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Development of a Computer-Based methodology for tolerance selection and optimization applied to the automotive sector

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Abstract

The design process of industrial products has always been subjected to continuous evolution. Over the years, increased competitiveness and limited profit margins have forced the development of advanced techniques for product design optimization, to improve product quality while reducing time-to-market and production costs. Concurrent Engineering practices are central in this context and their application is growing, especially in major sectors such as the automotive industry.

Since automobiles are composed of a large number of components with different functions, materials, and manufacturing processes, the cost management is very complex and comprises all phases of the product life cycle, starting from product design. In this context, the control of geometrical and dimensional variations is essential to comply with product and process requirements: geometrical product specification and tolerance analysis practices, known as Dimensional Management (DM), are increasingly common, supported by the use of international standards such as ISO-GPS and ASME-GD&T. As a result, tolerance effects on products can be early considered during the design process, with the support of Computer-Aided Tolerancing (CAT) tools, enabling the so-called Design for Tolerancing (DfT) approach. However, a methodological approach to systematically support DfT is still missing. Indeed, tolerance design is a complex activity, and many factors hinder the optimal application in the industrial field, with the difficult implementation of standards and tools on real products. Moreover, CAT tools address the effects of tolerances on product functionality and assembly requirements but do not yet provide the economic assessment of tolerance costs. In addition to the process capability analysis, the estimation of manufacturing costs must be properly considered for tolerance design optimization. On the cost estimation side, the design approach for cost optimization, known as Design to Cost (DtC), is supported by specific tools for manufacturing cost estimation. However, their industrial application is commonly limited to the final stages of product development, to optimize manufacturing processes rather than product design.

Motivated by these issues, the tolerancing activity has evolved consistently in the last decades: several methodologies and design strategies have been proposed to achieve the optimal tolerance design. In particular, tolerance-cost optimization is becoming the key practice to provide an effective application of DfT and DtC approaches by enabling a connection between product tolerances and associated manufacturing costs. However, despite the growing interest in this topic, a profitable application in the industry of these techniques is hampered by their complexity: the high number of interdisciplinary elements, the difficult modelling of the relationships between influencing factors, and the lack of detailed information about processes are the main obstacles. This results in three critical areas, namely, data and parameters sharing, flexibility to application complexity, and integration of

simulation tools. Among these, the definition of a systematic framework, capable of enhancing the concurrent use of engineering software, is the key element to improving design optimization, enhancing the potential of Computer-Aided tools and Model-Based Definition (MBD) practices. Therefore, an integrated design methodology for design optimization is required to better exploit the new capabilities of integrated and advanced simulations.

The present doctorate research aims to define and develop an appropriate design methodology for product/process design integration, involving the application of the DM approach combined with cost management practices. The methodology is developed through the implementation of predictive models and optimization methodologies to integrate DfT and DtC approaches. The main focus is the design optimization of automotive components, considering the effects of the dimensional and geometric variations on functional and economic requirements, starting from the earliest stages of development.

Aiming to provide a solution for the aforementioned issues, the research activity has been divided into two steps. Firstly, a methodological and systematic approach is defined for DfT: starting from the definition of a Computer-Aided tolerance specification approach, the modelling procedure for CAT simulation is developed as a central element of the entire design methodology. Several case studies have been considered for the assessment of the methodology, to identify the impact of tolerances on functional and assembly requirements, and to provide corrective actions. Secondly, the evaluation of manufacturing costs related to tolerances is provided, following a model-based and Computer-Aided approach, to be integrated with dimensional variation simulations. This integration leads to the definition of a Computer-Aided Integrated framework for tolerance-cost optimization: each phase of the methodology has been developed, from the setting of multi-disciplinary optimization (MDO) to the integration of GD&T semantic annotations, involving several case studies. The final application of the integrated framework on a high-performance V12 engine assembly returns the expected results of tolerance design optimization, achieving the targets of assembly and functionality, as well as cost reduction.

From a scientific point of view, the proposed methodology provides an improvement for the tolerance-cost optimization of industrial components. The integration of theoretical approaches and Computer-Aided tools allows to analyse the influence of tolerances on both product performance and manufacturing costs. The case studies considered have proved the suitability of the methodology for its application in the industrial field, as well as the identification of further areas for improvement and refinement.

State of the art

As for many industrial fields, the automotive sector has grown consistently over the last decades. The evolution of the automotive sector is leading to an important revolution, widespread in many industrial sectors: from material extraction to recycling, from market analysis to production plant definition. Since automobiles have a strong influence on modern culture, each phase of vehicle engineering must be carefully considered, being the subject of many research activities. The overall complexity of vehicles and the large number and heterogeneity of components lead to many challenges related to this type of product: homologation requirements, economic evaluation, and qualitative expectations constrain vehicle design like never before. Moreover, recent trends such as electric mobility and autonomous driving force engineers to address new complexity to vehicles. This results in a constant search for a perfect balance between the achievement of product performance and the economic feasibility of the products.

The main driver of any industrial product is the economic feasibility, through which to reach the expected level of profit. Cost Management must consider all product components and production phases, from market analysis to the end of the product life cycle. Therefore, this challenging and complex task requires economic evaluations throughout product development, bearing in mind the multidisciplinary effects of product quality and performance on costs, both in terms of production cost and impact on long-term economic success. For the automotive sector, this means optimizing product design to achieve the economic targets for the whole system, acting on every individual component.

A vehicle can be considered as a multi-level hierarchical system, in which different groups and sub-groups, made up of different components with different materials, are joined together according to assembly and manufacturing processes. As a result, functional, aesthetic, manufacturing, and economic requirements must be properly considered during the design of complex products: Concurrent Engineering (CE) approaches are required to consider the mutual interrelationships between the different areas of product development. Aiming to involve all the product life cycle constraints from the earliest phases of the design process, CE requires a systematic integration during product design, breaking down the competence barriers between product and production process development.

Since the quality of a product starts in the early stages of development, through the definition of the fundamental requirements from a functional, performance and technological point of view, the application of Computer-Aided tools and methodologies is necessary to reduce the time to market and the production costs. Thanks to the widespread diffusion of Computer-Aided software and the increasing application of model-based practices, most of the product development phases can be anticipated and, therefore, product design can be further optimized. This has led, over the years, to the diffusion of specific techniques for design optimization: Design for X (DfX) practices allow engineers to address specific requirements from the earliest stages of product design using specific tools.

Furthermore, one of the main issues related to a system composed of heterogeneous groups is the compliance with the assembly and packaging requirements: the accumulation of variations provided by a group of components could significantly influence the whole product, first in terms of functionality. Therefore, engineers are interested in quickly identifying the sources of variation so that quality products can be produced in the shortest possible time. Since the geometric and dimensional variations have a direct effect on both quality and costs, the prediction and control of product tolerances are essential to comply with the expected targets. As a result, the methodologies for the management of dimensional and geometric variations of industrial products, known as Dimensional Management (DM), have quickly become a standard reference and have assumed a central role during product development. The systematic approach provided by DM allows the control and optimization of admissible variations to be more robust and effective in its practical applications. This chapter presents an overview of the current design process adopted in the industry, concerning Dimensional Management and Cost Management (CM) approaches.

1.1 Engineering design systematic approach

To fully understand the importance of the techniques and methodology related to Dimensional Management and Cost Management in the context of product design, it is important to underline the main phases of the systematic approach to engineering design (Pahl and Beitz, 2013; Ulrich and Eppinger, 2011). This design approach, commonly implemented in industry, is based on a hierarchical order of steps, composed of different process levels, and arranged with iterative loops.

- *Product planning and task clarification* - This initial phase aims at defining the design goal of the product, through the formal description of the product requirements and constraints. Among the main requirements, the functional requirements are the key targets to be defined, since they have a direct connection with the selection of the technical solutions and the definition of technical specifications, i.e., the product tolerances (Krogstie and Martinsen, 2012).
- *Conceptual design* – It consists of identifying the optimal solutions to achieve the requirements and constraints previously set, providing a direct translation into the first design concepts.
- *Embodiment design* – After selecting the optimal solutions, the overall layout of the product has to be defined. The preliminary configuration must provide the geometry of the components, their materials and manufacturing processes. During this maturity phase, every critical element and weak point must be considered, analysed, and solved: the design optimization results in an improvement in performance and in the achievement of requirements.
- *Detail design* – The models resulting from the previous phase are completely defined, through detailed modelling and numerical simulations, in their final design for each element, i.e., by defining its shapes, dimensions, properties, and couplings. The output of this phase is the final design of the product, followed by the processing of manufacturing documents, bills of materials, and the technical drawings of each component and their assembly.

The subsequent phases consist of testing physical prototypes to improve the product by setting and optimizing its performance. For the automotive sector, prototypes are needed for functional and customer compliance testing, and for reliability and performance information to identify required changes in the final product. After that, the start of production is considered from a manufacturing system perspective, optimizing the process and setting up series production. As a final test to be performed on the final product, the efficiency of the entire process is verified and, acting in a retrofitting way, further modifications and design improvements are considered for both the product and production process. In this way, the company's know-how can grow to facilitate the development of new products.

Therefore, during the design phase, most product requirements are translated into specific features and properties on the components. This requires transforming a theoretical project into a concrete object, establishing requirements on materials, shapes, and dimensions, both in terms of nominal values and tolerances: the Technical Drawing is the moment in which the Quality performance of the product is formalized by providing a standard language. In this way, the Mechanical Technical Drawing is an essential part of the product development path: it becomes both the means of transferring information to the various departments involved (quality, laboratories, technologies, production) and the contractual element through which the product is completely defined.

In the past, design processes were centred around two-dimensional (2D) drawings, i.e., the master records of the product definition. With advances in technology and continuous business challenges to shorten product development cycles, 2D drawings have reached their limits. The exponential growth of convenient three-dimensional (3D) technologies, i.e., Computer-Aided technologies (CAx), has led to the widespread use and popularity of 3D visualization. As a result, 2D drawings have become inadequate for several reasons:

- 2D drawings are generated from 3D models, so recreating the drawings is time-consuming and wasteful of energy.
- 2D drawings are more prone to interpretation errors which can lead to non-compliant projects and data inaccuracies.
- 2D drawings are not suitable for widespread collaboration to overcome geographical barriers.

In addition, interpretation errors, duplication errors or revision inconsistencies can contribute to costly mistakes that quickly translate into lower quality and productivity. Consequently, even if 2D product documentation is no longer the most effective, it still has a dominant contractual role and unchallenged legal value (Ricci and al., 2014): 2D drawings still contain instructions for manufacturing a part, but the actual manufacturing process requires both the 3D form and 2D information to produce a correct part. Furthermore, a simple change in the product definition not only requires up to date 3D digital data but also necessitates numerous engineering changes to all 2D documentation associated with the product. This takes time to update the documentation and recreate CAD models throughout the product development cycle. As a result, errors and information losses (due to the reading, interpretation, and transmission of drawing information) can occur during this process, reducing the integration between the design, manufacturing, and verification phases.

In this scenario, the diffusion of Computer-Aided technologies and Model-Based Definition (MBD) practices has led to significant benefits during product development (Pippenger, 2013; Goher et al., 2019). Not only does this reduce the need to generate 2D drawings, moving drawings from paper to digital format, but it also allows downstream applications to directly access this information to automate tasks. As a result, product teams have enterprise-wide access to the right data at the right time with the right amount of detail, reducing errors and development times because there is no need to re-enter data from a drawing.

Computer-Aided Technology

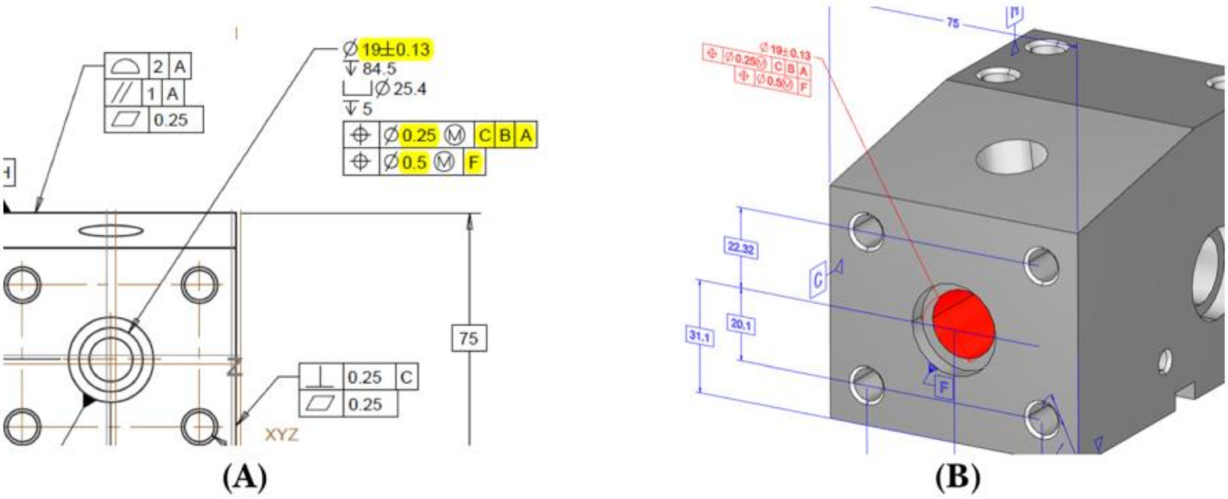
As already described, the engineering design process requires a systematic approach based on simulations, tests, and iterative optimization cycles. Since the design of industrial products deals with the complexity of requirements, solutions and processes, the support provided by software tools to technicians and engineers is essential. Over the decades, the evolution of computer technology and computational capabilities has grown exponentially and these tools, now called Computer-Aided technology (CAx), are the reference for industrial product engineering (Hirz et al., 2013). Depending on the specific task they deliver, modern CAx tools aim at enabling design optimization and supporting product development through advanced analysis and simulations: Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Computer-Aided Manufacturing (CAM), etc. Thanks to the possibility of anticipating tests and simulations, the widespread use of CAx leads to a reduction in development times and costs, improving the quality, profitability, and innovation of research. The result is that today the choice of the CAx platform has an impact on the entire design cycle, from the concept definition to the detailed and complete product definition. Therefore, the operations that must be performed to obtain a working product directly depend on the tools adopted. In addition, the CAx tools allow the diffusion of Product Lifecycle Management (PLM) approaches, based on Product Data Management (PDM) software systems (Ricci and al., 2014).

The design process starts with the use of CAD software, through which the product geometry is defined as 3D model. The modelling procedure can be performed following different approaches and modelling techniques, depending on the product to be designed and including geometry information, topology representation, product structure and additional data. Thanks to the integration of geometric data, the 3D models obtained are the starting elements for the subsequent activities of virtual product and process development, commonly provided by CAE tools. Although these tools are usually adopted as a final check during the detail design, to validate the final layout and specification of the product, the advent of the early design approach has progressively anticipated the use of geometric modelling and, therefore, the application of CAE during the embodiment design. This approach aims to provide many results already in the early design phases, enhancing the integrated product/process design. This is becoming possible even if the information available in the early stages is not completely defined, thanks to the development of integrated platforms and advanced optimization tools, classified as Multi-Disciplinary Optimization (MDO) platforms. These platforms enable the integration of simulation tools to improve multi-objective design optimization of systems and, although they are relatively new and their application is still limited, they are becoming more common and attractive to different applications along the design process. Most of the application of MDO platforms focuses on CAE simulation, through which to perform simulations starting from preliminary models, with rough information and overall boundary conditions (i.e., geometrical data, objectives, and constraints), obtaining optimized component designs. The most common MDO platforms currently available are Altair HyperStudy® by Altair Engineering Inc., ModeFRONTIER® by Esteco©, ModelCenter® by Phoenix Integration Inc., and Simulia Isight® by Dassault Systèmes®. Thanks to the development of new optimization techniques and strategies, an effective application of MDO platforms combined with several CAx tools can be foreseen, supported by the growing diffusion of Model-Based practices.

Model-Based Definition

The development of 3D visualization technologies and tools to support engineers during the design process is the direct consequence of the need of reducing time, costs and risks related to product development and systems distribution. As the complexity of these systems is growing exponentially over the years, a systematic approach is required for integrating and managing information associated with products. Therefore, the Model-Based Definition (MBD) is the engineering approach to address this purpose (Hedberg et al., 2016). MBD creates complete technical data packages (TDPs), including the 3D model and associated data items to offer a complete definition of the product: they constitute a single data source useful to query, analyse, build, and inspect the product. TDPs can be shared across the product development environment, communicated, and effectively used by all downstream customers, without the need for 2D drawings. Instead, MBD is part of the Model-Based Enterprise (MBE), a collaborative and fully integrated environment that shares validated and authorized data of MBD throughout the company, allowing the creation of products from the concept to the end of life: all parties involved in the organization can access a complete definition of the digital product not only when necessary, but also according to the required specifications.

