st edition, 1989.

[48] Y. Gong, Y. Xue, L. Xu, and D.E. Grierson. Energy-based design optimization of steel building frameworks using nonlinear response history analysis. *Journal of Constructional Steel Research*, 68(1):43–50, 2012.

[49] Robert M Grant. Toward a Knowledge-Based Theory of the Firm. *Strategic Management Journal*, 17:109–122, 1996.

[50] Anil K Gupta and Vijay Govindarajan. Knowledge flows within multinational corporations. *Strategic Management Journal*, 21(4):473–496, mar 2000.

[51] Yousef Haik and tamer m. Shahin. *Engineering Design Process*, volume 134. Cengage Learning, 2003.

[52] Grady Hanrahan and Kenneth Lu. Application of Factorial and Response Surface Methodology in Modern Experimental Design and Optimization. *Critical Reviews in Analytical Chemistry*, 36(3-4):141–151, dec 2006.

[53] Ulf Harlou and N. H. Mortensen. *Developing product families based on architectures: Contribution to a theory of product families.* PhD thesis, Technical University of Denmark, 2006.

[54] A. Haug. *Representation of Industrial Knowledge – As a Basis for Developing and Maintaining Product Configurators.* PhD thesis, Technical University of Denmark, 2007.

[55] Michael A Hitt, R Duane Ireland, David G Sirmon, and Cheryl A Trahms. Strategic Entrepreneurship: Creating Value for Individuals, Organizations, and Society. *Academy of Management Perspectives*, 25(2):57–75, 2011.

[56] Wen Tai Hsu, Yi Lu, and Travis Ng. Does competition lead to customization? *Journal of Economic Behavior and Organization*, 106:10–28, 2014.

[57] Lars Hvam, Anders Haug, Niels Henrik Mortensen, and Christian Thuesen. Observed benefits from product configuration systems. *The International Journal of Industrial Engineering: Theory, Applications and Practice*, 2013.

[58] Lars Hvam, Niels Henrik Mortensen, and Jesper Riis. *Product customization.* Springer, 2008.

[59] Lars Hvam, Niels Henrik Mortensen, and Jesper Riis. Product customization. *Product Customization*, 51:1–283, 2008.

[60] U. Junker. Configuration. In *Handbook of Constraint Programming*, chapter 24, pages 837–873. Elsevier, 2006.

[61] Yohanes Kristianto, Petri Helo, and Roger Jianxin Jiao. A system level product configurator for engineer-to-order supply chains. *Computers in Industry*, 72:82–91, sep 2015.

[62] Gang Li, Ren-Gen Zhou, Lian Duan, and Wai-Fah Chen. Multiobjective and multilevel optimization for steel frames. *Engineering Structures*, 21:519–529, 1999.

[63] Kai Li, Yunlong Wang, Yan Lin, Wei Xu, and Manting Liu. A novel two-stage optimization method for beam-plate structure design. *Advances in Mechanical Engineering*, 8(11):1–18, 2016.

[64] Tingwen Li, Sreekanth Pannala, and Mehrdad Shahnam. CFD simulations of circulating fluidized bed risers, part II, evaluation of differences between 2D and 3D simulations. *Powder Technology*, 254:115–124, 2014.

[65] Lâm Laurent Lim, Gülgün Alpan, and Bernard Penz. A simulation-optimization approach for sales and operations planning in build-to-order industries with distant sourcing: Focus on the automotive industry. *Computers and Industrial Engineering*, 112:469–482, oct 2017.

[66] Bente R Løwendahl, Øivind Revang, and Siw M Fosstenløkken. Knowledge and Value Creation in Professional Service Firms: A Framework for Analysis. *Human Relations*, 54(7):911–931, 2001.

[67] Ross McKinstray, James B P Lim, Tiku T Tanyimboh, Duoc T Phan, and Wei Sha. Comparison of optimal designs of steel portal frames including topological asymmetry considering rolled, fabricated and tapered sections. *Engineering Structures*, 111:505–524, mar 2016.

[68] Marc H Meyer and Alvin P Lehnerd. *The Power of Product Platforms - Building Value and Cost Leadership*. The Free Press, New York, 1997.

[69] Gaetano Nino Miceli, Maria Antonietta Raimondo, and Stefania Farace. Customer attitude and dispositions towards customized products: The interaction between customization model and brand. *Journal of Interactive Marketing*, 27(3):209–225, 2013.

