



# A model-based simulation approach to support the product configuration and optimization of gas turbine ducts

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## ABSTRACT

Nowadays, product configuration and optimization are very important topics in several industrial applications such as the manufacturing of Engineered-to-order (ETO) products, where there is a fierce increase in market competition. The product configuration allows past design solutions to be reused and new product variants to be defined and pre-designed. However, the delivery of new configurations of products requires a technical feasibility analysis before closing the contract of the order with the customer. There is a lack of commercial tools which can support the designer from the early configuration phase to the product optimization with the automatic generation of geometric models and simulations. While traditional software tools can be used for the product configuration, with automation in the CAD modeling, other ones can combine optimization algorithms with numerical simulations. However, the combination of all these design levels requires the development of a dedicated platform tools. The research aims to reduce time and cost related to the early design phase of an oil & gas system, focusing on gas turbine ducts. The paper proposes a methodological approach to integrate the design optimization with the product configuration using Model-Based simulations to verify the technical feasibility and to optimize the product design. As a test case, the early design of a gas turbine chimney is proposed.

## KEYWORDS

Product configuration;  
Product optimization;  
Model-Based simulation;  
Virtual prototyping; oil & gas

## 1. Introduction

Nowadays, product configuration and optimization are very important topics in several industrial applications such as the manufacturing of Engineered-to-order (ETO) products [15], where there is a fierce increase in market competition [22]. Generally, the enterprises, which develop ETO products, gradually focus competition on how to increase the external variety of products to meet customers' individual requirements under time and cost constraints by decreasing the internal variety of products, thus realizing the maximization of enterprise profit [22, 24]. The bottleneck issue regards how to satisfy the personalized customer requirements under the current production conditions and cost constraints [10]. Another important issue is the evaluation of the product compliance with the related legislation and normatives. This aspect is difficult to automate in a worldwide company where customers require different normatives to be evaluated. Concerning complex ETO products such as big steel structures, the normative check related to the structural performance needs numerical calculations to be evaluated.

The development of tools to support the product configuration of ETO products allows to reduce time in the product definition, to reuse past configurations, and to propose standard solutions to be evaluated with the customer [5, 10, 11].

Configurator systems are tools which allow designers to engineer a product satisfying to customer's requirements and standards of the specific domain, even if the required product has been not yet developed in the past [10]. To improve this activity is crucial to acquire and formalize explicit and implicit knowledge [8, 10, 11], define the "best practices", and develop Object-Oriented tools. Knowledge Based Engineering (KBE) is a methodological approach and a category of tools for the development of Object-Oriented applications to aid expert engineers to automate the process such as product configuration and to avoid loss of knowledge and knowhow [10]. KBE is in fact a research field that studies methodologies and technologies for capturing and re-using product and process engineering knowledge to achieve automation of repetitive design [20]. KBE methodologies can improve time, cost, and quality performance if they are applied

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during the early phases of product design [3, 7, 13]. The reusable knowledge is usually represented as rules; in this way, different software platforms, such as ICAD [17], DriveWorks [5] and Rulestream [3], have been developed since the 80s to support the Rule Based Design (RBD) approach [5]. These platforms provide tools to implement tailored KBE applications using scripts and programming codes. The use of RBD programs enhances a reduction in design cycle time by 50% [5]; thus, the designers can allocate their time in value-added activities for the enterprise. Around 20% of the designer's time is dedicated for searching and analyzing past available knowledge, while 40% of the required information is identified through personally stored information, although other sources of information may be more reliable [12]. The current engineering design process shows an imbalance between the time required for non-creative activities and the time available for the exploration of innovative design spaces. The imbalance has been growing over time and becomes excessive for complex products [16].

Many examples of KBE tools based on a customized software architecture are presented and discussed in literature [7, 8, 17]. Raffaelli et al. proposed a Configurable Virtual Prototypes (CVP) approach for designing recurrent product modules [23]. A tool was used for eliciting knowledge introduced by parametric template CAD models and reusing it in new 3D models. In this case, semantic rules were used to recognize parts parameterization and assembly mating constraints form 3D CAD models. Some KBE tools implement rules with analytical and numerical solvers to support the configuration process [7, 17]. The use of numerical software such as CFD solvers (Computer Fluid Dynamics) or structural FEM tools (Finite Element Method) allows to investigate the performance of product configurations not yet prototyped. On the other hand, typical RBD systems need a complete prediction of all design variations and possibilities [5]. Each configuration and possibility must be captured in the programs before running them. During the configuration, the user can manipulate independent variables and the RBD system determines the remaining dependent variables. They work with simple products as well as with complex ones such as a packaging machine [5] or an automatic assembling line [3].

A limit of traditional RBD systems is the difficult to solve open-ended problems such as optimization studies where the possibilities and design variations are difficult to predict. There are problems like combination explosion and difficulty of multi-objective optimization [18]. La Rocca et al. proposed an optimization loop integrated with a configuration tool based on ICAD platform to support the RBD process in aircrafts design [17]. This

case shows an optimization tool which can change the parameter values without the need for the user interactive sessions. However, this research does not consider evolutionary algorithms such as Genetic Algorithms (GAs) to support the optimization analysis of the design variables. A solution was analyzed by Li et al. [18] which proposed a multi-objective optimization method of production configuration, based on multi-object genetic algorithms. They confirm that a configuration-oriented model is necessary to describe the composition of the components' relationship in a product. Their approach works well for assemble-to-order (ATO) products like personal computers; however, it needs integration to be applied for ETO products, such gas turbine ducts or steel structures. While ATO products are modularized and components are standardized [25], ETO products also require technical analysis to be included in the optimization loop to support the engineering phase [24]. Willner et al. proposed a model for analyzing and improving design automation activities in ETO companies such as the use of sales-configurator and technical configurator.