The key component of an MBD is the integration of product-related engineering information into the 3D model by means of Product and Manufacturing Information (PMI) (Quintana et al., 2010). PMI consists of 3D annotations associated with CAD features, including Geometric Dimensions and Tolerances (GD&T), material specifications, component lists, process specifications, and inspection requirements (Hedberg et al., 2016). Since this information, previously entered in 2D drawings, is specified directly in the 3D environment, PMI allows to speed up the development process, reducing errors, development times and costs. The information is directly linked to the affected part of the model shape or 3D geometry and grouped into multiple saved views to aid visual consumption. Since the main benefit of MBD is the improvement of interoperability between software and simulation environments, several common file standards have been introduced to enable compatibility (International Organization for Standardization, 2014): derivative models, such as STEP (ISO 10303-242 – known informally as the Standard for Exchange of Product model data or AP242), JT and 3D PDF files, are required for the consumers who do not have direct access to the CAD system in which the native MBD model is defined. The 3D annotation provided via PMI is commonly classified in two different representations (Feeney et al., 2015): the Representation PMI, also known as semantic PMI, and the Presentation PMI, addressed as graphical PMI. Representation PMI is the machine-readable PMI: in this case, the information is semantically correlated to the 3D geometric features of the parts, and this allows for automatic readability by different CAx tools. In this way, software developers have stressed this ability to automate various design, manufacturing, and inspection functions. On the other hand, the graphical PMI is applied to display information, as for a 2D drawing. In this case, it is only the transposition of comments and annotations in a 3D environment: it is human-interpretable since it represents symbols commonly adopted by technical product documentation standards (i.e., ASME and ISO, covered in the next section). While not suitable for automated machine-reading and interpretation, this type of PMI is very useful for visualizing design intent and, for this reason, is the most applied: it can be organized into saved views, provided with annotations that support cross-highlighting of affected geometry. As reported by Hedberg et al. (2016), this results in three different ways of representing the PMI for a geometric feature, as shown in Figure 1.




```xml
<?xml version ="1.0" encoding="UTF-8"?>
<ModelTree3D Version = "1.0">
  <Node Name="DIM">
    <Property Name="cadEntityId" Value="1339"/>
    <Property Name="dimensionText" Value="{0: n }{1:@D}{2: # 0.13}"/>
    <Property Name="dimensionType" Value="DIMTYPE_DIAMETER"/>
    <Property Name="displayedValue" Value="19.000"/>
    <Property Name="gt1_gtolType" Value="GTOLTYPE_POSITION"/>
    <Property Name="gt1_isComposite" Value="false"/>
    <Property Name="gt1_isOverallTolerance" Value="true"/>
    <Property Name="gt1_isPerUnitTolerance" Value="false"/>
    <Property Name="gt1_materialCondition" Value="GTOLMATCOND_MMC"/>
    <Property Name="gt1_overallToleranceValue" Value="0.250000"/>
    <Property Name="gt1_primaryBasicDatumName" Value="C"/>
    <Property Name="gt1_secondaryBasicDatumName" Value="B"/>
    <Property Name="gt1_showAllAroundSymbol" Value="false"/>
    <Property Name="gt1_showDiameterSymbol" Value="true"/>
```


(C)

Figure 1. Examples of representation and presentation PMI in a drawing and model (Hedberg et al., 2016)

Given a hole on the component lateral face, it is possible to display the information in the 2D drawing (a), or in the 3D environment through MBD: as graphical PMI (b) or as representation PMI (c), commonly addressed using XML data format. The first two annotations are easily interpretable for human consumption, while the latter is suitable for computer applications.

As a direct consequence, PMI structure is the critical element of MBD. MBD is directly related to PMI and the efficiency of its representation models is still an important challenge: computer interpretability and data associativity allow MBD (and, therefore, MBE) to work. Although the classification of PMI is well-established, many researchers identify the lack of representation standards of PMI within CAD tools as a critical issue: PMI implementation strategies for CAD need to be standardized and systematically developed to enable effective verification and validation in the MBE. Many comparative reviews and research works have addressed the importance of MBD for digital evolution. In particular, Hedberg et al. (2016) highlight the benefits of using the MBD approach to demonstrate that model-based processes outperform drawing-based processes. Results showed that the model-based processes provided a 74.8% reduction in cycle time with respect to the drawing-based processes, Figure 2.

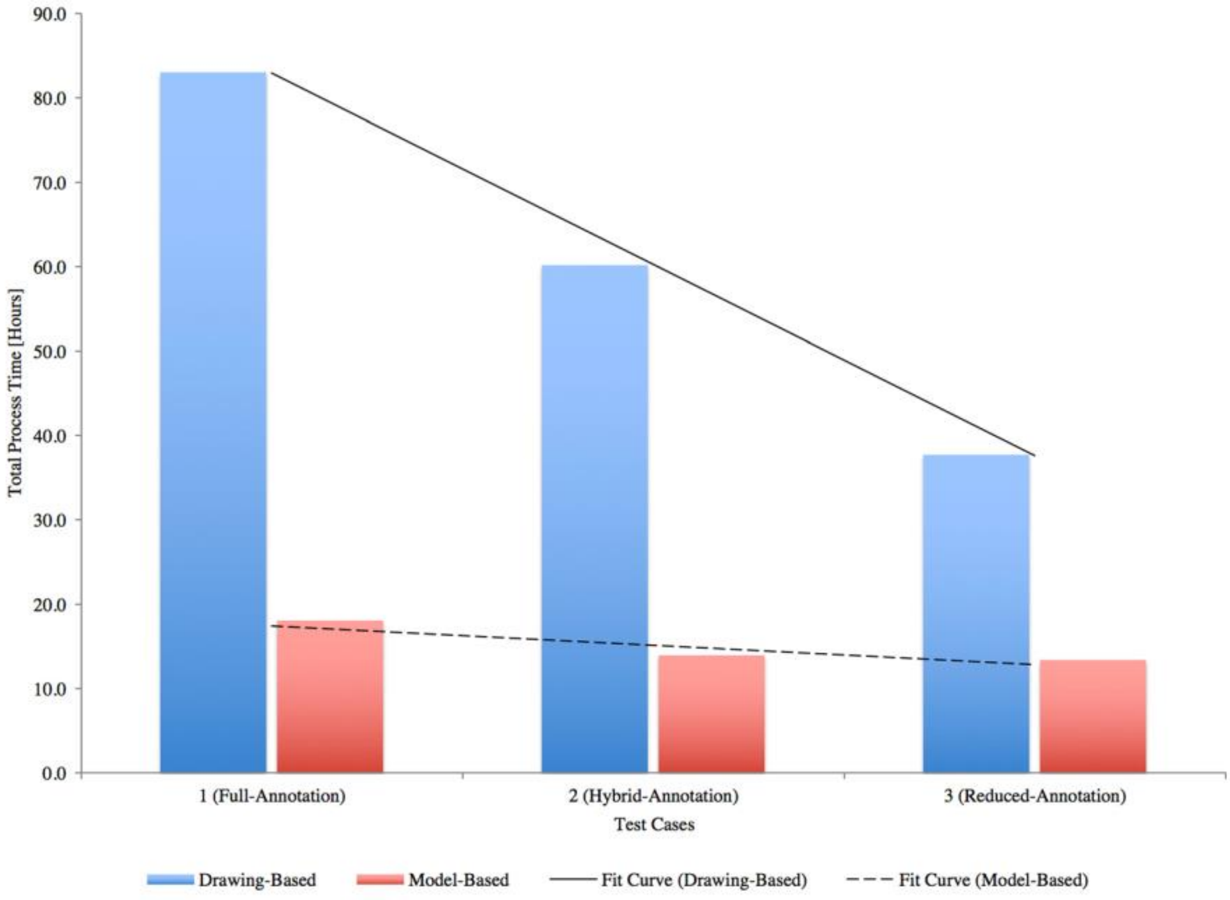


Figure 2. Comparison of drawing-based and model-based processes (Hedberg et al., 2016)

In particular, it has been pointed out that MBD can significantly decrease cycle time when applied as legal documentation for product delivering. Moreover, it reduces the risk of error from data re-entering, enabling the transition to digital manufacturing through the development of advanced methodologies for design optimization.

Design for X

The widespread diffusion of CAx technology has provided the ability to deepen each area relating to product and process development. In this way, geometric modelling can be supported already from the initial stages, involving all the product life cycle constraints, to define a balance between the different needs (i.e., product performance and product costs). As a direct consequence of CAx technologies, Design-for-X (DfX) techniques have been established and developed in recent years, supporting engineers during the product process development phase (Holt and Barnes, 2010).

These techniques allow to consider every aspect of the product along the entire life cycle of the product itself, providing specific support in all design and decision-making activities. These methods are distinguished in DFXvirtue and DFXlifephase: the former focuses on a product characteristic (cost, quality, usability, etc.) while the latter on a phase of the life cycle (manufacturability, assembly, disposal, etc.). However, as DfX techniques are specific to the area they refer to, they are sometimes unable to identify all effects and relationships related to the overall system when applied separately. Due to the variety of issues to be considered, multidisciplinary working groups have been defined to face the product development process in an integrated way, following the CE approach: by working simultaneously, a significant reduction in time-to-market can be potentially obtained, as well as a more efficient approach to design optimization.

Among these techniques, Design for Manufacturing (DfM) and Design for Assembly (DfA) are well-known and widely applied in the industry (Boothroyd et al., 2010). In recent years, the evolution of these techniques has led to a first attempt at integration to improve design optimization, through the so-called Design for Manufacture and Assembly (DfMA). DfMA consists of a systematic procedure for product design optimization from the point of view of production and assembly. It allows for simpler, more reliable, and less expensive products to manufacture and assemble, including DfM and DfA techniques. The goal of DfM and DfA, i.e., reducing the costs of a product, has always been the same, but with different modes of action: DfM focuses on the manufacturability of the components while DfA considers the overall structure of the assembly. Following DfM, cost reduction must be pursued by simplifying and optimizing the geometries according to the manufacturing processes necessary to obtain them. On the other hand, DfA implies trying to simplify the structure of the product to make the assembly process easier, minimizing the number of components of a product (even at the cost of increasing its complexity). Although sometimes the information provided by DfM and DfA can be conflicting, as also reported by Holt and Barnes (2010), the need for a competitive approach has led designers and process engineers to collaborate from the earliest stages of development to anticipate problems even before they occur. As result, DfMA has combined the approaches with the unchanged goal of evaluating and reducing product costs, both manufacturing and assembly, from the earliest stages of the development process, and identifying technically feasible or economically disadvantageous projects as soon as possible. Doing so minimizes delays, ensuring a reduced time-to-market which translates into a potential strategic advantage on the market. The complexity of some products requires the identification of the most critical subsystems to focus on: following the Pareto rule, 20% of the causes determine 80% of the effects. DfMA involves an initial analysis according to DfA, applying the criterion of the minimum number of components to simplify the product structure. Subsequently, materials and processes are defined and DfM is applied to obtain an initial cost estimate and choose the best concept. Once the concept is defined, a detailed analysis is carried out to identify potential cost reductions. The complete procedure, according to Boothroyd et al. (2010), is reported in Figure 3.

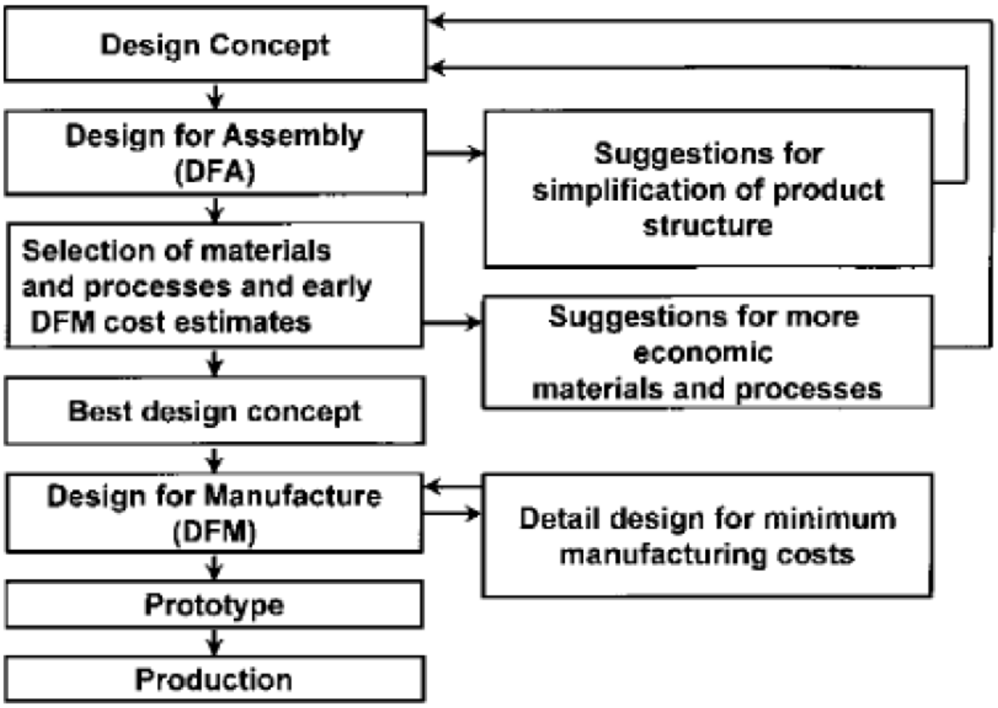


Figure 3. DfMA application (Boothroyd et al., 2010)

As with DfMA and the other DfX techniques, both the tolerancing and the cost estimation processes are part of the CE approach to design optimization. This leads to the definition of specific design techniques: Tolerance Design or Design for Tolerancing (DfT), and Design to Cost (DtC).

1.2 Dimensional Management

Dimensional Management (DM) is the widespread engineering practice to improve quality and reduce costs by controlling geometric and dimensional variations of industrial products. This engineering methodology, usually combined with Computer-Aided simulation tools, is based on the systematic approach for the assignment of the nominal parameter values and tolerances (Kacker, 1989; Taguchi et al., 2005). Since this process concerns the functional design, but also the production and inspection phases, the selection of component specifications has been theorized and standardized over the years.

Following Taguchi's approach to parameter design and quality engineering, known as the robust design method (Tsui, 1992; Eifler et al., 2013), the process of identification and translation of functional requirements on component geometry consists of three subsequent phases, as reported by Goetz et al. (2018): system design, parameter design and tolerance design, as shown in Figure 4.

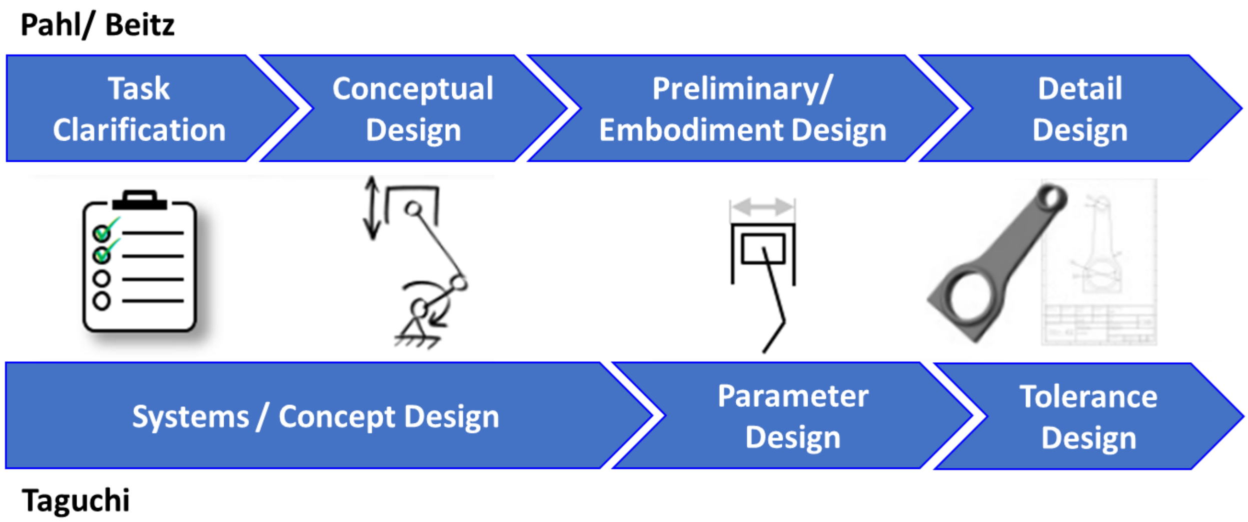


Figure 4. Product design process according to Pahl and Beitz and Taguchi (Goetz et al., 2018)

This approach follows the engineering design process: the first phase of system design defines the overall layout of the product, evaluating the conceptual solutions to identify the optimal one in terms of overall robustness. The second embodies the product through the definition of the nominal shape and dimensions, i.e., the design parameters. The last phase of tolerance design provides the product tolerances required to guarantee the expected quality, limiting the variations from the nominal. Although subsequent to the previous steps, tolerance design is the essential phase for achieving product requirements, providing the link between product and process design.

Before introducing the theory, the methodologies, and the tools related to tolerance design, a brief description of the process of parameter design is needed to introduce some general concepts.

Parameter design

Parameter design specifies the nominal geometry of a product: the shape, the size, the position, and the orientation of the component features. Since each element defining the component must be dimensioned, the dimensions must be provided following a standardized representation.

The dimensioning and tolerancing processes are governed by current standards and regulations, to which they must be consistent. Two international organizations provide indications and representations of dimensions and tolerances in the technical product documentation: ASME (American Society of Mechanical Engineers) and ISO (International Organization for Standardization), operating respectively in the United States and in Europe. In the industrial practice, the application of these standards regulates the process of transferring information to the various departments involved (quality, laboratories, technologies, production). For this reason, during product development dimensions, annotations, and tolerances must completely define the component and clarify its properties. Since the technical drawing must ensure that the product properly works, the dimensions can be classified as functional, manufacturing and inspection according to the different approaches used, due to different purposes or different requirements in technical drawing (Henzold, 2006; Tornincasa et al, 2020).

- *Functional dimensions* – The goal is to express product functionality, including the assembly and the single component involved. The functional dimensions describe the usability conditions, i.e., the assembly conditions, the mechanism functions, and the geometric properties. The process of functional dimensioning is regulated by the UNI ISO 129-1 standard (International Organization for Standardization, 2018). Together with the definitions of the UNI EN ISO 10209-1:1995, it provides the correct principles for understanding the features of each component and its function within the assembly (Manfè et al., 2001). Every mechanical component should be completely defined in its functional dimensions to ensure the correct functionality, addressing the principles of product interchangeability and repeatability of the manufacturing process. In this way it is possible to consider each functional feature as a new case, referring to the standard principles but without a given determined scheme.