[70] F Moukalled, L Mangani, and M. Darwish. *The Finite Volume Method in Computational Fluid Dynamics - An Advanced Introduction with OpenFOAM and Matlab*, volume 113. 2016.

[71] Anna Myrodia, Katrin Kristjansdottir, and Lars Hvam. Impact of product configuration systems on product profitability and costing accuracy. *Computers in Industry*, 88:12–18, 2017.

[72] Anh-Tuan Nguyen, Sigrid Reiter, and Philippe Rigo. A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy*, 113:1043–1058, jan 2014.

[73] Adnan Niazi, Jian S. Dai, Stavroula Balabani, and Lakmal Seneviratne. Product Cost Estimation: Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128(2):563, 2006.

[74] Ikujiro Nonaka. Dynamic Theory of Organizational KnowledgeCreation. *Organizational Science*, 5:14–37, 1994.

[75] Patrick Ademola Oduguwa. *Cost Impact Analysis for Requirements Management Academic*. PhD thesis, Cranfield University, 2006.

[76] C Ou-Yang and T S Lin. Developing an integrated framework for feature-based early manufacturing cost estimation. *The International Journal of Advanced Manufacturing Technology*, 13(9):618–629, sep 1997.

[77] R Owen and I. Horváth. Towards product-related knowledge asset warehousing in enterprises. In *4th international symposium on tools and methods of competitive engineering, TMCE 2002*, pages 155–170, 2002.

[78] Murat Ozturk, Sinem Kocaoglan, and Fazil O. Sonmez. Concurrent design and process optimization of forging. *Computers and Structures*, 167:24–36, 2016.

[79] Athanasios Papageorgiou and Johan Ölvander. The Role of Multidisciplinary Design Optimization (MDO) in the Development Process of Complex Engineering Products. *Proceedings of the 21st International Conference on Engineering Design*, 4(August):109–118, 2017.

[80] V. Pareto. *Manuale di economica politica, società editrice libraria*. New York: Augustus M. Kelley, 1906.

[81] H.-S. Park and X.-P. Dang. Structural optimization based on CAD–CAE integration and metamodeling techniques. *Computer-Aided Design*, 42(10):889–90, 2010.

[82] Dmitry Pashchenko. Comparative analysis of hydrogen/air combustion CFD-modeling for 3D and 2D computational domain of micro-cylindrical combustor. *International Journal of Hydrogen Energy*, 42(49):29545–29556, 2017.

[83] Roberto Raffaeli, Andrea Savoretti, and Michele Germani. Design knowledge formalization to shorten the time to generate offers for engineer to

order products. *Lecture Notes in Mechanical Engineering*, pages 1107–1114, 2017.

[84] Roy Rajkumar and Kerr Clive. COST ENGINEERING : WHY , WHAT AND HOW? Technical report, Cranfield University, 2003.

[85] Benny Raphael and Ian F. C. Smith. *Fundamentals of Computer-Aided Engineering*. John Wiley & Sons, 2009.

[86] S. Rehman and M.D. Guenov. A Methodology for Modeling Manufacturing Costs at Conceptual Design. *Computers & Industrial Engineering*, pages 623–626, 1998.

[87] R. F. Riesenfeld, R. Haimes, and Cohen E. Initiating a CAD renaissance: multidisciplinary analysis driven design - framework for a new generation of advanced computational design, engineering and manufacturing environments. *Computer Methods in Applied Mechanics and Engineering*, 284:1054–1072, 2015.

[88] Anupam Saxena and Birendra Sahay. *Computer Aided Engineering Design*. Springer, 2005.

[89] Petra Schubert, Lincke David-Michael, and Schmid. Beate. A Global Knowledge Medium as a Virtual Community: The Netacademy Concept. In *AMCIS 1998*, Baltimore, MD, 1998.

[90] C Scruton, D E J Walshe, and National Physical Laboratory (Great Britain). *A means for avoiding wind-excited oscillations of structures with circular or nearly circular cross-section*. National Physical Laboratory, [Teddington], 1957.

[91] Jaroslaw Sobieszczanski-Sobieski. Multidisciplinary Design Optimization: An Emerging New Engineering Discipline BT - Advances in Structural Optimization. pages 483–496. Springer Netherlands, Dordrecht, 1995.