Typical ETO products are oil & gas systems, which are designed and customized based on the customer requirements [4]. Generally, the manufacturing of complex ETO products is characterized by a negotiation phase [18, 24], where customer deals with different manufacturers, in order to choose the best partner for the product fabrication in terms of cost, results, and timeline. Configuration and quotation are complex activities, that today use computer systems for the direct interaction with the customer. The process from the request for quotation to the order confirmation is one of the strategic processes for the industrial competitiveness and its efficiency [10]. Therefore, it is very important for the producer to approve and deliver a project quote as soon as possible, according to the customer timeline and specifications. On the other hand, a quote needs a preliminary design and a technical analysis of feasibility. These studies begin within the negotiation phase, involving the procurement office, and continue inside the technical offices until the negotiation is final. Thus, there is a necessity to reduce the time of each early design phase, increasing efficiency and optimizing cost and performance of the product [6, 16]. As a solution, some industrial players have been paying attention to design tools and methods which support the engineers in the reduction of cost and time [6, 9, 14]. One of these solutions is the development of configuration tools [15], which allow past design solutions to be reused and new product variants to be defined and pre-designed. However, the delivery of new configurations of products requires a technical feasibility analysis before closing an order with the customer. The other solution to reduce cost and time is the use of a multi-objective

optimization (MOO) analysis [6, 18]. Generally, objectives of MOO analyses are focused on the searching of configurations which maximize the product performance and minimize weight and manufacturing cost. Wei et al. presented a multi-objective optimization of a modular product configuration [21] to support the search of feasible solutions that satisfy customer requirements and product constraints. This research is based on genetic algorithms (GA); however, they do not consider numerical simulations into the optimization loop.

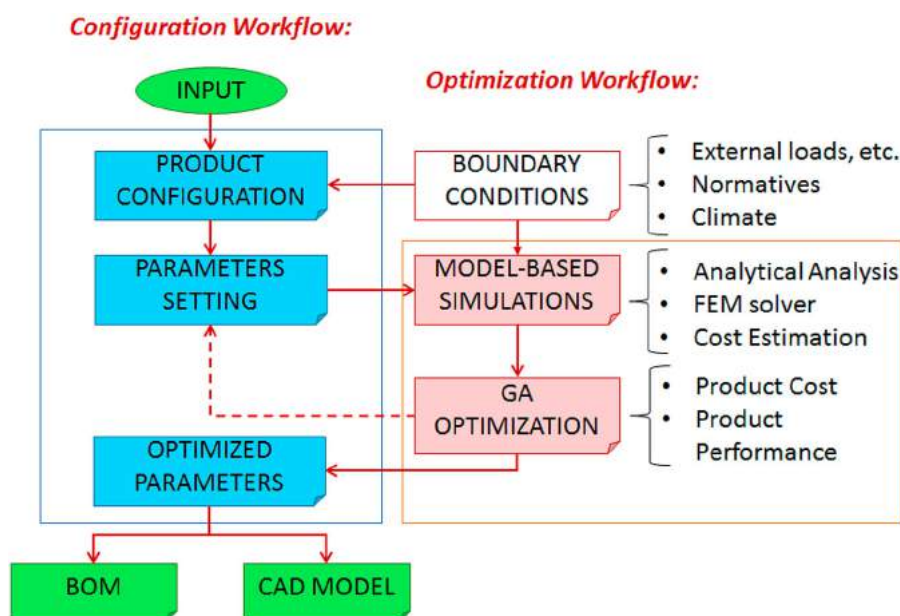
There is a lack of commercial tools which can support the designer from the early configuration phase to the product optimization with the automatic generation of geometric models and simulations. While traditional software tools can be used for the product configuration, with automation in the CAD modeling, other ones can combine optimization algorithms with numerical simulations. However, the combination of all these design levels requires the development of a dedicated platform tools.

The research aims to reduce time and cost related to the early design phase of oil & gas systems such as gas turbine ducts. The paper proposes a methodological approach to integrate the design optimization with the product configuration using Model-Based simulations to verify the technical feasibility and to optimize the product design. The scope of the scientific contribution is the study of design methodologies and practices to integrate processes of multidisciplinary optimization inside configuration activities mostly based on RBD approaches. As a test case, the early design of a gas turbine chimney is proposed in this paper.

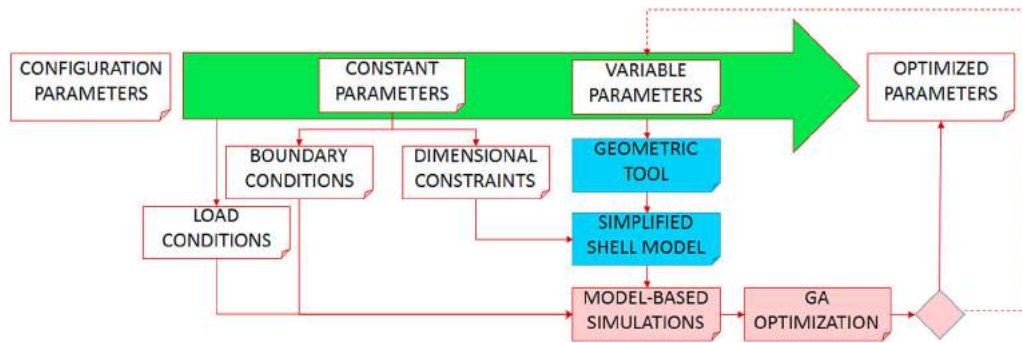
## 2. Approach

Fig. 1 describes the methodological approach, where the Model-Based simulation is the connection point from the configuration phase and the optimization one. The product configuration requires the definition of the input specifications, the related normative, the selection of the boundary conditions, and the setting of the functional and geometrical parameters. The output of the proposed configuration process is the automatic generation of a parametric product BOM and CAD-models with optimized parameters. Traditional configuration tools search already defined solutions from a database of products or create new components/assemblies from parametric models. Generally, the configuration of ETO products aims to reuse past-solutions in a customized product. However, it is difficult to re-use the same ETO solution in a different application. The complexity is due to many issues such as the variety of normatives and customer's requests. A configuration tool can search and find a suitable solution to be employed, however it is always necessary to provide a technical analysis to validate the proposed solution. Additionally, optimization analyses are often performed to improve the product behavior and reduce the related cost.

The approach aims to reduce time and cost during the early technical analysis using a platform tool which integrates a configuration workflow with a product optimization loop (Fig. 1). The proposed method has been tested in the configuration and optimization of a gas turbine chimney. The resulting workflow increases the complexity of the design platform and introduces a computational



**Figure 1.** The proposed methodological approach.



**Figure 2.** The interaction of the configuration parameters inside the optimization loop.

cost due to the simulations involved in the optimization loop. The computational time and the hardware resources are related to the simulation solvers involved. Analytical solvers are quick and do not require a high-performance computing. On the other hand, FEM simulations can require an increasing computational cost, which is related to the complexity of the geometry and equations involved. However, it is possible to reduce the effort of complex 3-D analyses using simplified geometrical models.