- *Manufacturing dimensions* – This dimensioning approach aims to identify the dimensions involved in the production process. Due to the specific manufacturing process, different aspects must be considered: machines and tools selection, material, precision, etc. Consequently, the manufacturing (or technological) dimensioning is necessary to reflect the manufacturing process, in particular to underline the reference system from which to correctly position the workpiece to be machined and to ensure repeatability of the machining.

- *Inspection dimensioning* – Product inspection and conformity assessment require specific information related to the design intent. Therefore, the inspection dimensioning provides the dimensions and tolerances necessary to establish a clear and measurable scheme for a certain and unambiguous evaluation (Manfè et al., 2001).

Although the classification is not always applicable due to the complexity of real components, the design intent behind each type of dimensioning must be clear. In fact, the dimensioning strategy adopted during the production of the technical product documentation has an effective impact on component tolerances. If two parts are related by different features, how they are specified influences the number of tolerances contributing to the allowed variations. As a general best practice, functional dimensions must be arranged and correlated to minimize tolerance accumulation between related features (Henzold, 2006).

1.2.1 Tolerancing

According to Fischer (2011), *a tolerance is the specified amount a feature is allowed to vary from nominal. This may include the form, size, orientation, or location of the feature as applicable*. In conjunction with parameter design, tolerancing acts in the technical representation of mechanical components. Their application to mechanical drawings is fundamental, as manufacturing and measurement imperfections make it impossible to produce components without deviation from the nominal shape (Srinivasan, 2007). Dimensional and geometrical variations are unavoidable, with deviations in size, form, orientation, and location (Figure 5). The goal is to minimize part variations to meet product quality requirements: excessive deviations could heavily compromise product functionality. For this reason, each component must be completely specified with tolerances: all its features and properties must be defined in terms of allowed variation from the nominal. The tolerancing process is the key activity to ensure both product functionality and economic feasibility, as it provides information to minimize this variation only where necessary, avoiding manufacturing companies from being uncompetitive in the market. In this way, it is possible to produce parts as precise as necessary and economical as possible. In addition, the adoption of a common design language, regulated by ISO and ASME standards, reduces the possibility of defects, damages, and reworking pieces due to incomplete or ambiguous drawings.

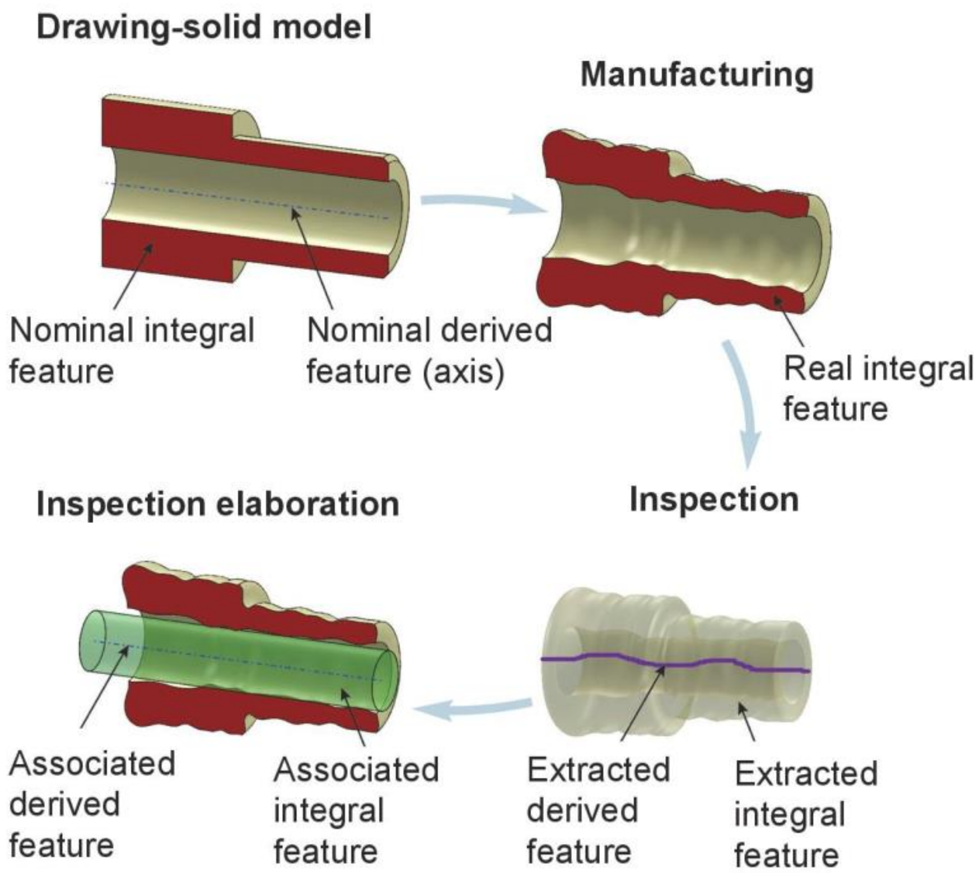


Figure 5. Real vs ideal part (Fischer, 2011)

As a result, tolerances are the means of quantifying the amount of variation allowed, considering the errors along the production process. To express this intent, tolerances are classified into two groups: dimensional and geometrical variations, as reported in Figure 6.

Dimensional tolerances relate to dimensional or size deviation, i.e., the difference between actual size and nominal size, and are classified in deviation from the nominal linear size (ISO 8015, ISO 286, and ISO 14 660-2) or from the nominal angular size (ISO 8015, ISO 1947). According to the standards, these tolerances are expressed in the same unit of the nominal dimension, with the variability range expressed using the upper and lower limits (International Organization for Standardization, 2018).

On the other hand, geometric variations are classified into two categories, namely, micro-geometric and macro-geometric errors.

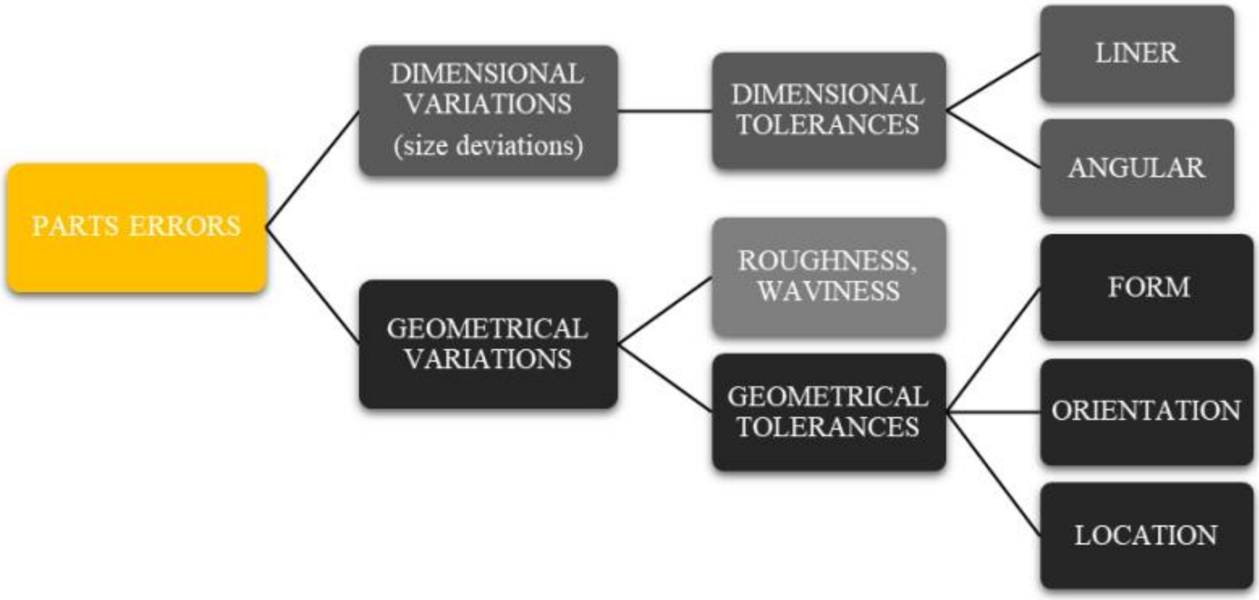


Figure 6. Part errors

Micro-geometric errors include waviness and roughness, whose combined effect (superposition) gives the irregular surface. Waviness identifies the periodic irregularities of a surface, caused by form deviations of manufacturing tools or vibration during the manufacturing process (Henzold, 2006). Roughness consists of periodic or non-periodic irregularities of a surface with small spacings due to the manufacturing process, generally due to the direct effect of the cutting edges and cutting process. Macro-geometric errors are classified into three main types of deviation (Tornincasa et al, 2020):

- *Form deviation* – This deviation occurs when a geometric feature deviates from its nominal form. In general, these deviations refer to the entire feature, unless otherwise specified. Different factors affect form deviations: error in the fixtures of the workpiece, deflections of the machine tool or the workpiece, looseness or error in the bearings of the machine tool, hardness deflection or wear, etc.
- *Orientation deviation* – This deviation consists of deviation in form and orientation of a component feature with respect to one or more reference elements, i.e., the Datum feature. Therefore, it also includes the form deviation. This type of error could be caused by an erroneous fixture of the workpiece after remounting on the machine tool.
- *Location deviation* – This deviation is related to the deviation of a component feature from its nominal position, with respect to one or more Datum features. This deviation includes both form and orientation deviations, as it concerns variations of surfaces, axis, or median faces. As for size, form and orientational deviations, location is generally caused by errors during manufacturing processes and machine tooling (Henzold, 2006).

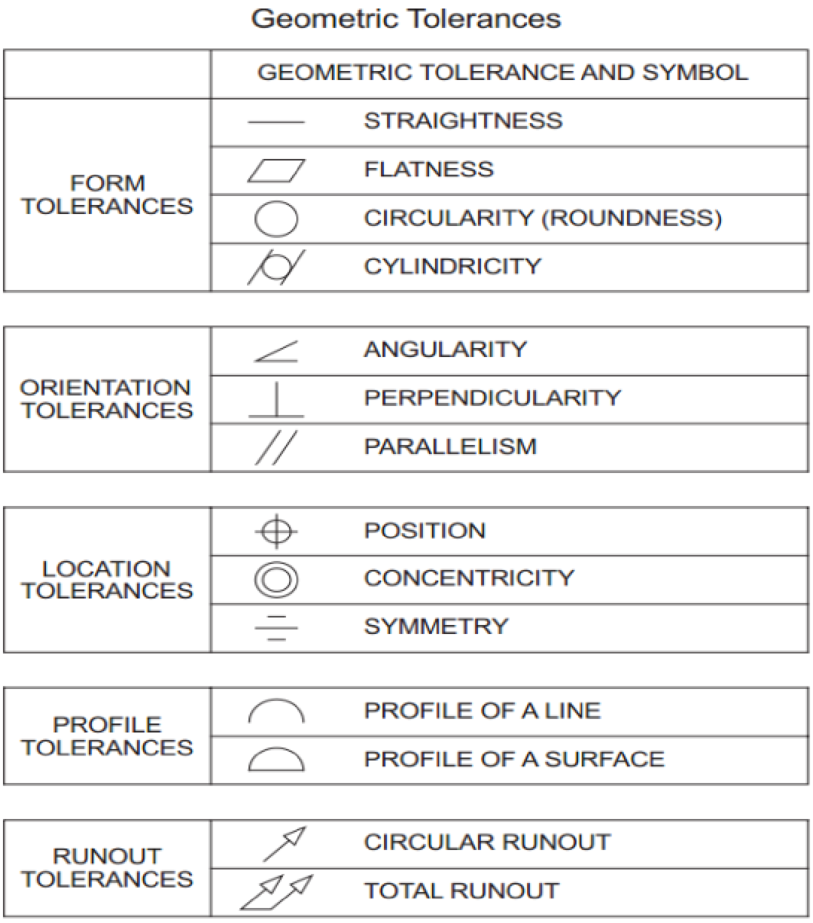


Figure 7. GD&T symbols for geometrical tolerances according to ASME Y14.5 (American Society of Mechanical Engineers, 2018)

As a result, the main types of geometric tolerances can be briefly summarized in Figure 7. Please refer to technical books and the ASME and ISO standards for an in-depth description of each of them.

- *Form tolerances* – These tolerances control straightness, flatness, circularity, and cylindricity. They provide the maximum allowed value of the form deviation within a tolerance zone: all points of the feature must be contained in this specific limited region in which the controlled feature may have any form, unless otherwise specified.

- *Orientation tolerance* – These tolerances control parallel, perpendicular, and all other angular relationships, limiting the deviations of a feature from its ideal orientation with respect to the Datum(s). The tolerance zone is in the ideal geometric orientation with respect to the Datum(s) whose width is defined by the tolerance value.

- *Location tolerances* – They control position, concentricity, and symmetry, limiting the deviations of a feature from its ideal geometric location (orientation and distance) with respect to the Datum(s). The location tolerance zone is in the ideal geometric orientation and location with respect to the

Datum(s) and the tolerance value defines the width of this zone. Theoretical exact dimensions (TEDs) are commonly adopted to locate the true position.

- *Profile tolerances* – These tolerances are used to define a tolerance zone to control form or combinations of size, form, orientation, and location of one or more features relative to a true profile. Depending on the design requirements, profile tolerance zones may or may not be related to Datums. The tolerance zone is the distance between two boundaries equally or unequally disposed with respect to the true profile or entirely disposed on one side of the true profile.

- *Run-out tolerances* - These tolerances are applied to control the functional relationship of one or more features to a Datum axis. They are partly orientation tolerances (axial circular run-out tolerance, axial total run-out tolerance) and partly location tolerances (radial circular run-out tolerance, radial total run-out tolerance).

GD&T - Geometric Dimensioning and Tolerancing

The dimensioning and tolerancing schemes play a huge role in determining the accepted variability of components and, therefore, in achieving product quality targets. To precisely define the technical product specification in an objective and systematic way, the Geometric Dimensioning and Tolerancing (GD&T) symbolic language has been defined. GD&T is a global approach in which products and processes are considered in an integrated way, addressing specifications on functional design, production, and inspection requirements, through principles concerning representation, indication methods and working principles. GD&T allows to precisely define part geometry, identifying and representing the allowed variation in size, form, orientation, and location of component features. In particular, the tolerance zones addressed by the GD&T are specified with respect to their Datum Reference Frame (DRF), i.e., the reference features used to establish the origin of the measurements. According to GD&T, the geometric tolerances can be specified through feature control frames, with a characteristic symbol associated to each geometric tolerance, see Figure 7.

The strength of the GD&T approach is related to a more robust control of product design, ensuring functionality, manufacturability, and repeatability. Using a standardized design language also improves interoperability, through enhanced intercorrelation between design areas. Even if ASME and ISO standards share most of the principles and symbols adopted regarding geometric specifications, there are still some differences: please refer to technical books or Standards for further information.

As for the principles of GD&T, it is worth summarizing the main topics (American Society of Mechanical Engineers, 2009):

- *Datum feature* – It is the real feature of a part referred to as a Datum, i.e., as a reference element.
- *Datum Reference Frame (DRF)* – This is the reference to which all requirements are connected. Theoretically, it consists of three mutually perpendicular intersecting Datum planes, creating the origin for dimensions for manufacture and inspection (Figure 8). DRF is composed of the actual features of the part, i.e., the Datum features.

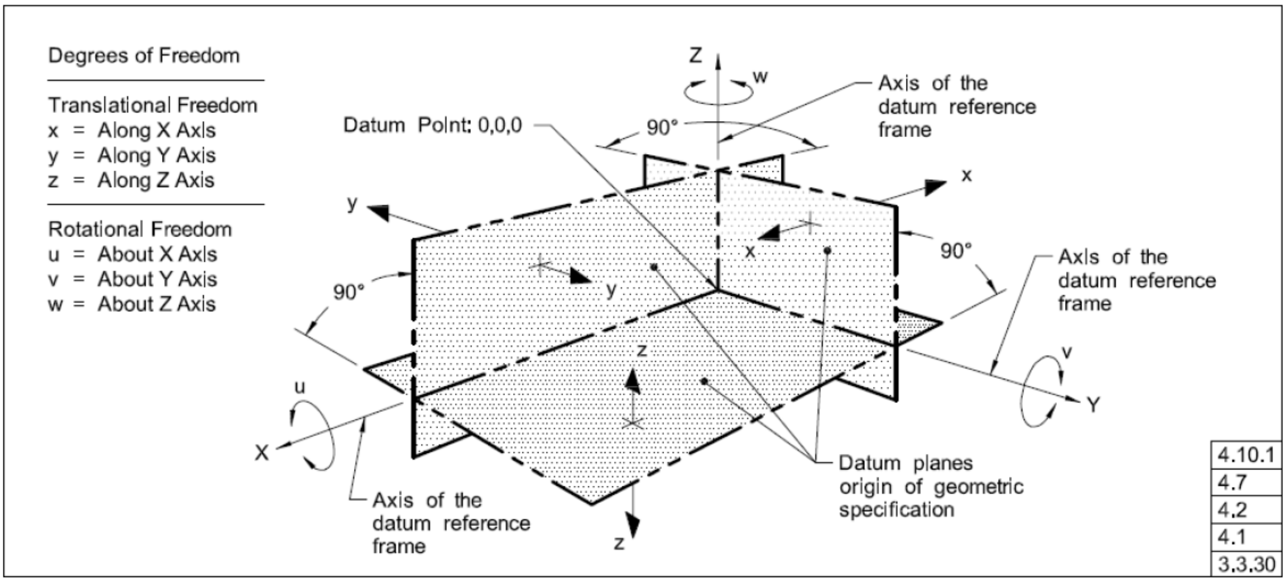


Figure 8. Datum Reference Frame (DRF) (American Society of Mechanical Engineers, 2018)

- *Choice of the Datum features* – Datum features are selected due to their role in the product requirements and their functional relationship with the other functional features of the component. In general, these features must be accessible on the part and with sufficient size to be easily used.
- *Datum order of precedence* – Datum features are specified in a specific order, according to the importance of each Datum for the specification of component features. For a part with all planar Datums Rule 3-2-1 applies: the primary, secondary, and tertiary Datums control the orientation, position and locking of the part, respectively. Changing the order of precedence of the Datums, for a given part, could ha ave direct impact on the measurements of the other features.
- *Qualification of the Datum features* – The qualification process consists in collecting Datum features by applying appropriate geometric tolerances or indirectly by dimensions, following specific rules.
- *Multiple Datum feature (Co-Datum)* – Co-Datums are used when more than one surface or Datum feature is selected to define a single reference element (i.e., Datum feature simulator) for the other functional features.