[92] R. Sriram. *Intelligent systems for engineering: a knowledge-based approach*. Springer Verlag, 1997.

[93] W. Starbuck and B. Hedberg. Saving an Organization from a Stagnating Environment. *Strategy + Structure + Performance*, pages 249–258, 1997.

[94] Ingrida Steponavič, Sauli Ruuska, and Kaisa Miettinen. A Solution Process for Simulation-based Multiobjective Design Optimization with an Application in the Paper Industry. *Comput. Aided Des.*, 47:45–58, feb 2014.

[95] S. Sunnersjö. A Taxonomy of Engineering Knowledge for Design Automation. In *TMCE 2010 Symposium*, 2010.

[96] Abdourahim Sylla, Delphine Guillon, Elise Vareilles, Michel Aldanondo, Thierry Coudert, and Laurent Geneste. Configuration knowledge modeling: How to extend configuration from assemble/make to order towards engineer to order for the bidding process. *Computers in Industry*, 99:29–41, aug 2018.

[97] Abdourahim Sylla, Delphine Guillon, Elise Vareilles, Michel Aldanondo, Thierry Coudert, and Laurent Geneste. Configuration knowledge modeling: How to extend configuration from assemble/make to order towards engineer to order for the bidding process. *Computers in Industry*, 99:29–41, 2018.

[98] K. Tornberg, M. Jämsen, and J. Paranko. Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. *International Journal of Production Economics*, 79:75–82, 2002.

[99] M. Torres. *Methodology to create cost estimation models for engineer-to-order operations*. PhD thesis, University of Florida, 2011.

[100] Alessio Trentin, Elisa Perin, and Cipriano Forza. Product configurator impact on product quality. *International Journal of Production Economics*, 135(2):850–859, feb 2012.

[101] D.G. Ullman. *The Mechanical Design Process*. McGraw-Hill, 1992.

[102] Karl Ulrich. The role of product architecture in the manufacturing firm. *Research Policy*, 24(3):419–440, 1995.

[103] JM Vasconcellos, M Harduim, and P Araujo. Multi-criteria optimization applied to tankers preliminary design. In *Maritime Technology and Engineering*, pages 309–314. CRC Press, 2014.

[104] Alessio Vita, Vincenzo Castorani, Marco Mandolini, Alessandra Papetti, and Michele Germani. Cost and Temperature Homogeneity Optimization of the Heating System for Composite Materials Air Press Molding. *Computer-Aided Design and Applications*, page In Press, 2019.

[105] G Gary Wang and S Shan. Review of Metamodeling Techniques in Support of Engineering Design Optimization. *ASME Transactions, Journal of Mechanical design*, 2006.

[106] Tian Wei. A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews*, 20:411–419, 2013.

[107] Karl M Wiig. *Knowledge management methods: practical approaches to managing knowledge*. Schema Press, Arlington, TX, 1995.

[108] A. L. Wilkins and N. J. Bristow. For Successful Organization Culture, Honor Your Past. *Academy of Management Executive*, 1:221–229, 1987.

[109] Olga Willner, Jonathan Gosling, and Paul Schönsleben. Establishing a maturity model for design automation in sales-delivery processes of ETO products. *Computers in Industry*, 82:57–68, 2016.

[110] Olga Willner, Daryl Powell, Aldo Duchi, and Paul Schönsleben. Globally distributed engineering processes: Making the distinction between engineer-To-order and make-To-order. *Procedia CIRP*, 17:663–668, 2014.

[111] Shuyou Zhang, Jinghua Xu, Huawei Gou, and Jianrong Tan. A Research Review on the Key Technologies of Intelligent Design for Customized Products. *Engineering*, 3(5):631–640, 2017.

[112] Pai Zheng, Xun Xu, Shiqiang Yu, and Chao Liu. Personalized product configuration framework in an adaptable open architecture product platform. *Journal of Manufacturing Systems*, 43:422–435, apr 2017.

[113] O C Zienkiewicz. *The Finite Element Method: Its Basis and Fundamentals*. Elsevier, 6-th editi edition, 2005.

[114] Xiao-Kang Zou. Optimal Seismic Performance-Based Design of Reinforced Concrete Buildings. In *Structural Seismic Design Optimization and Earthquake Engineering*, pages 208–231. IGI Global, 2012.