The automation of the design workflow is like what achieved by a configuration tool with design automation features. The user can use a configuration platform to set attributes, boundary conditions, and design requirements. The proposed platform (Fig. 1) solves the product configuration, using implemented rules and formulas, and it generates 3D models and BOM (Bill of Materials). In this workflow, several parametric model-based models are captured in a repository to be re-used for an optimization analysis. The optimization analysis is automatic and it is based on data defined in the configuration phase (Fig. 10). The optimization functions are the weight and the cost reduction with the structural constraints provided by standards and normatives. After the phase of the configuration setting, the user is involved in the decision-making process where a report shows him a list of all configurations which satisfy the Pareto frontier in the Multi-Object Optimization analysis.

Concerning the approach highlighted in Fig. 1, the input data is the collection of the customer's requirements and specifications. The workflow is divided into two parts: the *configuration workflow* and the *optimization* one. The configuration workflow concerns the use of a user interface to select the product characteristics on the basis of the customer specifications. As already discussed, ETO configurations need a technical analysis for closing the negotiation phase. Therefore, the *optimization workflow* aims to validate the resulting configuration and to optimize the related variables. In the case of oil & gas ducts, variables can be related to sheet metal thickness,

connections, reinforcements, etc. The approach considers the sizing and the setting of variables as a function to be evaluated through the optimization loop. In this context, model-based simulations are necessary to evaluate the behavior of a complex ETO product.

The parameters involved in a configuration process can be constant or variable (Fig. 2). The constant parameters describe dimensional constraints, boundary conditions, and load conditions. Variables are geometrical dimensions which can change values into a defined range. Fig. 2 describes the interaction of the configuration parameters inside the optimization loop. The optimization loop focuses on the investigation of the geometrical variables. The design user can define the range and values of all parameters to be optimized.

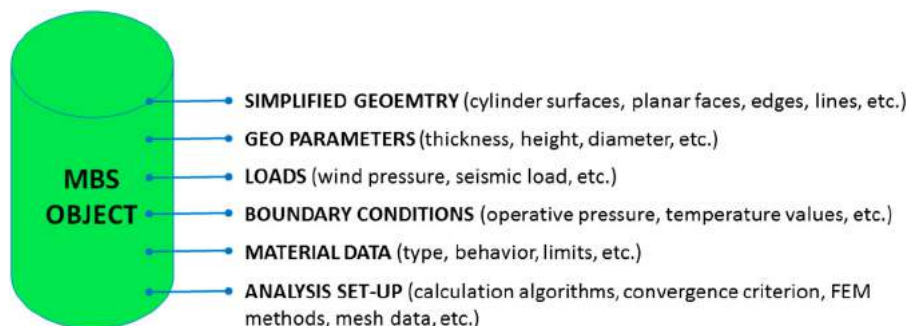
As described in Fig. 1 and 2, model-based simulations are involved in the optimization loop. These simulations regard simplified 3D geometries of models with parametric attributes, boundary conditions, and load conditions (Fig. 10). Simplified geometries can be 3D shell surfaces, edges, simple solids, etc. Attributes are related to material type and characterization, geometrical thickness, normative requirements. Boundary and load conditions are related to the design cases to be simulated. The employment of simplified geometries reduces complexity and time in the calculation activity. Since model-based simulations are parametric analyses, variable and constant data can be easily changed and set for each design configuration.

The optimization loop is based on GA (Genetic Algorithm) methods, which are evolutionary tools used for solving optimization problems [19]. These methods are inspired by nature and reproduces the biological model of chromosomes, which contain genetic information represented by location and value of their genes. The implementation of a genetic algorithm requires the definition of representation, fitness function, parent selection and survivor selection mechanisms as well as matching and mutation operators [19]. The five steps of a GA are: the definition of an initial population, the

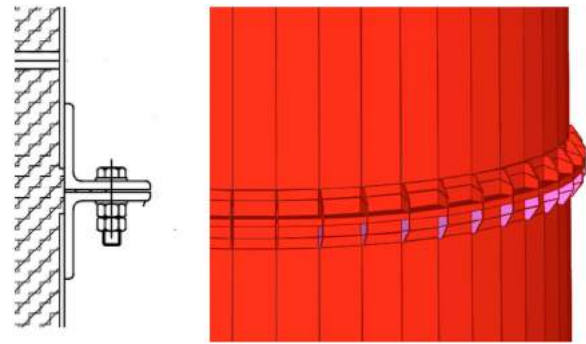
evaluation phase, the selection, the crossover, and the mutation. The population of candidate solutions (individuals) is evolved toward better solutions by an iterative process. Each individual has a set of properties called chromosomes which can be mutated and altered (crossover and mutation), and in each generation, the fitness of every individual in the population is evaluated. Fitness is defined as the value of the objective function related to a defined population.

### 2.1. Model-based simulations

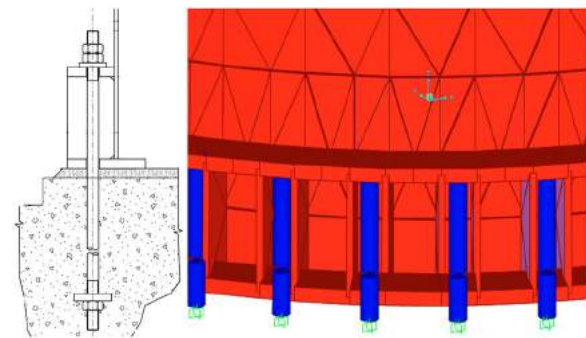
A Model-Based simulation is a physical system represented by object-oriented (O-O) blocks, where each block contains information and functions regarding the calculation of performance and system behavior (Fig. 3). The model-based approach is an engineering design method applied in several fields such as mechanics, informatics, and electronics. The simulations involved in this paper regard the structural analysis and the early analytical calculation of the cost estimation related to the configuration analyzed. One of the advantages of a Model-Based simulation is the definition of previous parametric models, which are easy to reconfigure for the analysis of further product configurations. The updating of a Model-Based simulation also regards the definition of boundary conditions and load combinations to be analyzed. The load combinations are related to parameters such as the environmental conditions, and normative to be applied. Regarding the simulation analysis involved in this paper, the SAP2000 software by CSI America was used to solve the structural behavior of the duct items. The related simulations concern the study of the mechanical behavior of a simplified geometry with shell surfaces. Using the API tools provided by SAP2000, an algorithm has been implemented with VB script to update each Model-Based simulation with parameters and geometrical models related to a specific duct configuration to be analyzed. Typical parameters to be optimized for a gas turbine vertical duct are thickness and height.