Therefore, the selection of the proper set of DRFs is critical to avoid errors or personal interpretation of the product specification. In particular, the systematic application of GD&T is the key practice for a concurrent approach to product development using a unique language for design, manufacturing, and inspection. Figure 9 collects a useful summary of the most common Datum features with relative drawing indication, associated Datum simulators and constrained degrees of freedom (DOFs) from the ASME Y14.5 (American Society of Mechanical Engineers, 2018).

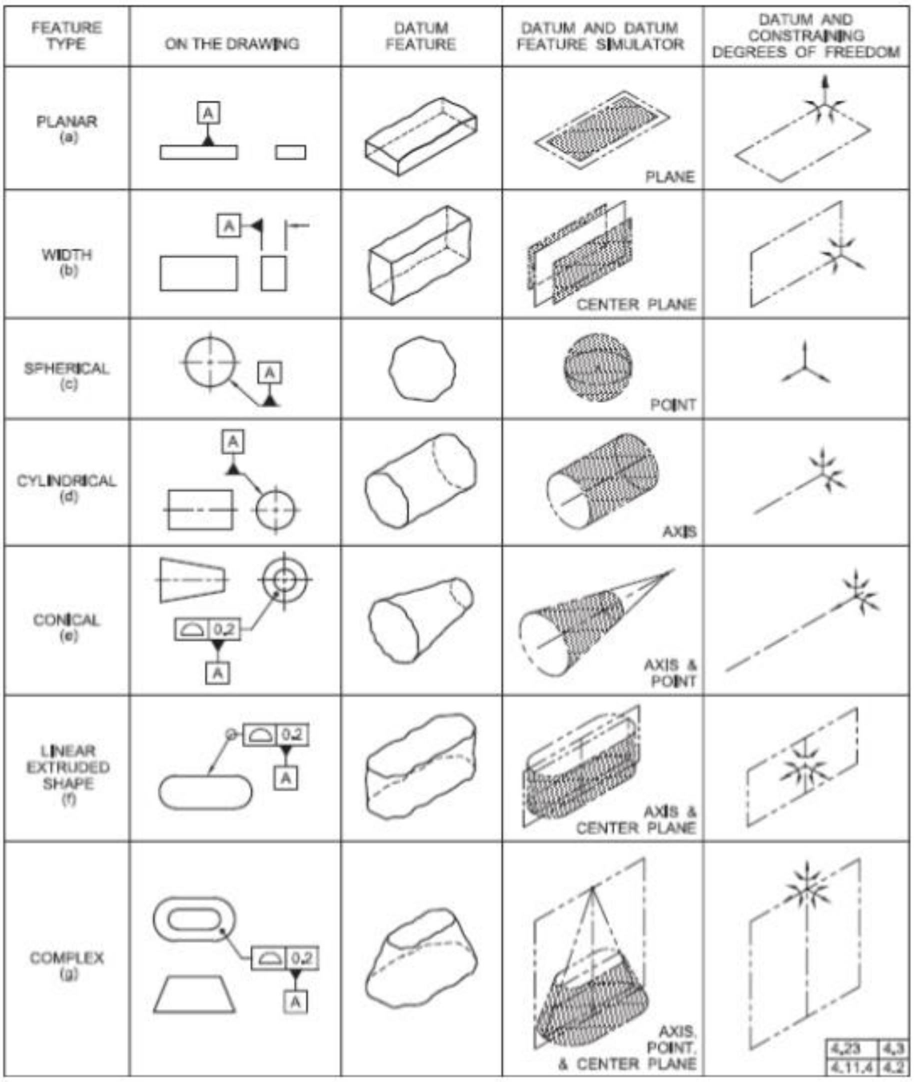


Figure 9. Summary of Constrained Degrees of Freedom for different primary Datum features (American Society of Mechanical Engineers, 2018)

1.2.2 Design for Tolerancing (DfT)

The activity behind the tolerancing process must deal with product requirements, but also numerous manufacturing issues, to ensure interchangeability of parts and enable a profitable production of quality products. The tolerance design phase must specify the allowed variations of the product, made by a sequence of different machining operations. Therefore, the variation of a finished product is affected by many factors, including variations in the component, assembly process and inspection process.

Tolerance design deals with product optimization, aiming at minimizing the accumulation of errors due to the most common sources of variation. For this reason, today the tolerance design activity is leading to a proper process of Design for Tolerancing (DfT), through which to optimize these variations to affect the functionality of the product as early as possible in the design phase. This approach is based on the main strategies applied during the tolerance design phases, in particular: robust design methodology, GD&T based modelling, statistical process control, and the use of Computer-Aided tools to support optimization through advanced simulations.

The choice of the proper dimensioning and tolerancing scheme, starting from the definition of the reference points (i.e., Datum), plays a critical role in determining the impact of each dimension and tolerance on a specific requirement (i.e., tolerance stack-up).

Traditionally, the process of tolerance design is divided into three phases (International Organization for Standardization, 2012):

- *tolerance specification* – definition of the tolerancing scheme, i.e., DRFs and tolerance types for all component features.
- *tolerance allocation* – assignment of a numerical value to each component tolerance.
- *tolerance analysis* – analysis of the deviation induced by the tolerances verifying the achievement of the product targets.

These three main phases cover the common steps of the tolerancing activity (Hong and Chang, 2002; Singh et al., 2009a). However, further phases are considered to meet the requirements and optimize product design. In particular, the *tolerance synthesis* phase is addressed as the iterative process of tolerance updating to match product requirements and functional objectives (Singh et al., 2009b). Starting from these objectives, it aims to identify the suitable values and types of tolerances, as a result of the iteration of the three main phases (Schleich et al., 2017).

Motivated by the advantages of CE approaches, the tolerancing activity has evolved consistently in the last decades, aiming to improve the integration between product and process design into tolerance design. As a result of this trend, *tolerance optimization* practice has become very popular as a key research topic for achieving optimal design. Through the application of advanced optimization techniques, the identification of the optimal set of tolerance values for a prescribed tolerance specification scheme can be further enhanced (Hong and Chang, 2002). The natural consequence of the tolerance optimization approach is the development of *tolerance-cost optimization* techniques. These techniques, covered in detail in the following sections, are becoming increasingly important in the field of DM, allowing to identify a more effective and direct link between product tolerance and associated manufacturing costs. Therefore, the development of tolerance-cost optimization techniques has enhanced the interest in DfT and multi-objective optimization strategies. The next sections will provide a brief analysis of the most important research works and methodologies for the main phases of tolerance design, briefly presented here.

Tolerance specification

The tolerance specification phase consists of the process of identification and translation of functional requirements on the product geometry. The tolerancing schemes must provide an unambiguous definition of the functional features of the components, capable of representing the functional requirements, in compliance with the tolerancing standards (ASME and ISO). According to Colosimo and Senin (2010), the tolerance specification process involves the identification of functional requirements, the selection of functional features (i.e., the features that need tolerances), and the definition of the GD&T scheme.

The correct identification of the product functional features has a significant impact on the result of the design activity: the functional features, also known as Key Characteristics (KC), play a fundamental role in achieving the product requirements. According to Thornton (1999), KCs are the features whose variation from nominal directly affects the final cost, performance (including the customer's perception of quality) or safety of a product. Therefore, special controls should be applied to such KCs if the cost of variation justifies the cost of the control. Consequently, it is important to assign dimensional and geometric tolerances for each functional, assembly and manufacturing feature, avoiding unnecessary tolerances on non-functional elements and, therefore, an increase in product costs. The definition of the proper GD&T scheme, starting from the selection of the reference elements as DRFs, is required to check the variability of the selected features with respect to Datums or their nominal geometry.

This decision-making process requires a lot of knowledge and experience to address conflicting requirements and influencing factors (Haghighi et al., 2015). The main difficulty is the translation of rules and standards on the specific case, considering functional and manufacturing issues. Indeed, in most cases this process is based on the experience of the design engineer and empirical data handed down from previous projects, as well as from handbooks for designers: this results in possible ambiguities and interpretation errors during the specification of geometrically complex products (Wang and Thamma, 2012; Hallmann et al., 2020a).

However, over the years researchers have stressed the topic to address robustness during this design phase. Several authors have proposed different approaches for function-oriented tolerancing: empirical methods (Sun and Gao, 2020), automated process models (Colosimo and Senin, 2010; Haghighi et al., 2015) and algorithms to support GD&T implementation and tolerance specification (Wu and Gu, 2016). In particular, Armillotta (2013) introduced an automated feature-based method for tolerance specification, for more extensive tolerancing of component and assembly features.

A different approach proposed in the literature for tolerance specification is based on the graph theory. In this way, the product structure is represented by the use of graphs to identify the relationships between the components and their features (Anselmetti, 2006): each feature or component is associated with a node, whose edges identify their linkage in tolerance graphs. Several graph-based models have been introduced, with a higher level of detail, but in general these methods focus on fully designed parts, without considering the design stages where geometry has not yet been fully defined. On the other hand, some research works aimed to provide support for the transition from a concept to a fully defined part, by means of graphs for data management (Dantan et al., 2003) and diagrammatic sketches for product structure graph generation (Goetz et al., 2018). Other interesting works address the use of decision-making algorithms, such as the work of Zhao et al. (2020), where this approach is applied for automatic evaluations of static and dynamic factors related to manufacturing and quality requirements. While very attractive, these methodologies are relatively complicated. In addition, most of the time these approaches are not supported by the Computer-Aided tools commonly adopted by manufacturing companies. As a result, the effective implementation of these methods in the industry is still difficult.

Tolerance allocation

The tolerance allocation phase provides a numerical value to each specified tolerance. The process of assignment and distribution of the allowed variability among the components of an assembly generally refers to two different approaches.

The first one is based on the assignment of tolerance values for functionality, without considering the associated manufacturing costs (Ostwald and Huang, 1977). This approach, commonly based on designers’ know-how and empirical data, produces tighter values of tolerances to achieve functional requirements. However, it avoids any possibility of cost reduction and design optimization (Speckhart, 1972). The result is the development of products with high-quality levels but with higher manufacturing costs. In general, this approach requires many iterations along with the following tolerance analysis to improve tolerance values. Most of the time, the re-allocation is based on a time-consuming trial-and-error approach: if the starting values of tolerances are not acceptable, they are tightened until the functional target is verified (Iannuzzi and Sandgren, 1996).

The second approach is aimed at finding a balance between product quality and manufacturing costs (Etienne et al., 2008): tolerance values must be identified by minimizing a cost function subject to manufacturing constraints. Therefore, the second method requires a more complex strategy compared to the previous one. Referring to the second approach, the literature proposes many methodologies for tolerances allocation, and three main strategies can be identified:

- *Indirect cost reduction* - Generally referred to as analytical methods, these methods rely on the definition of different weighting factors to identify the correlation between costs and tolerances (Chase et al., 1990). These factors act to allocate the appropriate tolerance values according to simple rules, providing only qualitative information on manufacturing costs (Kumar et al., 2009). As a result, these tolerance allocation strategies are severely limited by the lack of quantitative information and it is usually not possible to identify the optimal tolerance set. However, they are commonly applied during the preliminary phases of tolerance definition during early design, thanks to their simple implementation (Ji et al., 2000). Examples of indirect cost reduction strategies are: allocation by proportional sizing, allocation by proportional scaling, allocation by constant precision factors, allocation by difficulty factors, allocation by process variability and allocation by process capability (Islam, 2008).

- *Direct cost reduction* – In this case the tolerance values are assigned through a direct model correlation with the manufacturing costs. In this way, it is possible to optimize tolerances to minimize process-related costs by defining tolerance-cost relationships and empirical tolerance-cost data (Dong and Hu, 1991; Sanz-Lobera et al., 2016). Traditionally, tolerance-cost models can be classified into two categories: continuum model, based on an algebraic relationship, and discrete model, in which tolerance values cannot vary in a continuum manner (Chase et al., 1990). The advantages provided by this approach are very attractive for modern product development, compared to the first one. However, as this strategy requires manufacturing costs as an input, it is limited to the final stages of detail design, when this information is available.

- *Quality loss and/or productivity loss reduction* – Compared to direct cost reduction, this tolerance allocation strategy introduces an additional contribution to tolerance-cost models, the concept of quality loss. This concept, developed by Taguchi, addresses the effects of a product deviation from the target value on the customer perception of quality (Söderberg, 1993; Hallmann et al., 2020a). As with the second strategy, both methods require manufacturing costs and, in addition, maintenance costs (i.e., replacing and repairing costs) as input data. Therefore, applying these methodologies during the early design stages has always been difficult.

In addition to the methodologies briefly presented, several other strategies for tolerance allocation have been developed and presented over the years. Each of them, starting from similar input data, is based on different solution techniques, such as expert system, fuzzy logic, neural network, genetic algorithm, and experimental design (Islam, 2008). In general, these methods are very interesting to achieve an effective selection of tolerance values, but the lack of available manufacturing data and the difficult identification of parameters and cost function make the industrial implementation very complex and always limited to the end of the development process (Goetz and Schleich, 2020). To overcome the main issues and limitations during tolerance allocation, most of these strategies have found a solution through the development of optimization techniques: only with a robust optimization strategy the tolerance allocation problem can be addressed and formulated. For this reason, a more in-depth analysis of their mathematical formulation is provided in the section dedicated to tolerance-cost optimization.

Tolerance analysis

Tolerance analysis is commonly considered the critical phase of tolerance design as it directly affects the standardization of the production process and the functionality of the product (Corrado et al., 2016). Tolerance analysis aims to predict the effects on the product requirements of the dimensional and geometric tolerances assigned to the components of an assembly (Marziale and Polini, 2011; Qin et al., 2018). This term includes two main activities: the process of identifying the most relevant tolerances, and the process of determining the allowed cumulative variation (Peng and Peng, 2020). The first activity involves the definition of specific methodologies to identify the meaning and the importance of each tolerance.

The second activity deals with the generation of the tolerance stack-up as a combination of dimensions and tolerances, according to the assembly sequence (Fischer, 2011). The terms tolerance analysis and tolerance stack-up are used to describe the analysis of variation, although some sources of variation do not derive directly from tolerances. To solve the stack-up, the overall variation of a product function (i.e., requirement) is determined by combining the nominal values and the tolerance ranges of each component (Colosimo and Senin, 2010): these dimensions are added to form a chain of dimensions and tolerances, from which to predict the global effect (Figure 10). The selection of dimensions and tolerances to include in a stack-up is determined by many factors, in particular:

components and assembly geometry, sequence of assembly operations, GD&T schemes of the components, and the direction of the tolerance stack-up (Fischer, 2011). Stack-up results determine whether any dimensions or tolerances must be changed to meet the expected targets. In some cases, even the GD&T schemes (i.e., the dimensioning and tolerancing strategy), the assembly operations and the manufacturing process can be modified, sometimes with even more beneficial effects.