**Figure 3.** The description of the model-based simulation object.



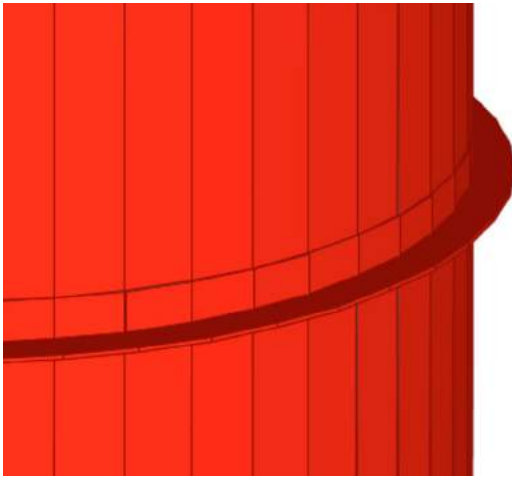
**Figure 4.** A simplified bolted flange.



**Figure 5.** A simplified ground fixing.

From Fig. 4 to 6, some geometrical simplifications are described to represent the 3-D model of a gas turbine chimney. Fig. 4 shows a simplified bolted flange without the representation of the bolting, and Fig. 6 reports a simplified circular reinforcement using shell surfaces. Fig. 5 highlights the use of simple cylinders to describe the fixing of the stack base without reproducing a complete bolting.

The load conditions to be considered during the design process are related to the installation case (geographical region, local conditions, normative and regulations, etc.). The structural checks are related to the specific normative required and agreed upon with the customer. As example, ASCE/SEI 7-05 [2] is a typical standard used for the definition of the design loads and



**Figure 6.** A simplified circular reinforcement.

cases to be applied in structural analysis. The strength criteria for a structural analysis are defined by normative such as ANSI/AISC 360-10 [1]. Generally, design loads considered in a structural check for steel structures such as exhaust systems are:

- **Dead loads:** the total weight of the structure with all equipment, machineries, and accessories;
- **Live loads:** variable loads related to the use of the structure and their accessories such as the crane;
- **Wind load:** the action of the wind in each direction (+X, -X, +Y, -Y);
- **Seismic load:** the simulation of the dynamic load related to a possible earthquake. Response spectra are

very useful tools for analyzing the performance of structures and equipment in earthquakes;

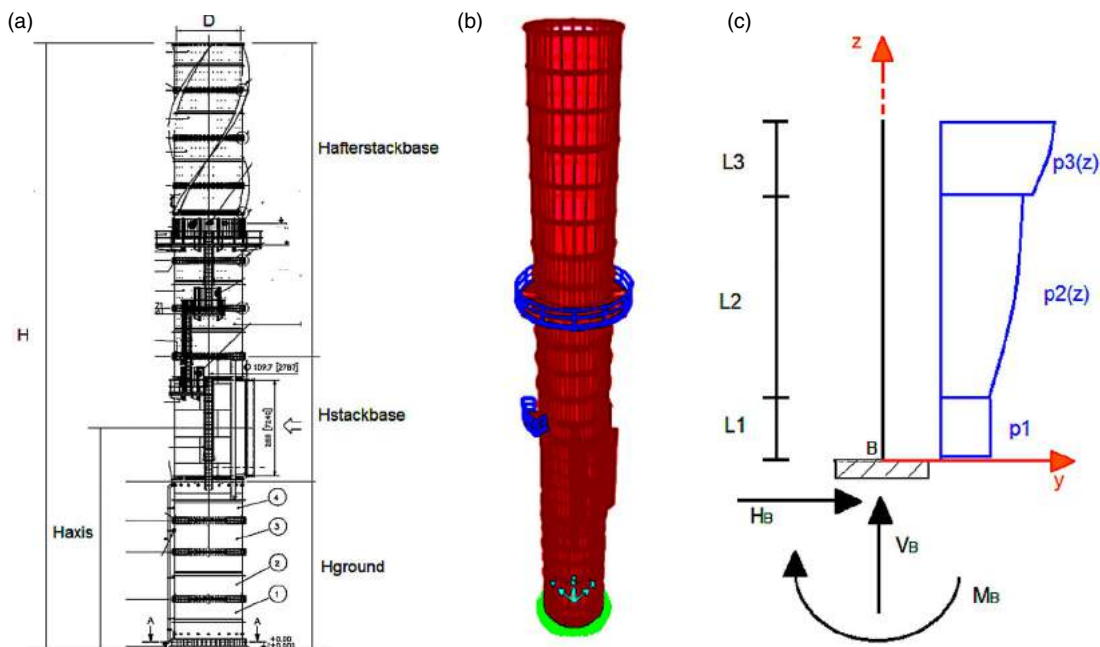
- **Operative pressure:** the nominal operative pressure inside the structure;

Generally, each normative, which is focused on the structural analysis for steel construction, defines a combination of loads to be evaluated in different design cases. Eq. (1) shows a typical load combination with dead load (*Dead*), operative pressure (*Op.Press.*), wind action in +X direction (*Wind<sub>+x</sub>*), live forces in +x direction (*Live<sub>+x</sub>*), and seismic load as response spectra in X direction. The coefficients (A, B, C, D and E) are calculated on the basis of the related normative to be applied in a specific case. The design of a steel structure includes the analysis of different load combinations with different numbers of load applied. Each combination provides different values for the highlighted coefficients.

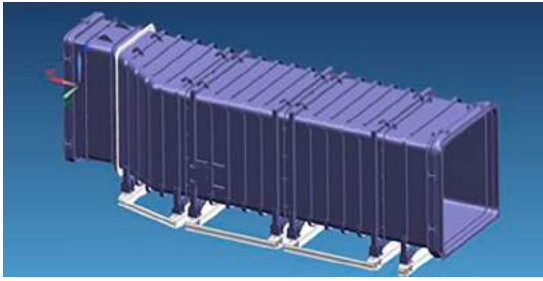
$$A \cdot Dead + B \cdot Op.Press. + C \cdot Wind_{+x} + D \cdot Live_{+x} + E \cdot SeismicResponseSpectra-x \quad (1)$$

### 3. Exhaust system

The operation of a gas turbine provides several health risks related to noise, heat, and flue emissions which must be minimized through the design of the exhaust system. The exhaust system of a gas turbine consists of ducts, expansion joints, filters, and special items. Ducts can be composed of vertical items (Fig. 7) or horizontal ones (Fig. 8). The main functionality of this system is to guide



**Figure 7.** a) An example of an oil & gas chimney for gas turbine plants; b) a shell model of a chimney; c) a schematic representation of Wind action on an equivalent fixed beam.



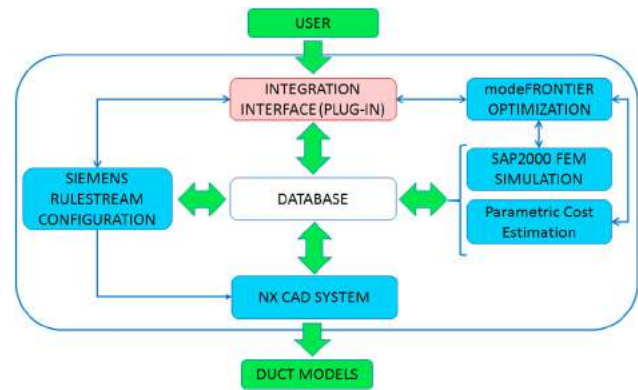
**Figure 8.** Example of a horizontal exhaust ducts for gas turbines.

the exhaust gasses from the gas turbine into the atmosphere. The exhaust system is mandatory because the flue gases can reach temperatures between 400 and 650 °C. A secondary function of the exhaust system is to reduce the level of sound pressure, which is produced by the gas turbine during operation. Therefore, each exhaust item has an insulating layer to reduce thermal exchange and noise propagation. The loading conditions require thermal resistance materials because the exhaust ducts operate under enormous strain from turbulence and pressure fluctuations from the gas turbine. Possible failures can be lead to cracks, damages on ducts and insulation walls under high temperature.

A gas turbine chimney, which is the object of the proposed case study, is a vertical insulated steel duct with a circular section (Fig. 7 (a) and (b)). The inner diameter is constant and its value depends on the size of the gas turbine involved in the power plant to be engineered. A chimney, used in gas turbines, consists of several flanged cylindrical ducts. The thickness of the ducts decreases from the base duct to the last item, and this issue was considered in the proposed optimization analysis. The parameters to be optimized, during the early design phase of an oil & gas chimney, are the thickness and the height of each duct item. Since the total height of a chimney is fixed, the definition of the height of each duct is an indirect way to limit the number of duct items.

#### 4. Design platform

The proposed methodology involves a software platform which includes tools such as configurator, CAD system, database, FEM solver, optimization tool, and a tailored software tool which performs the connections with all mentioned software. While the workflow of this design system has been already described and discussed in Section 2, this section introduces the tools and how they interact in the implemented design platform (Fig. 9). The platform tool is a test case application of the proposed method. Particularly, the case study regards the configuration and optimization of a chimney used in exhaust systems for gas turbines.



**Figure 9.** The proposed software platform.

##### 4.1. Configuration and optimization

An already developed software has been used as a kernel to configure and generate 3-D models of exhaust ducts. This configuration framework was implemented using the development framework provided by Siemens Rulestream. Rulestream is an Objective-Oriented platform to develop ETO software (such as configuration tools) by storing configuration rules in a relational database. This platform provides tools to interact with database and CAD systems.

The configuration process regards the filling out of a configuration sheet, which collects all information for the CAD modeling and the early BOM generation. This configuration tool already implements the knowledge for the correct selection of components and materials. In particular, Fig. 10 shows the configuration platform to design an exhaust system including duct items. This platform (Fig. 10) is a prototypical interface, developed using Visual Studio and the ASP.NET programming code. The use of the ASP.NET language is related to the necessity to provide a client-server application. This tool, called *Integration Interface*, integrates the use of a configuration software and an optimization one. While the configuration software is the tool already developed using the Siemens Rulestream technology, the optimization tool is a design workflow developed using the modeFrontier software.

The already developed configuration software implements design rules, database, and formulas for the definition of all attributes of the product structure. The embedded knowledge was gathered and organized in collaboration with a design office which works on the development of oil & gas solutions. The knowledge acquisition mostly required documents arrangements (book parts, manuals, scientific and technical publications, standards, 3D CAD models, 2D drawings, etc.) for the definition of the explicit knowledge. The acquisition of the tacit

Integration Interface (Exhaust Configuration) Home About Contact User-1 Log out

Duct Project  
Horizontal Items  
H1: Expansion Joint - P  
H2: Spacer Block  
H3: Silencer Block  
H4: Expansion Joint - C  
H5: Transition  
Vertical Items  
V1: Stack Base L= 6000 THK= 12  
V2: Stack Duck L= 6000 THK= 10  
V3: Stack Duck L= 6000 THK= 8  
V4: Stack Duck L= 6000 THK= 8  
V5: Stack Duck L= 6000 THK= 6  
V6: Stack Duck L= 6000 THK= 6  
< Prev Next >

Installation Setup Gas Turbine On Ground  
Gas Turbine Type GT125 - Single Cycle  
Orientation Lateral Left with Double Silencers and Stack  
Geographical Region North America  
State USA  
Normative:  
 ASCE/SEI 7-05  
 ANS/AISC 360-10  
Accessories:  
 Flue Gas Probes  
 Walkway System  
 Aircraft Light  
Expansion Joints:   
Material:  
 S275JR  
 ASTM A516 Gr. 60  
 ASTM A240 TP304L  
 ASTM A240 TP316L  
Analytical Check

Variable	Description	Lower Value	Upper Value
Var1	Items number	5	7
Var2	Thickness (mm) 0 - 6000 mm	12	15
Var3	Thickness (mm) 6000 - 12000 mm	10	12
Var4	Thickness (mm) 12000 - 18000 mm	8	10
Var5	Thickness (mm) 18000 - 24000 mm	6	10
Var6	Thickness (mm) 24000 - 30000 mm	6	8
Var7	Thickness (mm) 30000 - 36000 mm	6	8

Setting Data:

L1	15000	mm
H1	2500	mm
H	3000	mm
H2 - Chimey Height	36000	mm

Optimization Analysis: Run Analysis

ITEM	Conf. Height (mm)	Conf. THK (mm)	Analytical Check	Opt. Height (mm)	Opt. THK (mm)	FEM Check
1	8000	15	OK	6000	12	OK
2	6000	12	OK	6000	10	OK
3	9000	10	OK	6000	8	OK
4	6000	8	OK	6000	8	OK
5	7000	6	OK	6000	6	OK
6	-	-	-	6000	6	OK
7	-	-	-	-	-	-