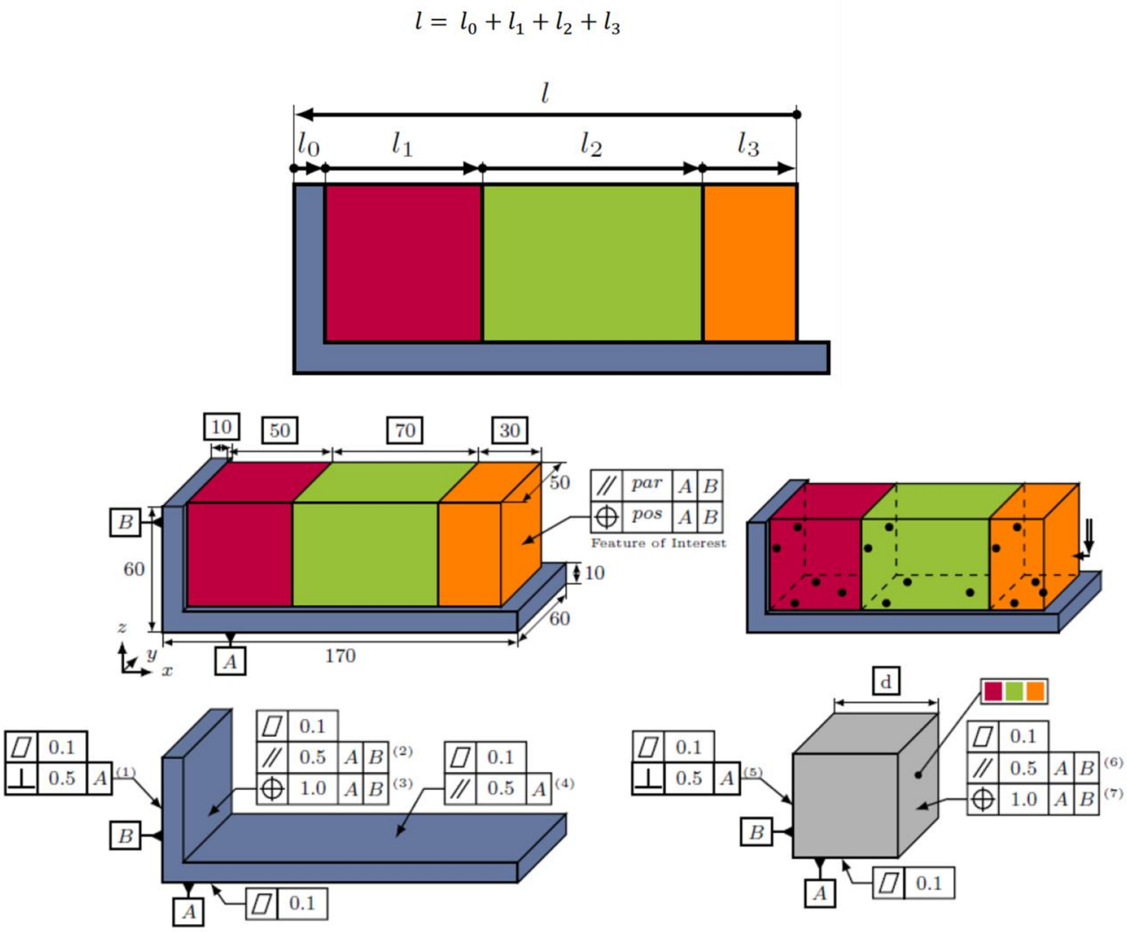


Figure 10. Tolerance stack-up and specification of the single parts (Schleich and Wartzack, 2016)

To provide a mathematical formulation of a tolerance stack-up, the relationship between product requirements and components dimensions must be formalized. The functional requirements are translated into a set of product functional dimensions (y) to be limited with tolerances. Considering a general assembly, these dimensions are directly influenced by the individual dimensions and tolerances of each component, x_i whose values depend on the manufacturing process. Since the component dimensions are independent variables, the mathematical relationship, known as Assembly Response Function, is determined as:

$$y = f(x_1, x_2, \dots, x_n) \quad (1)$$

The tolerance stack-up resolution requires two methodological tools, respectively to provide the mathematical description of the problem and to define the solution strategy. The former, known as modelling method, describes the assembly response formulation (y), formalizing the relationship between the components involved in the stack-up. The latter, called solution method, describes how to consider the contribution of each tolerance to the result. Depending on the specific case, different resolution methods can be used for the same modelling method.

Correspondingly, as reported by Schleich and Wartzack (2016), the main issues concerning tolerancing analysis are related to: mathematical representation of geometric deviations, geometric specifications, and geometric requirements; strategies for modelling the geometric deviations on the assembly and the system behaviour; solution techniques for these models (such as worst-case or statistical evaluations).

Modelling methods

Over the years, a large number of methodologies for the tolerance stack-up modelling have been proposed, and their classification consists of two main categories: deviation accumulation methods, based on geometric component deviation; tolerance accumulation methods, based on multidimensional spaces to define the tolerance zones (Dantan and Qureshi, 2009). For each category several models can be found in the literature, as reported by Corrado and Polini (2020): vector loops, variational, matrix model, Jacobian model, parametric tolerance analysis, simple tolerance stacks, solid offsets, direct linearization method, Small Displacement Torsor, Tolerance-Maps®, deviation domains, polytopes. All these methods have the common limitation of not supporting the point cloud representation of variant parts: this means that is not possible to manage geometrical form errors. However, new models for tolerance analysis have been presented and, among them, the skin model (Schleich et al., 2014) seems very promising: this model, based on the real representation of the workpieces (i.e., not ideal), allows the management of point clouds and geometric errors.

Some of these modelling methods are of particular interest for industrial application, in particular as regards the methodologies currently used by Computer-Aided Tolerancing (CAT) tools. Therefore, a more detailed description of the models implemented by CAT tools, the Vector Loop and the Variational models, is provided here to identify their main characteristics and provide a general overview of the topic.

- *Vector Loop Model* – This model bases its representation of variational effects by means of a series of vectors, arranged in a loop in the same way as the real dimensions in the assembly (Colosimo and Senin, 2010). These vectors represent the dimensions involved in the stack-up for a given assembly:

each one corresponds to a component dimension or an assembly functional dimension. Three types of variations are addressed: dimensional variations, to represent the dimensional tolerances as variation of vector length; geometric variations, representing geometrical tolerances by means of displacement vectors and rotation matrices; kinematic variations, modelled as kinematic joints to represent the displacement of components and assembly adjustments. A specific modelling procedure has to be followed through the definition of an assembly graph to schematically represent the product, the identification of the DRF scheme, and the selection of kinematic joints and reference paths (Gao et al., 1998).

- *Variational Model* – This model manages the variability of an assembly, considering both tolerances and coupling conditions, using a parametric mathematical model. Several variants have been proposed over the years with respect to the first mathematical formulation (Boyer and Stewart, 1991), transforming this model into a family of models. This model bases its structure on a strong relationship with the 3D models provided by Computer-Aided tools, as the assembly is read directly from the CAD models, in which the nominal geometry of components has already been defined. Here, each feature involved in the tolerance stack-up is identified allowing for dimensional and geometric tolerances to be set: a local reference system is assigned to individual features, while a global reference system is given to each component. The representation of the variation is provided by the use of different transformation matrices, which represent the location and the displacements of the local reference systems, and the shifts induced by the coupling conditions. Thanks to these matrices it is possible to simulate the variation of each feature with respect to the global reference system: this allows to express the functional requirements in terms of equations that the software can solve. The Variational model can handle all types of stack-up, as well as the Vector Loop model, but it is unable to represent geometric form variations because the shape of the features is assumed to be ideal (Colosimo and Senin, 2010).

According to the literature (Salomons et al., 1996; Polini, 2012), none of the aforementioned models provides a complete representation of the tolerance analysis phenomena. As reported, the Vector Loop and Variational models appear to be the most complete models, even if they do not fully comply with ISO and ASME standards. They also do not allow to manage the interactions between tolerance zones. The Vector Loop allows to consider geometric form errors, while the Variational model allows to consider the order of precedence of the Datums and to apply the material modifiers.

Solution methods

Concerning the calculation of the tolerance stack-up, many approaches have been developed over the years. For all of them, the key element is the means to reproduce the effects of the sources of variations, considering that both the dimensions and the shapes obtained during the manufacturing process can vary randomly. The analysis of the tolerances defines a procedure for estimating the resulting variations of an assembly size. The literature describes different approaches for tolerance analysis, which can be grouped into three categories: deterministic, statistical, and sampled.

Deterministic approach - Worst-Case Analysis

Worst-Case tolerance Analysis (WCA) determines the absolute maximum possible variation for a selected distance or gap. This method assumes that each dimension involved in the tolerance stack-up may have the same probability to occur within its tolerance range. Therefore, with an extremely pessimistic approach, it considers that all the chain dimensions are simultaneously in their worst-case conditions: adding all the maximum and minimum values, the extremes of variation of the assembly are achieved. From an analytical perspective, the method can be described by the equation:

$$T_{asm} = \sum_{i=1}^{n} t_i \quad (2)$$

where T_{asm} is the total assembly variation, while the t_i is the $i-th$ tolerance in the chain. The WCA guarantees 100% assemblability: it predicts the maximum and minimum variations, but at the same time it may lead to over-design. Indeed, for long tolerance chains, in order to respect the functional variation, each tolerance should be very tight to respect the acceptance window, with a consequent increase in manufacturing costs. Moreover, the probability of finding these conditions is very low. For this reason, this approach can be used in the design of safety and critical assembly systems or at least with short tolerance chains.

Statistical approach

As already highlighted, since quality and profitability are directly correlated, quality must be defined in terms of production yield and reliability through the use of specific indices. These indices provide the number of out of specification parts and therefore the probability of defects on the entire production batch. When engineers perform tolerance analysis, during the design phase, they essentially convert the design intent into a statistical or probability-based design model.

Statistical tolerance analysis determines the maximum probable variation possible for a selected functional dimension. Compared to the worst-case, this method is more realistic as it assumes that it is highly unlikely that all dimensions involved in the chain are simultaneously at their worst-case limit. A certain distribution is assigned to each dimension: in some cases, the normal distribution function is a good approximation of the real variation of the processes, since it is quite common for most of the dimensions to approach their nominal value. Consequently, the statistical approach shows less variation than the worst-case analysis for the same tolerance stack-up, allowing to increase tolerances by choosing more cost-effective manufacturing processes or to get high-quality parts and assemblies through tighter clearances (Fischer, 2011).

As reported in the literature, some general rules guide the choice of the correct approach. First, the number of dimensions involved in the stack-up: the greater this number, the better the performance of the statistical approach. Other important parameters are the number of parts to be produced, the manufacturing process controls, the supplier quality, etc. In general, a statistical tolerance analysis should have a controlled manufacturing process and a centered normal Gaussian distribution for each tolerance. Furthermore, every tolerance in the stack-up must be independent of the others.

Many calculation methods have been proposed over the years (Chase and Parkinson, 1991; Fischer, 2011): Root Sum Square, Six Sigma, Method of Moments, and Numerical Integration, just to cite few of them. Among them, the most common are Root Sum Square and Six Sigma, described below.

- *Root Sum Square (RSS)* – This method is based on the normal Gaussian distribution for each dimension of the loop, which is centred on the nominal values and independent of each other. The variation of each tolerance is assumed between $\pm 3\sigma$, i.e., six times the standard deviation (σ) of the process. The functional assembly deviation T_{asm} is calculated through the equation

$$T_{asm} = \sqrt{\sum_{i=1}^{n} t_i^2} \quad (3)$$

where t_i are the individual tolerances. Since real distributions can be quite different from normal Gaussian distributions, this method sometimes predicts fewer defects than in a real assembly process (Henzold, 2006). To solve this problem, alternative methods have been developed over the years: some of them are based on correction factors (Cf), which simply shift the midpoint of the distribution, to approach the real distribution.

- *Six Sigma* – This method, developed in the ’80s to achieve high-quality production processes, applies a variation range of $\pm 6\sigma$, corresponding to 0.002 defects per million (Placek, 1989). Therefore, even if the real distribution is different or shifted, there will still be a gain before reaching a poor value of process capability. This model introduces two statistical parameters to measure process quality, commonly used in the production world: C_p and C_{pk}. These process capability indices represent the process spread and process centring, respectively (Figure 11).

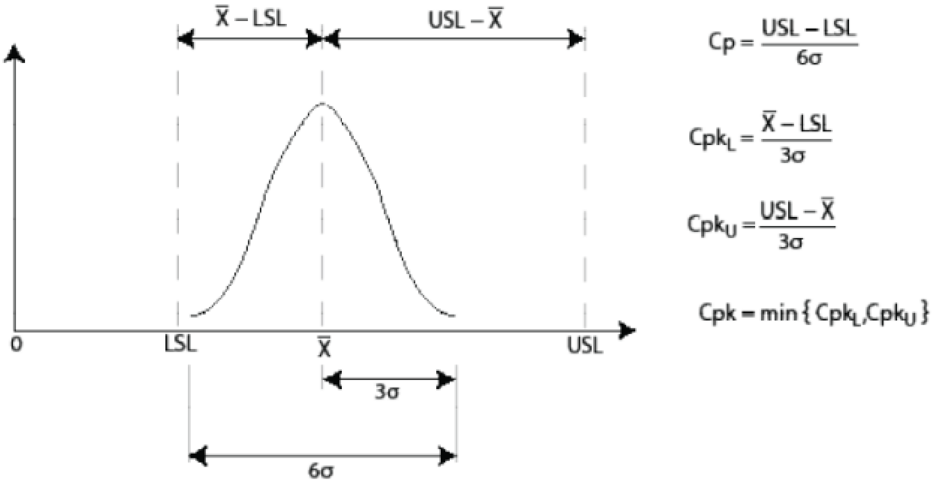


Figure 11. C_p and C_{pk} meaning (Henzold, 2011)

The LSL (Lower Specification Limit) and USL (Upper Specification Limit) represent the functional limits required by the design engineers and, consequently, the statistical tolerance limits. The new deviation σ_i and process capability C_{pi} are introduced to get a more realistic distribution:

$$\sigma_i = \frac{T_i}{3C_{pi}(1 - m_i)} \quad (4)$$

$$C_{pi} = \frac{USL - LSL}{\sigma_{proc}} \quad (5)$$

where σ_{proc} is the manufacturing process standard deviation, and m_i is the mean displacement factor which considers the shifting of the process over time. Figure 12 represents a typical statistical production process trend (based on the $\pm 3\sigma$), in which the deviation over time, from the nominal value, occurs on the total manufacturing time.

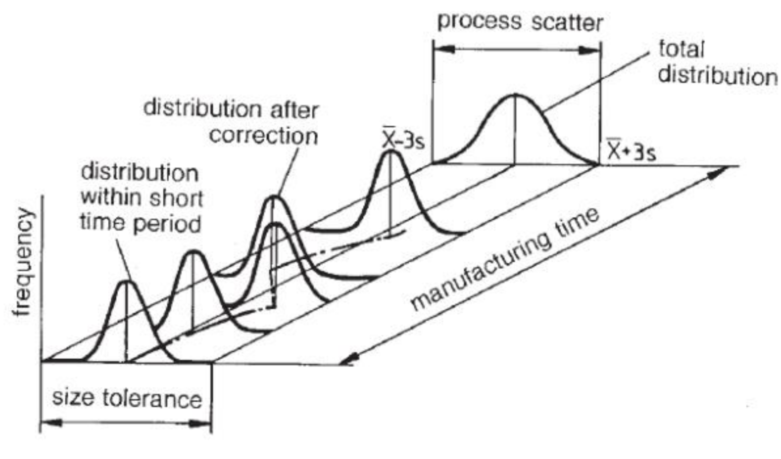


Figure 12. Shifting phenomenon during the production process (Henzold, 2006)

Sampled approach - Monte Carlo method

Sampling methods are very common for the estimation of phenomena related to random events. The use of numerical simulation provides automatically generated sequences of random numbers, to quickly collect series of data and provide estimation using statistical methods (Chase and Parkinson, 1991). Among them, the Monte Carlo method is a tolerance analysis method based on the theory of random numbers: different assembly combinations are simulated by creating a set of component dimensions that change randomly to simulate the process variations. For each set of random component dimensions, the resulting assembly dimensions are calculated: the number of rejects and out of specification is addressed, and this procedure is repeated until the process capability target is reached. This method consists of four sequential steps:

- *Assembly response function definition* – The functional dimensions of components and assembly are identified, and their correlation provides the assembly response function.
- *Probability density definition* – The statistical distribution is specified for each component dimension by the tolerance limits due to the manufacturing process. The shape of the curve and tolerance values are also defined.
- *Random sampling and simulation* – A set of random values for the dimensions is obtained from random sampling. The assembly response function is then calculated by providing the resulting assembly functional dimensions, compared to the design limits.
- *Yield estimation* – The previous step is repeated iteratively to simulate the assembly operations. The yield of the assembly process is obtained from the calculated distribution curves.

Moreover, this method has several advantages due to its flexibility: it allows non-linear tolerance analysis, tolerance allocation, and any component distribution as input. In addition, it allows both the sensitivity analysis, to understand how each source of variation affects the overall behaviour of the model, the computation of the distribution curve, and the number of rejects for a given process, with respect to the specification limits. On the other hand, Monte Carlo simulation is computationally expensive, not allowing a rapid design iteration. Today the Monte Carlo method is used for many purposes and is commonly adopted for tolerance stack-up calculation due to its simplicity and flexibility. Therefore, it is widely adopted by several CAT tools.

Tolerance-cost optimization

As described in the specific subsection, the process of tolerance allocation is very demanding and often concerns determining the manufacturing costs related to tolerances. In particular, the optimal allocation of tolerances is related to the minimum manufacturing cost (Armillotta, 2020a). However, establishing this connection is not always easy: without the proper tools and strategies is not possible to provide an accurate estimate of tolerance related costs, especially during the early stages of product development (Gust et al., 2019). This is due to a lack of quantitative cost information and, in particular, of a systematic approach to cost estimation (Hallmann et al., 2020a). State of the art developed many optimization techniques to address the issue, with the aim of identifying the trade-off between machine workability, production time, surface quality and dimensional accuracy (Mahshid et al., 2018).

Consequently, tolerance-cost optimization practices become the cornerstone of design optimization assuming a central role in the DfT approach.

As evidence of the high interest and potential of these techniques, a large number of researchers is working to improve the tolerance-cost optimization. Tolerance-cost optimization can be addressed to robust design techniques, primarily represented by Taguchi's theory, for improving the quality, reliability, and cost of an industrial system (Tsui, 1992).

As reported by manuscripts and well-established reviews, the structure of a tolerance-cost optimization can be divided into main areas: tolerance-cost model, optimization model, technical system model and tolerance analysis model (Hallmann et al., 2020a):

- *Tolerance-cost model* – It deals with the definition of the tolerance-cost relationship for different manufacturing processes. It employs the selection and definition of the tolerance-cost function, including the quality loss contribution, and the identification of the main cost elements (i.e., cost drivers).

- *Optimization model* – It consists in setting the optimization problem, including the definition of design variables, objective functions, constraining conditions, and the selection of the optimization algorithms.