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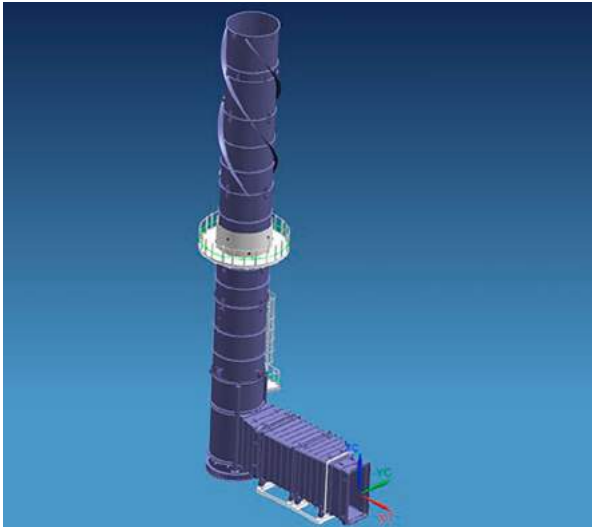
Figure 10. The developed *Integration Interface*.

knowledge was more complex and required interviewers of experts who described in detail their design activities and decisions. The implemented tacit knowledge concerns the definition of procedures for the sizing of sheet metal objects, the design of the insulation, the external connections, etc.

The interface highlighted in Fig. 10 has been performed for the design of exhaust systems including chimneys. All input information is necessary to support the configuration process and to define the parameters for the optimization loop. In particular, the configuration software runs in the background and sends the results to the prototypical *Integration Interface* (Fig. 10). The *Integration Interface* can execute a design optimization analysis in the background for giving the results to the designer. An optimization workflow has been defined for each type of exhaust configuration, however this paper is focused on vertical ducts such as chimneys. The design optimization of a chimney is

focused on the sizing of ducts in terms of item thickness and height. The *Integration Interface* also implements a first analytical 0-D analysis which gives feedback regarding the average stress applied to a simplified chimney structure. This 0-D analysis is based on a parametric model which considers the duct as a beam fixed at one end with uniformly distributed load for the wind action and concentrated load at any point for the weight of accessories. Fig. 7c shows a schematic representation of the distributed load related to the wind action. The 0-D analytical study considers all input values such as geometrical dimensions, material properties, and normative. The output is the reduction of the values range to be investigated for each duct thickness. The second level of analysis involves the optimization of a 3-D chimney model using the values range defined in the first study. This approach aims to reduce the computational cost due to the complex 3-D FEM simulations.



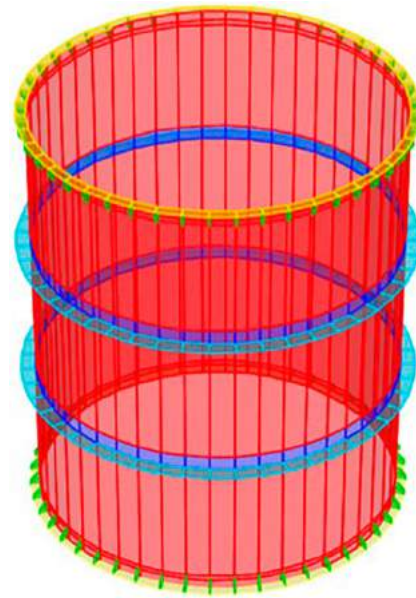


**Figure 11.** An example of an exhaust system with chimney.

The input data of the configuration of exhaust ducts regards information such as the gas turbine involved, the climate data, the geographic location, the reference normative, standards, and the dimensional constraints. Generally, in the case of a chimney duct, the dimensional constraints are the maximum height of the chimney, the inner diameter of the cylindrical duct, and the height of the stack base, which is the first item of the vertical ducts (Fig. 11). The traditional output of a configuration workflow for exhaust systems is the definition of ducts and chimneys using many already engineered items and few customized parts. The objective of the proposed test case is to enlarge the configuration workflow using tools and methods to optimize the output model using a MOO approach. The optimization analysis, proposed in this research, is based on Model-Based simulations to evaluate the product performance and product cost.

Regarding the cost estimation, the paper proposes a parametrical calculation based on the ducts weight, the number of items involved, and the constant cost related to accessories and inner insulation (Eq. (2)). In particular, the target is focused on the chimneys' analysis. As mentioned before, the inner diameter of a chimney is already defined by the applied gas turbine machinery, therefore the inner insulation can be considered as a fixed layout in a configuration project as well as the requested accessories.

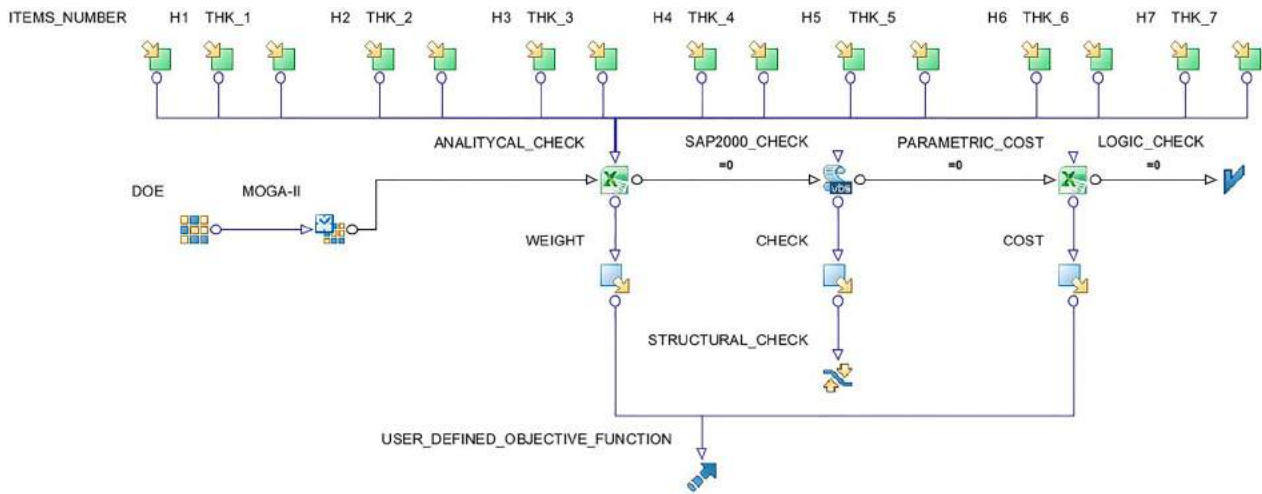
$$Cost_{chimney} = C_s \cdot \sum_{i=1}^N Weight_{i-duct} + (N - 1) \cdot C_j + \sum_{j=1}^M C_{j-accessory} + C_{insulation} \quad (2)$$



**Figure 12.** A simplified shell model of a duct item.

Eq. (2) describes the parametric cost estimation related to a gas turbine chimney. While the  $C_s$  term represents the specific cost related to a kilogram (kg) of a steel duct, the  $N$  term is the number of duct items employed in the chimney configuration and the  $Weight_i$  term is the weight of each item. The second term  $(N-1)C_j$  represents an average cost for the ducts' junctions. Finally,  $C_j$  is the cost of each accessory and  $C_{insulation}$  is the cost related to the inner insulation, which is not a variant cost in the proposed chimney configuration.

The *Integration Interface* (Fig. 10) reads all parameters from the configuration sheet and sets the variables in the optimization workflow. The modeFrontier platform has been used to develop the optimization workflow because this tool implements GA methods to solve maximum and minimum problems. The performed optimization workflow imports all constant and variable parameters related to the chimney project to be configured and optimized. The connection between *Integration Interface* and modeFrontier was performed with VB scripts code. The model-based simulation approach allows to rapidly re-size and re-configure the virtual models to be analyzed during the optimization workflow. Each model-based simulation includes a simplified shell geometry (Fig. 12). A database collects different templates of model-based simulations. Each simulation includes a CAD model with parameters to set geometrical entities, loads for the check analysis, and boundary conditions. Using a simplified geometrical representation, a duct item can be described with shell objects such as cylinder surfaces and planar patches (Fig. 12).



**Figure 13.** The optimization workflow developed using modeFrontier GUI.

Fig. 13 shows the optimization workflow implemented using the modeFRONTIER tool. The proposed *Integration Interface* (Fig. 9) can connect each design variable with the parameters guided by GA methods in the modeFrontier project. Regarding the optimization loop, the GA iteration starts with the definition of an initial population. A population is a set of values which represents a configuration of parameters. Each optimization process considers at each loop the calculation of objective functions to be maximized. Each function is calculated by simulations such as the FEM structural analyses used in this paper. According to the GA theory, the evaluation process focuses on the definition of non-dominated individuals, the calculation of objectives, the fitness evaluation, and the rank assignment to add the solution on the Pareto dominance. The GA method used in this paper is the MOGA-II algorithm, and the FEM solver used for the structural analysis is SAP2000.

## 5. Test case

This section discusses about the result of a chimney design using the proposed methods and tools. The configuration regards a 36-m chimney for a single-cycle gas turbine used in oil & gas applications with a requested power over 10 MW. The configuration setting is the same highlighted in Fig. 10. As example, the configuration has been defined for a North America installation. The comparison is between the final optimization model and a reference model which was designed before. As highlighted in Tab. 1, the proposed approach can reduce 7% of the total weight related to the steel material involved for the construction of the duct items, and about 10% is the possible cost reduction estimated in the configuration phase. The number of duct items is 6. This number is

**Table 1.** The comparison between the optimized model and the reference project.

Weight Reduction (steel)	7%
Time Reduction in Design Activities	100 h
Cost Reduction	10%
Number of items	6 (instead of 5)

one more than the reference project, which employed 5, because, using the proposed optimization approach, the final configuration enhances the use of ducts with standard height to reduce additional manufacturing costs. A table reported inside Fig. 10 shows the difference between the reference configuration and the optimal one in terms of ducts height, thickness, and number. The resulting CAD model of the configured chimney is described in Fig. 11. The reduction of time related to design activities considers the benefits due to the configuration process and the optimization one. The detailed values related to cost, timing, and weight are not reported in this paper because it is confidential information which cannot be published. However, the paper describes the methodological approach and the connections between the Model-Based analyses (FEM simulations and analytical calculation) and the design framework which includes a configuration software and an optimization tool.

The selection of the optimal solution has been managed inside the optimization workflow developed with the modeFrontier platform. The optimization analysis is based on a MOO algorithm which is MOGA-II, where the objectives are the reduction of weight and cost and the constraint is the structural check (performed by SAP2000). The variables are the number of items, and the height and thickness of each duct. Traditional solutions for a MOO analysis are based on the Pareto front, however a user-defined objective function (Eq. (3)) has been

used to evaluate the optimal configuration of chimneys in this test case. This approach allows to automate the selection of the optimal solution, because after several iterations the configuration with the higher score is defined as the optimal one.

$$OBJ = C_1 \cdot Weight_{criterion} + C_2 \cdot Cost_{criterion} \quad (3)$$

The user-defined objective function (Eq. (3)) considers a different weight related to weight and cost reduction. The coefficients defined as  $C_1$  and  $C_2$  represent the different weights assigned to weight and cost reduction (the sum of these coefficients is 1). The quality characteristic is Small-is-Better (SiB) for both criteria (weight and cost reduction). The terms  $Weight_{CRITERION}$  and  $Cost_{CRITERION}$  represent how the solution is better than the target values. The target values regarding the cost and weight were defined as 80% of the values related to the reference project. Eq. (4) describes the calculation of the criterion related to the product weight, where the term  $Weight_{MAX}$  is the weight of the reference project and  $Weight_{MIN}$  is the 80% of the max value. The weight of the configuration analyzed at each optimization step is the term  $Weight_i$ .

$$Weight_{criterion} = \frac{Weight_{MAX} - Weight_i}{Weight_{MAX} - Weight_{MIN}} \quad (4)$$

## 6. Conclusion

An approach to support the design optimization during the configuration phase has been proposed for ETO products in order to reduce design time and cost for the order quote. An ASP.NET software interface has been implemented to connect the configuration process with the workflow developed for the optimization with Model-Based simulations. The proposed method aims to overcome the limits of traditional commercial tools which are not performed to integrate product configuration with design optimization based on GA methods. A test case was performed on the configuration of an optimized gas turbine chimney. The use of the proposed tools and methods has brought a great benefit in terms of reduced design time and weight in the context of chimney design. The proposed test case shows the possibility to reduce about 10% of the product cost using a product configuration approach integrated with a GA optimization.