- *Technical system model* – It concerns the representation of the specific system, i.e., the industrial product and its components. This means the mathematical representation of the functional features (KCs) of each component, in terms of size, shape, deviations, and the modelling of the assembly structure and behaviour.

- *Tolerance analysis model* – This model analyses the variation of the technical system verifying the functional requirements identified by the KCs. The most common tolerance analysis methods (described in the dedicated section) are adopted depending on the specific case. If optimization is supported by the use of CAT tools, variational models and statistical approaches are generally selected. However, due to their benefits, sampling techniques are also applied in some tolerance analysis software. All of these areas play an essential role in the optimization and many contributions can be found on each field. Among these, the researchers focused mainly on the definition of the tolerance-cost function, i.e., the key element that drives all optimization, and on the optimization strategies themselves.

Summarizing the general approach behind tolerance-cost optimization, the goal is to minimize manufacturing costs by reaching the minimum requirements for quality and functionality. This must be achieved through the identification of the optimal set of tolerance values. Additional constraints can be added to limit the allowed variation of both tolerance values and optimization objectives. In this way, the general structure can be mathematically translated into a single or multi-objective optimization, depending on the choice of the correct approach, i.e., least-cost optimization or best-quality optimization (Hallmann et al., 2020a). Once the mathematical problem is defined, the optimization algorithm and the tolerance analysis model act to iteratively generate populations of tolerance set and evaluate the response to identify the best configuration.

Tolerance-cost model

The tolerance-cost model aims to represent the relationship between product tolerances (t_i) and the manufacturing costs (C_i). Since the total cost of a product, considering its life cycle, consists of several contributions, also called cost drivers, the model must include all the most important contributions: manufacturing and machining operations, assembly process, tooling, inspection, rejects, maintenance, social costs, etc. Identifying and representing all these contributions is a challenging task due to many factors, primarily the lack of accurate and quantitative data available early in the design process: most of the time these values are approximations from previous products or from databases and tables. Even if empirical data are difficult to collect and depend on the specific case, the tolerance-cost model can still be identified.

Different formulations of the tolerance-cost function have been provided over the years to solve the allocation problem, both in terms of mathematical formulation and parameters: all identify the relationship $C_i(t_i)$ for each contribution (i.e., each KC for all the components of the assembly) (Armillotta, 2020a). However, for all types of function, both product geometry and machining operations must be addressed, balancing accuracy of data and ease of use (i.e., simpler formulations). As for the analytical formulation, the tolerance-cost function can be generally expressed by the equation:

$$C_i = Cf_i + Cv_i\,(t_i) \quad (6)$$

where the terms Cf_i and $Cv_i i$ are the fixed and variable costs (i.e., described in the Cost Management section), respectively (Armillotta, 2020a). The former represents the constant costs independent of tolerance t_i (e.g., material, labour) the latter represents the variation in manufacturing cost due to tolerance t_i (e.g., machining, rework, scrap, inspection etc.). The objective function, therefore, is given as the sum of each tolerance-cost relationship for each dimension of the stack-up. Starting from this basic formulation, the most common types of tolerance-cost function can be summarized, as reported in many reviews and comparative studies (Mahshid et al., 2018; Hallmann et al., 2020a): two-parameter functions (linear, reciprocal, reciprocal squared), three-parameter functions (reciprocal power, exponentials), more than three-parameter functions (combined or hybrid, Michael-Siddall, polynomial, discrete). In addition, considering the difficult selection of the proper type of function and coefficient values, advanced strategies have been proposed such as full factorial, gray relational, fractional factorial, Artificial Neural Network (ANN), fuzzy logic and genetic algorithm (GA).

Beyond these classifications, the literature identifies the generalized tolerance-cost function as one of the most applied (Diplaris and Sfantsikopoulos, 2000; Sanz-Lobera et al. 2016). According to Andolfatto et al. (2014), it can be expressed as:

$$Ci\,(t_i\,) = \,ai\, +\, bi\, \cdot e^{-m \cdot t_i} \cdot\, {t_i}^{-k} \qquad (7)$$

where the terms a and b represent, respectively, Cfi and Cvi, while the coefficients m and k provide the type of function (i.e., linear, non-linear, number of parameters etc.). In most cases, this function only addresses dimensional tolerances: geometrical tolerances are generally not considered (Saravanan et al., 2014). Hallmann et al. (2020a) report that some contributions consider statistical process control parameters (i.e., capability indices, process variance and procession) as an alternative to components tolerances. Furthermore, the formulation increases in complexity if alternative process can be considered, as well as if multi-stage processes are involved: in this case, different tolerance-cost curves have to be addressed.

In general, each formulation of the tolerance-cost function strongly depends on the quality of the available data: most of the time they provide a simplified description of the real relationship between the tolerance specification and manufacturing costs. This simplification may lead to deviations from the costs actually incurred. Nevertheless, it is still a good way to estimate the manufacturing costs caused by tolerances. Additionally, these functions can be used to determine cost-optimized tolerances using familiar mathematical optimization methods.

Quality loss function

As already mentioned, the concept of quality loss, introduced by Taguchi, aims to identify the economic impact of tolerances, in terms of deviations from the target output value. Quality loss belongs to one of the main approaches for the quality measurement: design for quality, based on quality loss, and design for reliability, focusing on non-conforming rate (Armillotta, 2020b). As for the first approach, it directly applies to tolerance-cost optimization, thanks to the important contribution provided by quality loss. This results in identifying the formulation of a quality loss function, to mathematically express this factor and combine it with the contributions of the manufacturing costs. It is generally expressed (Creveling, 1997) as:

$$L(Y) = k \cdot (Y - m)^2 \qquad (8)$$

where L represents the monetary loss, Y is the response of the system with respect to the target value m, and k is the quality loss coefficient. Since this coefficient regulates the dependency of the quality loss with respect to the system, its definition is critical. For this reason, many analytical formulations of quality loss function have been proposed (Hallmann et al., 2020a): different probability distributions, as well as different weights or correcting factors, have been proposed to obtain a realistic representation.

As reported by the recent literature, the contribution of quality loss increases the complexity of the tolerance-cost model and optimization strategies, since the optimal result must deal with an optimal balance between product functionality, manufacturing costs, and quality loss. Indeed, multi-objective optimization algorithms are required to manage these conflicting factors.

Cost Data and parameter selection

Regarding the identification of the manufacturing cost, this topic is deeply analysed in the Cost Management section, where the most common techniques for cost estimation are described. Focusing on the definition of cost data for tolerance-cost optimization, the main criticism is the difficulty of obtaining data during the early design phases. Most of the time, quantitative relationships between cost and tolerance can be identified only with respect to textbooks or based on general knowledge about manufacturing processes, providing only a rough approximation of the actual costs (Armillotta, 2020a). In general, the manufacturing process has to be identified for each tolerance, considering the properties of the component (i.e., material, shape, dimensions, production rate etc.). Once identified, the process must be decomposed into activities to estimate the machining time and the corresponding cost can be calculated, given the hourly rate of the machine. This approach belongs to the so-called Activity-Based Costing method (i.e., described in the dedicated section). Other approaches proposed in the literature introduce tolerance-cost graphs as datasets, from which each KC can be linked to specific processes. Most of the time, the datasets proposed in the literature differ both in terms of structure and type of application: they could be difficult to compare due to the important differences between them. Therefore, their application in the industry is very challenging.

This overall complexity also affects parameter selection, another critical aspect of the tolerance-cost model, since an incorrect or inconsistent selection directly impacts the optimization results. The selection should address all design variables influencing quality and manufacturing costs. Indeed, the heterogeneity of strategies is reflected in the techniques for the optimal selection: linear regression approaches, polynomial functions, neural networks, and fuzzy logic. In general, statistical approaches and sensitivity analyses appear promising for the estimation of quality costs, addressing costs due to deviations on assembly, scrapping or reworking (Armillotta, 2020a).

Optimization model

Even if the core of the approach refers to tolerance allocation, the overall aim of tolerance-cost optimization is to provide a comprehensive framework to support the process of tolerance design optimization. Therefore, compared to the traditional strategies for tolerance allocation, the recent evolution leads to a proper optimization problem. In general, this problem can be considered as the search for the best set of design variables, in this case the product tolerances. In particular, given the design variables X and the objective function $f(X)$ to be optimized (minimized or maximized), the problem is completed with the optimization constraints: a set of conditions to limit the possible variations of the design space. According to Rao (2019), once defined the constraints as $g_i(X)$ and $l_k(X)$, the optimization problem consists of:

find $$X = [x_1, x_2, \dots, x_l]^T \qquad (9)$$ which minimizes $f(X)$, subject to

$$g_i(X) \leq 0, \qquad \forall\ j = 1, \dots, J \qquad (10)$$

$$l_k(X) = 0, \qquad \forall\ k = 1, \dots, K \qquad (11)$$

In addition, limitations on design variables can be included, to restrain the variation range to technically feasible tolerance values. As highlighted, the correct definition of the optimization problem is one of the most critical tasks of the entire process, as it must collect every factor and contribution and let the optimization find the optimal solution.

Focusing on all the elements of the optimization problem, it is worth summarizing the main strategies of each:

- *Design variables* - Product tolerances of each product KC must be addressed to the problem, if possible, with their variation limits. Tolerances are generally considered to be continuous variables, more realistic but also complex than discrete variables. Most of the time, tolerances are independent from each other (uncorrelated), but in some cases correlation can be addressed.

- *Optimization objectives* – Even if function of the design variables, the proper identification of the objectives significantly influences the model, primarily the choice of the optimization algorithm. It reflects the design intent (Karmakar and Maiti, 2012): most of the time the objective is the total manufacturing cost of the product, given by the sum of each part contribution. However, some models focus on product quality parameters rather than overall cost: process capability and manufacturing yield are the most common. In general, as already mentioned, different types of functions can be considered: moving from linear to multi-objective problems, the accuracy increases as well as model complexity.

- *Optimization constraints* – The constrained problem introduces some equality or inequality conditions, and several approaches have been proposed to address these constraints into the optimization model. Direct approaches consider these factors as thresholds: if the condition is not respected the solution is discarded. Alternatively, methods such as Lagrange Multiplier, which uses optimality conditions or the Penalty method, which adds penalty factors if constraints are not satisfied, are commonly considered (Hallmann et al., 2020a).

Optimization Algorithms

The choice of the optimization algorithm is directly influenced by the specific design parameters, the objectives to be reached and the constraints to be respected (Khodaygan, 2019). In general, optimization algorithms are classified into two categories: deterministic and stochastic. Both methods require a feasible sample to start the optimization and termination (or stopping) criterion, to properly set up the optimization process.

According to Cavazzuti (2013), deterministic algorithms rely on linear algebra and are commonly based on the computation of the gradient of the response variables, both for objectives and constraints. Deterministic algorithms are widely applied thanks to their advantages, mainly the faster convergence to a solution compared to stochastic algorithms, meaning that the solution can be reached with fewer evaluations of the response variable. Among the large number of deterministic algorithms, the most commonly applied for tolerance-cost optimization are linear programming, nonlinear programming, and integer programming: they are suitable for simple allocation problems, but they reach their limits when complexity increases (Hallmann et al., 2020a). First of all, these algorithms are suited for single-objective optimization. Moreover, there is a risk that the optimal solution found by the algorithm may be a local optimum rather than a global optimum since they only look for stationary points in the response variable (Cavazzuti, 2013).

For this reason, when the optimization complexity increases, derivative-free algorithms are preferred, in particular stochastic algorithms (i.e., the most advanced approaches for optimization). These algorithms include randomness in the search procedure and, even if their convergence towards the optimum solution is slower compared to deterministic algorithms, they are the most applied for tolerance-cost optimization. Most of them are population-based algorithms, also called Swarm Intelligence (SI) algorithms. Within these algorithms, a starting set of samples evolves up to convergence, reproducing the behaviour of self-organized natural systems: thanks to randomness, they are able to overcome local minima and explore the whole design space, reaching the global optimum (i.e., a sort of trial-and-error strategy is performed). In this way, after the proper customization of the control parameters, the algorithm is well-suited for both single and multi-objective problems. Several groups of stochastic algorithms have been classified, the most common are: Evolutionary Algorithms (EA), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Game Theory-based optimization (GT), Simulated Annealing (SA). Among these, the most important categories are EAs and GAs. In addition to these algorithms, other minor algorithms have been applied for tolerance-cost optimization, but the most interesting evolution concerns the so-called Hybrid algorithms, a combination of deterministic and stochastic algorithms (Hallmann et al., 2020a).

To conclude, several optimization approaches have been developed over the years and, although the most powerful and suitable have already been identified, it is worth pointing out that the optimization results strongly depend on the specific parameter settings of the algorithm and on the environment in which the algorithm is applied.

1.2.3 Computer-Aided Tolerancing (CAT)

As previously highlighted, the process of tolerance design is rather complex as it is influenced by multidisciplinary and conflictual requirements. In addition, it is composed of several phases, all of which require adequate methodologies and strategies to address each aspect: in particular, the phase of tolerance analysis mainly impacts the quality of the final product. Since tolerance analysis is part of the Concurrent Engineering (CE) approach, in recent decades the evolution of Computer-Aided technology has provided specific tools, the Computer-Aided Tolerancing (CAT), nowadays the reference for the Dimensional Variation Analysis (DVA).

CAT software are directly based on the modelling strategies described in the previous section. Thanks to their link with the most common methodologies, these tools provide both the representation models of tolerance chains and the computational approach to tolerance analysis. This results in a more realistic model of variation than simpler linear tools, especially for complex industrial products such as automobiles. CAT tools allow to systematically select the manufacturing processes to achieve the functional design targets, thanks to the complete analysis of the assembly and functional performance of products, and through the use of sensitivity analysis and capability simulations (Corrado and Polini, 2020). As a natural consequence, today different CAT software exists, with specific advantages and disadvantages, showing the same limitations of the modelling and solution methods they adopt.

The most common CAT software are: CeTol **6σ**® (Sigmetrix), 3DCS® (Dimensional Control System) and VSA® (Siemens/Tecnomatix) which use parametric approaches (previous versions of CeTol 6σ® used vector loops), MECAMaster®, based on the SDT (Small Displacement Torsor), and PolitoCAT®, which employs polytopes. Some other CAD systems have an integrated module for tolerance analysis (Shah et al., 2007). Several research works and comparative reviews on these commercial software can be found in the literature, identifying the state of the art for these tools. Among these, Corrado and Polini (2020) present a useful comparative table on the three main software mentioned above: Cetol 6σ, 3DCS and VSA. The software are analysed by comparing the strategies through which they support engineers he product design and development. Figure 13 reports this comparative, in particular the ability of the software to interpret the different stages of tolerancing (i.e., representation, specification, analysis, and synthesis) and their compatibility with the most common CAD software. One of the main advantages of CAT tools is the possibility to manage complex 3D, non-linear, statistical tolerance stack-ups calculations (someone uses the Monte Carlo approach), instead of using manual calculations. In addition, these software enable Model-Based Definition practices, as 3D semantic annotations, i.e., the Product Manufacturing Information (PMI), can be directly imported from the CAD models, as can assembly constraints. This improves interoperability between tools, enhancing information sharing and, as a consequence, more accurate tolerance analysis performed in much less time. Following the model-based parametric approach, the tolerance model consists of representing the functional assembly dimension as an algebraic function (an equation or a set of equations) directly related to the variation contributors expressed as geometric parameters. Both dimensional and geometric tolerances can be included in the analysis: to consider these tolerances, transformations are applied to the perfect features (form tolerances are neglected) and the tolerance zones are simulated by putting limits on rotation and translation parts of the transformation matrix based on feature dimensions and tolerance values. By providing combined models of translational and rotational probabilistic effects and allowing the selection of different types of distributions (e.g., statistical, normal, skewed, uniform), the software automatically manipulates the same model to reflect a combination of geometric effects. Then, the algebraic function is linearized or solved directly through a non-linear Monte Carlo simulation. In the post-processing phase, commonly results are available: the list of contributors, the sensitivities, and the variance contributions (%), both in both worst-case and statistical analyses. CAT systems differ in the way they interface with CAD software and in the analysis they can provide (Shah et al., 2007).

Requirements\CAT Software	CeTol 6σ®	VSA®	3DCS®
Tolerancing scheme			
Dimensional tolerances	Yes	Yes	Yes
Geometric product specification (GPS)	Yes	Yes	Yes
Automatic utilization of CAD model, once defined GPS data	No	No	No
Tolerance analysis			
Worst-case approach	Yes	Yes	Yes
Statistical approach	Yes	Yes	Yes
Sensitivity analysis	Yes	Yes	Yes
Uncertainty qualification methods			
Monte Carlo	No (SOTA)	Yes	Yes
Simplifying assumptions			
Rigid body	Yes	Yes	Partial
Limit on variation size	No	No	No
Further considerations			
Compatible CAD tools	PTC Creo, Catia V5-6, SolidWorks, NX	PTC Creo, Catia V5-6, SolidWorks, NX	Creo, CatiaV5-6, SolidWorks, NX, STEP, IGES
Distributed/parallel computing	No	No	No
Integration with external CAE modelling tools	No	No	No
Accommodation of assembly loads	No	No	Limited

Figure 13. CAT tools comparation (Corrado and Polini, 2020)

- *CeTol **6σ**® (Sigmetrix)* – This CAT software is fully integrated into several CAD applications (i.e., CREO®, Solidworks®, CatiaV5®). As with most of the CAT tools, the representation of tolerances is done by parameterizing areas, where the tolerances are represented by small variations in the parameters used to define the nominal geometry. The modelling procedure consists of two main steps. The first is the modelling of the tolerance scheme on the nominal 3D model of the mechanical assembly, previously prepared with an external CAD tool. During this phase, tolerance specification and allocation are carried out, applying Datum, kinematic joints, and dimensional and geometric tolerances. There is the possibility to automatically import tolerances specified via external applications such as 3D semantic annotations (e.g., Catia.FT&A®). Otherwise, tolerances have to be manually inserted, as the software cannot automatically perform the specification of tolerances. As a second step, functional requirements are modelled as measurements between functional features, to create tolerance stacks, modelled by the Variational model and solved by simulation with the Monte Carlo method. The resolution of stacks tolerance, i.e., tolerance analysis, can be done using three different strategies: Worst-case, RSS and six-sigma. Even if a true automatic procedure for the tolerance synthesis is not available, several tools support the analysis: statistic and capability values (i.e, σ, C_p, C_{pk}, rejects), but also contributors list and sensitivity analysis to evaluate how each tolerance part affects the given measurement. It is also possible to assign weights to tolerances: in this way the software automatically returns the value of the same, identified by an optimization algorithm.