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## References

- [1] American Institute of Steel Construction, Specification for Structural Steel Buildings, ANSI/AISC 360-10, 2010.
- [2] American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05, 2006.
- [3] Ascheri, A.; Colombo, G.; Ippolito, M.; Atzeni, E.; Furini, F.; Feasibility of an assembly line layout automatic configuration based on a KBE approach, Proceedings of the 2014 International Conference on Innovative Design and Manufacturing (ICIDM), 2014. <http://doi:10.1109/idam.2014.6912715>
- [4] Caron, F.: Large Engineering Projects: The Oil and Gas Case, SpringerBriefs in Applied Sciences and Technology, 2013, 11–4. [https://doi.org/10.1007/978-88-470-5244-4\\_3](https://doi.org/10.1007/978-88-470-5244-4_3)
- [5] Cavalli, S.R.; Sen, C.; Mocko, G.M.; Summers, J.D.; Using Rule Based Design in Engineer to Order Industry: An SME Case Study, Computer-Aided Design and Applications, 5, 2008, 178–193. <http://doi:10.3722/cadaps.2008.178-193>
- [6] Cicconi, P.; Germani, M.; Bondi, S.; Zuliani, A.; Cagnacci, E.: A Design Methodology to Support the Optimization of Steel Structures, Procedia CIRP, 50, 2016, 58–64. <http://doi.org/10.1016/j.procir.2016.05.030>
- [7] Cicconi, P.; Landi, D.; Germani, M.; Thermal analysis and simulation of a Li-ion battery pack for a lightweight commercial EV, Applied Energy, 192, 2017, 159–177. <http://doi:10.1016/j.apenergy.2017.02.008>
- [8] Cicconi, P.; Raffaelli, R.: Knowledge Based Plants Layout Configuration and Piping Routing. Global Product Development, Global Product Development, Springer, 2011, 497–509. [http://doi.org/10.1007/978-3-642-15973-2\\_51](http://doi.org/10.1007/978-3-642-15973-2_51)
- [9] Cicconi, P.; Raffaelli, R.; Germani, M.: An approach to support model based definition by PMI annotations, Computer-Aided Design and Applications, 14 (4), 2016, 1–9. <http://doi.org/10.1080/16864360.2016.1257194>
- [10] Colombo, G.; Furini, F.; Rossini, M.; The Role of Knowledge Based Engineering in Product Configuration, Advances on Mechanics, Design Engineering and Manufacturing, Springer International Publishing, 2016, 1141–1148. [http://doi.org/10.1007/978-3-319-45781-9\\_114](http://doi.org/10.1007/978-3-319-45781-9_114)
- [11] Colombo, G.; Mandorli, F.; Evolution in Mechanical Design Automation and Engineering Knowledge Management. Innovation in Product Design, 2011, 55–78. [http://doi:10.1007/978-0-85729-775-4\\_4](http://doi:10.1007/978-0-85729-775-4_4)
- [12] Efthymiou, K.; Sipsas, K.; Mourtzis, D.; Chrysolouris, G.; On an Integrated Knowledge based Framework for Manufacturing Systems Early Design Phase, Procedia CIRP, 9, 2013, 121–126. <http://doi:10.1016/j.procir.2013.06.179>
- [13] Germani, M.; Mandolini, M.; Cicconi, P.; Manufacturing cost estimation during early phases of machine design, ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design, 5, 2011, 198–209. ISBN: 978-190467025-4.
- [14] Haug, A.; Hvam, L.; Mortensen, N.H.: Reducing variety in product solution spaces of engineer-to-order companies:

- the case of Novenco A/S, *International Journal of Product Development*, 18 (6), 2013, 531–547. <https://doi.org/10.1504/ijpd.2013.058556>
- [15] Kristianto, Y.; Helo, P.; Jiao, R. J.: A system level product configurator for engineer-to-order supply chains, *Computers in Industry*, 72, 2015, 82–91. <http://doi.org/10.1016/j.compind.2015.04.004>
- [16] La Rocca, G.; Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design, *Advanced Engineering Informatics*, 26(2), 2012, 159–179. <http://doi:10.1016/j.aei.2012.02.002>
- [17] La Rocca, G.; Krakkers, L.; Van Tooren, M.; Development of an ICAD Generative Model for Blended Wing-Body Aircraft Design, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, 2002, <http://doi:10.2514/6.2002-5447>
- [18] Li, B.; Chen, L.; Huang, Z.; Zhong, Y.: Product configuration optimization using a multiobjective genetic algorithm, *International Journal of Advanced Manufacturing Technology*, 30, 2006, 20–29. <https://doi.org/10.1007/s00170-005-0035-8>
- [19] Nguyen A-T, Reiter S, Rigo P, A review on simulation-based optimization methods applied to building performance analysis, *Applied Energy*, 2014, 113, 1043–58. <https://doi.org/10.1016/j.apenergy.2013.08.061>
- [20] Verhagen, W. J.; Pablo, B. G.; Van Dijk, R.; Curran, R.; A critical review of Knowledge-Based Engineering: An identification of research challenges, *Advanced Engineering Informatics*, 26, 2012, 5–15. <https://doi.org/10.1016/j.aei.2011.06.004>
- [21] Wei, W.; Fan, W.; Li, Z.: Multi-objective optimization and evaluation method of modular product configuration design scheme, *International Journal of Advanced Manufacturing Technology*, 75, 2014, 527–1536. <https://doi.org/10.1007/s00170-014-6240-6>
- [22] Wei, W.; Liu, A.; Lu, SC-Y.; Wuest, T.: Product Requirement Modeling and Optimization Method Based on Product Configuration Design, *Procedia CIRP*, 36, 2015, 1–5. <http://doi.org/10.1016/j.procir.2015.01.020>.
- [23] Raffaelli, R.; Cicconi, P.; Mengoni, M.; Germani, M.; Modular Product Configuration: An Automatic Tool for Eliciting Design Knowledge From Parametric CAD Models, Volume 1: 36th Design Automation Conference, Parts A and B. <http://doi:10.1115/detc2010-28242>
- [24] Raffaelli, R.; Savoretti, A.; Germani, M.: Design knowledge formalization to shorten the time to generate offers for Engineer To Order products, *Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing*, 2016, 1107–1114. [https://doi.org/10.1007/978-3-319-45781-9\\_110](https://doi.org/10.1007/978-3-319-45781-9_110)
- [25] Zhou, C.; Lin, Z.; Liu, C.: Customer-driven product configuration optimization for assemble-to-order manufacturing enterprises, *International Journal of Advanced Manufacturing Technology*, 38, 2008, 185–194. <https://doi.org/10.1007/s00170-007-1089-6>