- *VSA® & 3DCS®* - These two software are developed by different software houses but they share similarities both from a functional and an applicative point of view. VSA® (Siemens/Tecnomatix) is integrated into several CAD systems such as CREO®, CatiaV5®, NX®, and Solidworks®. 3DCS® (Dimensional Control System) has different versions: a stand-alone version, where the CAD neutral file format can be directly imported, a fully integrated version in CatiaV5® and V6 environments (appears as a Workbench System), and an integrated version in Solidworks, NX and CREO®, able to act directly on proprietary files without conversion. Both software represent tolerances using 3D points: a statistical distribution is associated with each point to simulate the variation of the feature, described by a series of points. These points can be associated with different types of statistical distributions (e.g., normal, uniform, triangular, Pearson, Weibull, etc.). As with CeTol $\mathbf{6\sigma}$, these tools require manual specification of tolerances, or they must be specified as PMI directly within CAD models and imported automatically. Furthermore, these software are based on the Variational model as modelling method and on the Monte Carlo method as solution method. Both software can derive a set of statistics values (mean, variance, etc.), data related to the simulated assembly process (C_p, C_{pk}, rejects, etc.), with the representation of the distribution function through a histogram, and sensitivity analysis. Results can be exported to various formats of data management (e.g., Excel, HTML, etc.).

As highlighted, commercial CAT software offer several advantages over traditional methodologies (i.e., manual, experience-driven and trial-and-error). However, despite their wide capabilities, some important limitations remain. First of all, the fact that not all the tolerances are supported (form, composite location…), despite complying with ISO/ASME standards (Corrado and Polini, 2020).

1.3 Cost Management

Manufacturing companies pose economic feasibility as the mean driver for the development of any industrial product. Commercial products must deliver the expected financial profits to be competitive in the global marketplace: therefore, along with product performance, quality, and innovation with respect to competitors, production costs play a key role in achieving product success. This has led, over the years, to a growing importance of Cost Management (CM) practices, spread through the industrial sector and more involved in all phases of product development. In fact, to achieve the expected cost targets a detailed analysis of cost is needed, which requires knowledge of the costs of all the product components, including the manufacturing process and all the phases of the product life cycle. The process of manufacturing cost estimation is well-known for its complexity: the factors that contribute to product costs must be identified and, when possible, quantified. However, this demanding activity must deal with factors usually belonging to different product development areas and differently located during the product life cycle as well (Agyapong-Kodua et al. 2012). Furthermore, the multidisciplinary effects of product quality and performance on costs need to be addressed as early as possible during product development, to systematically act to reduce product cost: otherwise, if manufacturing costs exceed targets, expected profits will not be achieved, requiring careful corrective actions. Since product costs are closely related to product design, being particularly influenced by early conceptual decisions, implementing cost-cutting measures later is only possible with significantly more effort. On the other hand, an early evaluation of costs is generally difficult as most cost-related data and factors are not yet defined or known by the engineers.

As a result, several attempts have been proposed over the years to improve the cost analysis and estimation, leading to different strategies for addressing, planning, and controlling costs during product development. In this context, the most interesting way to integrate CM techniques into the design process is through the Design to Cost (DtC) approach, as the central approach to optimize product design with respect to economic requirements right from the very beginning of the product development stage.

1.3.1 Design to Cost

Traditionally, costing is an activity that takes place at the end of the development process: cost represents a property directly derived from the product development process. The selling price of a product is subsequently determined by the cost of production plus the expected profit margins. However, considering costs only as a consequence of the product development process can be extremely dangerous: the developed product, once launched on the market, may not have the initially expected success and, therefore, must be offered at a lower price than the established one to be more competitive. Several studies have shown that most of the costs are committed when the principal solution has been selected and its embodiment has been completed (Duverlie and Castelain, 1999): at the time of the release of a project about 15% of the total cost has already been incurred while 85% has already been committed, as visible in Figure 14.

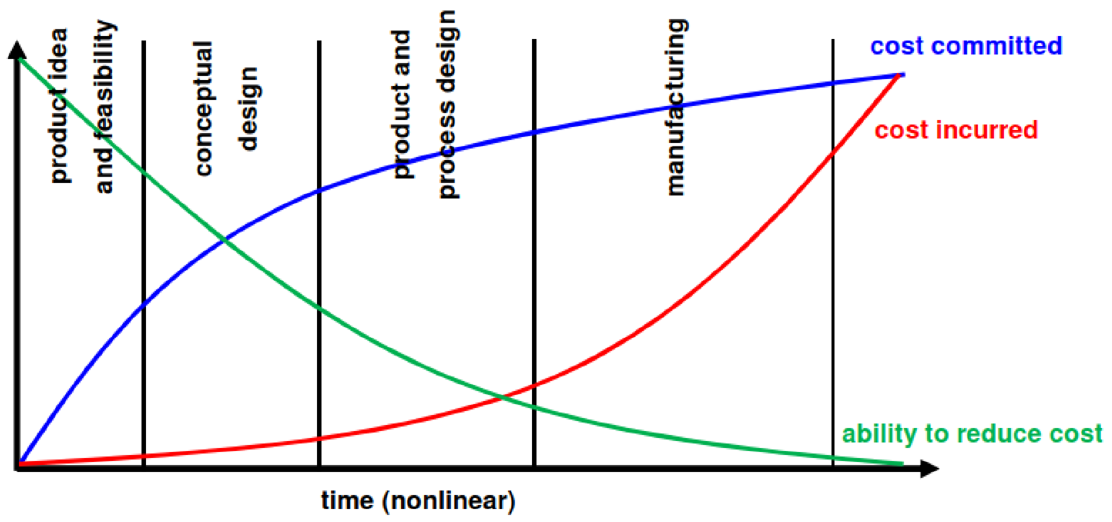


Figure 14. Product development costs

Therefore, the identification of cost factors already in the early stages is essential, as changes introduced in the advanced development stages are generally limited and their cost increases exponentially as the product life cycle progresses: any error in evaluation at this stage largely affects costs, and, at the time of launch, the investment made has yet to be fully repaid. From an economic point of view, there is a strong interest in seeking the optimization of a product already in the design phase as the potential savings are very high compared to the cost to be incurred to generate it.

To achieve cost optimization, manufacturing companies must address cost evaluation not as a consequence of the development process, but rather as an input equal to performance, quality, reliability, etc. Product design primarily defines manufacturing costs, but it also heavily influences the total costs and the entire life cycle costs. Therefore, when designing the product, it is necessary to have a multi-disciplinary and integrated knowledge of the whole product and its life cycle perspective.

In this context, several engineering design strategies for cost optimization have been developed. Among these, the most important is the Design to Cost (DtC) approach, which considers the amount of money the customer is willing to pay for the product as a design limit. The objective of the DtC is

therefore the definition of the target production cost, suitable to guarantee the desired profit margin for the product, without sacrificing quality, performance, etc. This means that, if not initially satisfied, engineers must iteratively redesign the product until the overall cost meets the given budget. Compliance with the Target Cost ensures that the product is competitive at the time of market launch or that in the event of a bankruptcy the economic impact is significantly lower. Achieving this goal is a challenging engineering problem as the definition of this target limit is quite complex. Moreover, it is very difficult to reach this limit through iterative processes in an efficient and robust manner, without uncertainties or errors. For this reason, the Design for Costing (DfC) approach has been developed as an evolution of DtC, mainly oriented towards minimizing product life cycle costs, while satisfying customer standards. The engineering process, therefore, aims to consider the product cost as an optimization objective rather than a target value, to ensure a better compromise between overall costs and product requirements, using different estimation methodologies and optimization tools.
Before analysing the most common models used for cost analysis and estimation, it is worth providing the general classification of manufacturing costs, as proposed by the literature.

Manufacturing costs calculation

The process of identification of the main cost factors can be conducted from different points of view, depending on the company division in which costs are assessed, the level of detail required, and the phases of product design in which the analysis is carried out.
Traditionally, in the literature, the cost for the realization of a product consists of two items, as presented by Pahl and Beitz, (2013):

- *Direct costs* - Costs that can be directly attributable to the single product unit, such as the cost of raw materials.
- *Indirect costs* or *overheads* - Costs not attributable to the single unit, such as the operating cost of the production plant.

The limitations of this approach arise when a detailed cost estimation is required along the entire product life cycle: materials and labour are easily attributable to the single product, unlike the company overheads which are attributed to a specific activity or department.
Another classification frequently used in literature considers the cost as a function of the production volume:

- *Fixed costs* - Costs that remain constant as the production volume varies over a given period of time (rent of the premises, wages of employees, etc.).
- *Variable costs* - Costs that depend on the production volume (raw material, tools, etc.).

This definition of costs is commonly applied during decision-making activities. The cost of production or manufacturing cost is the total costs for material and construction: it includes the additional costs for tooling and development costs such as design, prototyping and testing as long as these are assigned to a specific product. Although the production cost includes both fixed and variable costs, only variable costs, both direct and indirect, are considered for the decision-making activities. This is due to the fact that variable costs are directly influenced by the choices of the designers, for example through the choice of material, production times, the size of the lots, etc. On the other hand, fixed costs are supposed to be incurred regardless.

Therefore, variable manufacturing costs ($VMfC$) are defined as the sum of direct material ($DMtC$) and labour costs for manufacturing and assembly (PLC):

$$VMfC = DMtC + \sum PLC \quad (12)$$

The direct costs related to the material can then be evaluated according to the weight W or the volume V multiplied by the relative specific unit cost:

$$DMtC = c_W \cdot W = c_V \cdot V \quad (13)$$

The direct production costs are calculated as the sum of the times related to the individual production processes (primary time t_P, secondary time t_S and set-up time t_{SU}) multiplied by the labour cost factor c_L:

$$PLC = c_L \cdot (t_P + t_S + t_{SU}) \quad (14)$$

The difficulty in this case consists in being able to accurately allocate the indirect costs to the unit of product considered. One of the most used methods is to consider these costs as an increase in direct costs through appropriate multiplying factors. Typical values in the literature are from 1.05 to 1.3 for indirect material costs and from 1.5 to 10, or higher, for labour: when the multiplying factors are very high it may be useful, where possible, to try to reduce costs by modifying the production process. These factors can vary greatly from company to company. Although rather rough, this assessment is useful for obtaining a quick cost estimate and then conducting a detailed analysis.

Another classification of production costs is provided by Son (1991), who classifies costs into well-structured and ill-structured. The former involves labour, material, and machine costs, while the latter involves costs such as those associated with build failure, machine setup, and inventory. This category is well-suited to consider the concept of lean manufacturing, where the sources of costs (in particular with regards to waste costs) are classified into seven categories:

- *Overproduction* – These costs occur when more is produced than currently required by customers
- *Transportation* – Transportation costs must be addressed for each type of production. Even if the product is not affected by these costs, they are a source of risk to the product.

- *Rework/Defects* - Rejected defects result in wasted resources, or extra costs to correct the defect.
- *Over-processing* – These costs occur when more work is done than necessary.
- *Motion* – Depending on the organization and manufacturing process, unnecessary movements may be involved, resulting in unnecessary expenditure of time and resources.
- *Inventory* – This source of cost is similar to overproduction, resulting in the need for additional handling, space, people, and paperwork to manage extra product.
- *Waiting* – Depending on the lean development and organizational decisions, resources are wasted when workers and equipment are waiting for material and parts.

Manufacturing costs estimation

The process of Cost analysis and estimation has become a strategic activity for manufacturing companies, covering many functions (Niazi et al., 2006): evaluation of design alternatives, control of production costs, support for long-term financial planning, support in make-or-buy evaluations, control of supplier quotes.

To generate a comprehensive cost analysis for a project, designers need tools to accurately assess a wide range of potential cost drivers. A short list of factors that need to be considered includes:

- *Material specifications* - In addition to direct costs, the use of additional material indirectly affects process costs, ecological costs, and each of the other factors listed below. Everything from tolerance to processing requirements needs to be analysed.
- *Packaging, Shipping and Logistics* - Weight, volume, fragility, and storage requirements are all instrumental to the evaluation of the real cost of a project.
- *Feasibility* - From cooling times to plant availability to equipment costs, manufacturing is important to every aspect of the design.
- *Labour* - Adding a part that requires manual assembly, for example, can have an impact far out of proportion to the direct cost of materials.

None of these factors can be analysed in isolation since each design choice has consequences for the cost and functionality of the rest of the project. While these relationships may be clear (e.g., added weight requiring greater component tolerances), they can also exhibit a high level of complexity and interactivity (particularly when plant and supply chain costs are included). Accounting for complex and interconnected variables of this magnitude requires a serious organizational commitment to make cost management part of the product engineering culture, together with an investment in innovative tools for estimating production costs.

Since the process of cost estimation can be carried out during different stages of the process of product development, several methods for estimating costs have been proposed over the years (Niazi et al., 2006). They all address the main factors affecting product costs (i.e., material, manufacturing process, labour…). Depending on the cost model strategy, the cost estimation methods can be classified as:

- *Knowledge-based* or *Intuitive methods* - based on the experience of those making the estimation.
- *Analogical methods* - they exploit the similarities with similar products for which the cost is known.
- *Analytical methods* - the production process is broken down into elementary activities whose cost is known.
- *Parametric* or *rule-based methods* - they exploit the definition of parameters to characterize the product and its cost, even without fully describing it.

The main characteristics of the four methods are summarized by Favi et al., (2017) in Figure 15:

	Accuracy (how the method is accurate and consistent with the real final cost)	Robustness (how the method can easily adapt to the product with different features, dimensions, etc.)	Subjectivity (how the method is independent by the end-user)
Knowledge-based methods	Low (depends on product geometry)	Low	High
Analogical methods	Low (depends on product geometry)	Low	Medium
Analytical methods	High	High	Low
Parametric methods	Medium	High	Low

Figure 15. Method for cost estimation (Favi et al., 2017)

Intuitive and analogical methods are classified as qualitative methods, which have the advantage of quickly obtaining cost estimates. However, the estimate strongly depends on the experience of those who do it. For this reason, as highlighted by Maciol, (2017), quantitative models are preferable where there is mass production, allowing the definition of a statistical or analytical model for the evaluation of costs. For completely new products Relich and Świć, (2020) identify analytical methods as preferable, as it is not possible to make analogies with existing products. Parametric models seem the most attractive for industrial applications since they are based on geometric features recognition (e.g., hole, rib, slot, etc.) of the product and tooling as the basis for cost estimation. Therefore, these methods can address the complexity due to component geometry, starting with the solid model of the part (Farineau et al., 2001).

Considering parametric methods, they allow the definition of a product development project and company resources as a set of variables and constraints. This makes it possible to evaluate complex relationships between data and impose constraints to identify possible solutions. Parametric methods are usually based on different techniques: regression analysis (Liu et al., 2009), artificial neural networks (Kumar et al., 2020) or fuzzy logic systems with related hybrid approaches. Relich and Świć

(2020) propose a parametric approach based on Constraint Programming Techniques (CPTs) to appropriately specify constraints and variables: thanks to their flexibility, the use of CPTs allows to develop efficient methods specific to the considered domain rather than general methods. This approach allows to identify all possible project performance scenarios that meet the imposed constraints: budget, human resources, machines, etc. Therefore, it is extremely useful in all those cases where limited resources are available to allocate to a project, where additional attention must be paid to the management of new product development processes. However, despite the advantages of this method, it does not provide indication for corrective solutions and, above all, a large amount of historical data and parameters is required.

As highlighted, cost estimation techniques differ for the estimation strategy and, depending on their need for specific data or input parameters (i.e., product geometry, machine and tooling properties, etc.), there are more suitable for specific stages of product development. In general, the models for cost estimation are accurate enough to compare different manufacturing processes or design solutions, but commonly lack detailed manufacturing information (Hallmann et al., 2020a). This is mainly due to the difficulty of identifying detailed data, especially in the early stages of product development, with consequent severe limitations, even for the parametric models. The result is that some of these methodologies are not able to offer the degree of detail required for the analytical optimization of product geometry based on the specific process characteristics (Favi et al., 2017). In this context, the most interesting cost estimation techniques considered for Cost Management are the Activity-Based Costing and Target costing methods (Geiger and Dilts, 1996).

Activity-Based Costing (ABC) Method

The ABC is an analytical method for evaluating the cost based on the identification of the activities involved in the process and the related cost factors. This method allows to track costs by considering all the resources consumed by each activity to complete the entire product development process. The product costs derive directly from these activities through cost drivers, the attributes of the product in terms of resources used to complete these activities, such as the number of units produced, hours worked, hours of equipment use, or the number of orders received. Through cost drivers, the transfer of costs between resources, activities and products can be more easily characterized and quantified (Hallmann et al., 2020b; Gu et al., 2019).

Compared to traditional cost estimation methods, the ABC system differs in two ways: first, the cost pools are defined as activities rather than production cost centers and, second, the cost drivers used to assign activity costs are structurally different. In fact, this method models the use of the organization's resources based on the activities carried out and then links the cost of these activities to outputs, such as products, customers, and services. On the contrary, in traditional cost systems, direct materials and labour are the only costs directly attributable to the product. For this reason, the ABC is often used as part of total cost management (Etienne et al. 2009).

Several authors deal with the ABC method in the literature. In particular, Hassan et al. (2010) define the two-level procedure for assigning the cost of resources to product cost, as outlined in Figure 16: in the first phase, the cost of resources is allocated to the activities through the resource cost driver, in the second phase the costs of the activities are similarly allocated to the product through the activity cost drivers.

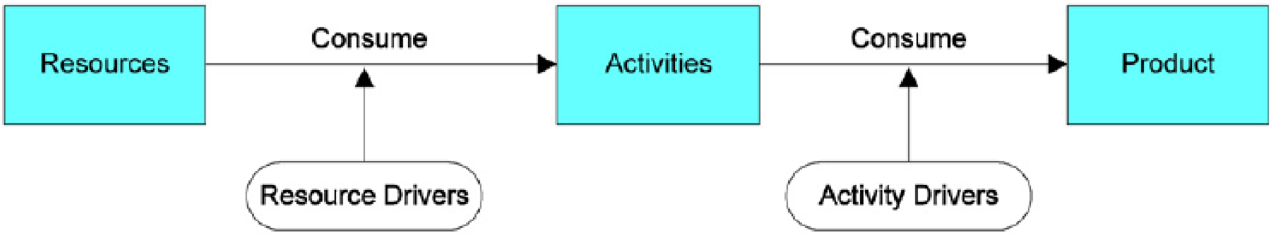


Figure 16. ABC method (Hassan et al., 2010)

Ben-Arieh and Qian, (2003) classify activities (e.g., requirements collection, design, process planning, prototyping etc.) into "added value" and "non-value added" activities. Non-value-added activities must be effectively identified as they involve the use of time and resources but do not add value to the product. This method adds a further level to the process described, in fact the cost center characterized by the relative cost factor is inserted between resources and activities. In this way, it is possible to combine the use of resources by highlighting how they are actually used. Activities can be further classified into four classes: unit-level activities, batch-level activities, product support activities associated with a given product as a whole, and facility support activities, which cannot be directly linked to a single product (e.g., building maintenance or general management activities).

The application of the ABC method leads to an extremely detailed analysis, following a multi-step procedure summarized below and represented in Figure 17.

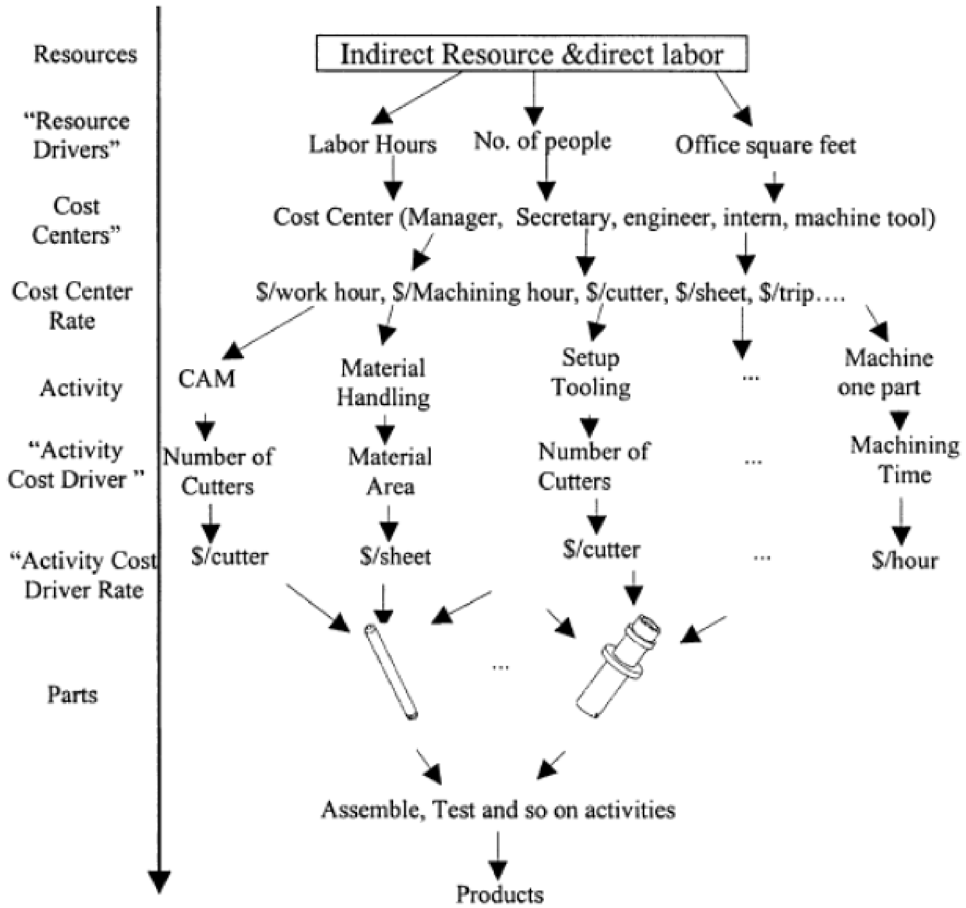


Figure 17. ABC process (Ben-Arieh and Qian, 2003)

- *Identification of cost centers (and related cost drivers)* - The cost centers group the resources used directly to make the finished product (both human resources such as designers, managers and engineers and the main equipment used): human resources (working hours), cost of electricity (number of people), cost of renting the premises (surface), designers (design hours), CNC center (milling hours), material handling (number of movements), etc.

- *Analysis of indirect costs and calculation of the related cost-drivers rate* - Indirect costs are the general expenses that must be attributed to the finished products (heating, rent of the premises, cleaning costs, etc.). The cost factor rate for a resource, identified as Resource Rate (RR), is the ratio between the resource's annual cost and the number of cost drivers used in a year:

$$RR\ (Resource\ Rate) = \frac{Total\ cost\ for\ 1\ year}{Resource\ drivers\ spent\ in\ 1\ year\ (RD)} \quad (15)$$

where RD is the amount of resources used by each cost driver belonging to the cost center in a year.

- *Allocation of resources for each cost center and determination of cost centers driver rates* - The cost of indirect resources is allocated to cost centers, based on the cost factors of the resources, i.e., the resource cost drivers. In this way the total cost of each center can be calculated, obtaining the relative cost factor for each cost center. The driver rate cost center is obtained for each center, and the total cost for each cost center in a year is calculated as:

$$Total\ annual\ cost = \sum_{i=1}^{number\ of\ resources} RR \times RD \quad (16)$$

- *Identification of the activities (and related activity cost driver and cost center employed)* - The activities carried out in the product development process are identified. The main activities are then broken down into more detailed elementary activities and assigned to an activity driver and to the cost center used:

- Part design (hours - designers),
- Discussion on the product (number of tools replaced - project managers, designers, coordinator),
- Calculation of the budget for the part (fixed cost - coordinator),
- Etc.

- *Calculation of the total cost of activities* - The total cost of each activity is determined on the basis of the cost-center resources as the product of the amount of cost factors consumed by each activity and the cost-center drivers' rate.

- *Definition of the cost factors of each activity and determination of the relative rates* – Since different types of activity cost drivers are used to represent the costs incurred by each activity, the activity cost driver rate ($ACDR$) is introduced as the ration between the cost of each activity and the related cost driver:

$$ACDR = \frac{Cost\ of\ one\ activity}{Activity\ cost\ driver\ spent} = \frac{\sum_{i=1}^{number\ of\ cost\ centers\ used}(CCR_i \times CCD_i)}{ACD} \quad (17)$$

where CCR_i, CCD_i, and ACD are the cost center rate for the center "i" used for the activiy, the amount of the driver of the center "i" used for the activity, and the amount of the cost driver of the activity used, respectively.

- *Calculation of the cost of the new component* - The total cost of the product is evaluated both in relation to the activities carried out during the development process and in relation to the cost centers involved, as:

$$Total\ cost\ of\ one\ part = \sum_{i=1}^{number\ of\ activities} (ACD_i \times ACDR_i) \quad (18)$$

As reported in the literature, the ABC method is able to overcome the difficulty of traditional methods for evaluating the cost of attributing overheads to the product unit. Traditional methods usually

underestimate the overheads attributed to machine time, such as the time required for prototyping and for setting working parameters. This discrepancy grows as part complexity increases since it requires further development and testing of production processes.
The main advantages of the ABC method are: accuracy of the cost estimate, robustness of the method when the complexity of the component varies, low influence of the subjectivity of the person making the estimate, and the possibility of investigating the factors that determine the cost. As highlighted by many researchers (Gunasekaran and Sarhadi, 1998), some issues remain regarding the implementation of the ABC method: lack of a practical guide for the application, lack of alignment between business and production strategies, and the lack of a structured approach for the analysis and improvement of essential activities such as production, marketing, etc. In addition, the accuracy of the estimation is influenced by system complexity, mainly the process of collecting and processing a large amount of cost information and managing a high degree of detail for each cost driver.

Target Costing

As defined by Cooper and Slagmulder (1999), the Target Costing (TC) technique allows to strategically manage the future profits of a company, ensuring that a product is profitable enough at the time of its launch on the market. Since market price and operating costs are the most important criteria for a customer to choose between competing products and processes, a successful application of Target Costing requires meeting the customer’s expectations (in terms of functionality, reliability, and attractiveness). Therefore, it must be managed by a development team that includes everyone involved in the product creation process, similar to the approach adopted for Simultaneous Engineering or Value Analysis. Target Costing aims to reduce the costs of new products while respecting product quality levels and time and market constraints, but also to provide cost reduction activities within the company, motivating employees to act systematically to achieve target profit. These goals are achievable by determining the Target Cost along the entire life cycle: the company must produce the product at this cost to generate the desired profit and be competitive in the market. Compared to conventional product development, the manufacturing cost is not determined retrospectively, meaning cost evaluation, but given as target costs for the subsystems to control the development of solutions. Therefore, Target costing can be considered as a management approach in which the cost is an input to the product development process and not a consequence of it, as required by DtC: it is determined by estimating the selling price of a product and subtracting the desired profit margin from it.

Target Costing is based on the cardinal rule that the target cost can never be exceeded: this is the only way to create sufficiently profitable products. Moreover, even in the event of bankruptcy, the financial loss is still significantly lower than that which would occur without the application of Target Costing. The only exception to this rule occurs when launching a product late has very negative repercussions: the product is launched anyway by lowering the target cost and planning a series of cost reduction measures to make the violation temporary. The degree of relaxation of the allowed costs is therefore a strategic cost reduction challenge: many companies have introduced the reserve for the production manager, a reserve of money to cover any problem that arises during the development process.

Several researchers have highlighted how the Target Costing application must be defined and disciplined in a highly systematic way to be used effectively in industry. In fact, the critical factors that influence the Target Costing implementation process, highlighted by Baharudin and Jusoh (2015), are the customer orientation, the degree of information availability, the relationship with the suppliers, and the degree of interaction with other systems or activities. In particular, according to (Cooper and Slagmulder, 1999), Target Costing consists of three main levels, as summarized below: market-driven costing, product-level target costing, and component-level target costing.

- *Market driven costing* - The main activity of this phase is the definition of the allowable costs, typically obtained through a market analysis. This phase focuses on customer requirements, using the concept of allowable costs to convey market pressure to product designers and component suppliers. Five main steps are identified: definition of the sales objectives and the company's long-term profit; organization of product lines to maximize profit; definition of the target selling price of the product; calculation of the target profit margin of the company for achieving long-term goals; calculation of allowable costs as

$$Allowable\ cost = Target\ selling\ price - Target\ profit\ margin \qquad (19).$$

As the allowable costs are influenced by many contributions, their calculation is a very complex and critical step for the whole process, especially during the design phase. In addition, it is worth highlighting that the allowable costs are based on the company’s long-term profit objectives, reflecting the competitiveness of the company: this does not correspond to a benchmark with respect to competitors. Moreover, these costs are defined on the basis of economic and financial aspects and conditions external to the company, without considering the design and production capabilities of the company and its suppliers. For this reason, there is no guarantee that the allowable costs will be respected.

- *Product-level target costing* – This phase involves the product development in compliance with the cost objectives and requirements defined in the market-driven phase. The pressure of the market is transferred to the designers, whose task is to combine functionality, quality, and cost reduction to satisfy the customer requests at the defined cost. As compliance with the allowable costs is not always possible, as explained above, it is sometimes necessary to reasonably raise the allowable costs to address these factors. This activity aims to define the product level target cost ensuring its achievement through target costing, to reach the target cost of the product without sacrificing quality and functionality. The product-level target cost is calculated as:

$$Product\ level\ target\ cost = \ Current\ cost - Target\ cost\ reduction\ objective \quad (20)$$

where the current cost of the product is obtained from the manufacturing costs required for each function, and the cost reduction objective is identified as the degree of cost reduction required to reach the allowable cost. Once defined, the product level target cost is the objective that designers must consider in the product development process.

- *Component-level target costing* – In this last phase, the need for cost reduction, defined at the product level, is transferred to the components and their suppliers. Usually, the breakdown into components is carried out considering the main subsystems of the product. Opportunities for cost reduction can be found, in particular, in those subsystems (function groups or assemblies) which contribute significantly to the overall cost and offer the potential for considerable cost reduction (e.g., changing tasks, material, production processes and the assembly methods). At this level of the process, the choice and management of suppliers are of fundamental importance, because their activity allows the successful or unsuccessful implementation of the cost reduction strategy defined at the company level. In particular, this goal is critical in horizontally organized companies, as they purchase large quantities of materials and components from external suppliers. To calculate the component-level target cost, the product-level target cost is broken down into its main functions, i.e., the product sub-groups essential for achieving system functionality. In this way, each working group is responsible for the cost of the corresponding components. Therefore, the management and selection of suppliers are based both on make-or-buy decisions and on rewards for the suppliers who act mainly to reduce costs.

As described, the product development process begins after the definition of allowable costs: for this reason, it is essential to start this step as soon as possible. However, to obtain a realistic estimate of the selling price, the product design must be advanced enough to demonstrate and quantify the main qualities and functionalities.

Therefore, target costing is important to continuously monitor the process and the progress achieved, to ensure that corrective actions can be quickly defined in the event of problems. Only through a careful cost analysis can failures differ from those that can occur without target costing, where products could be withdrawn from the market even before they are launched, or worse, after launch. Given the importance of product compliance with target cost, various engineering techniques have been proposed to support this process (Ibusuki and Kaminski, 2007; Holt and Barnes, 2010; Hassan et al., 2010): Value Engineering (VE), or multidisciplinary approach, which aims to maximize the value for the customer in terms of functionality and quality while reducing costs; Design For Manufacturing and Assembly (DFMA), focused on reducing costs by simplifying production and assembly while maintaining the functionality; Quality Function Deployment (QFD), based on the translation of market requirements into technical requirements at all project levels to ensure the satisfaction of customer needs during product development; Failure Mode and Effects Analysis (FMEA), which considers and evaluates all the causes and effects of a system failure to ensure quality and reliability.

1.3.2 Product Cost Management (PCM)

Design for Cost (DfC) and Design to Cost (DtC) approaches are the key design methodologies for the optimization of production costs. Therefore, over the years the evolution of engineering techniques and strategies for manufacturing cost estimation has been remarkable. Robust methodologies have addressed most of the well-known issues, but the application of these models in industry has always been limited due to several factors, in particular: the time-consuming nature of the cost estimation process, the high level of knowledge required to choose the right parameters, and the high level of complexity of industrial applications (Shehab and Abdalla, 2002). However, the evolution of the software has led to the introduction of specific tools, known as Product Cost Management (PCM), to support engineers for the objective evaluation of manufacturing costs through the product life cycle and the enhancement of Design to Cost automation.
As reported by Ehlhardt (2014), a generic name for this type of software has not yet been adopted, mainly due to their recent development (compared with other CAx tools). However, since their application in manufacturing industries is gaining increasing interest and popularity, the literature provides several terms to classify these tools: Product Cost Management (PCM), Product Cost Estimation (PCE), or Computer-Aided Cost Estimating (CACE) are the most common (Ehlhardt, 2014; Shehab and Abdalla, 2002). PCM tools support objective evaluation of production costs through advanced manufacturing simulations: over the years they are becoming more complete, easy to use and effective for many industrial applications, thanks to the use of manufacturing and process

databases and libraries. In this way, these software provide a digital and Computer-Aided approach as a modern and efficient alternative to traditional tools for calculating costs, mainly templates based on Microsoft Excel or Access.

At the moment there are no fixed standards for these software, neither regarding the approach to the calculation, neither the user interface nor the functionalities: this is because PCM practice throughout the manufacturing industry is not systematically defined (Ehlhardt 2014). As several software vendors have developed their own cost estimation tool, different cost estimation approaches are available in the market and, therefore, PCM tools are applied in different phases, engineering departments, and for different purposes. The ability to estimate costs makes it possible, for example, to check suppliers' estimates and compare them with costs for internal production, thus supporting make-or-buy choices. Another extremely important aspect is linked to the evaluation and comparison of the cost according to the production technology (e.g., the choice between machining from solid or casting). Moreover, their application can be considered both in a concept phase, to have an initial indication of the cost, and in the actual cost evaluation phase, as in most cases.

A large number of methods can be used to estimate the cost of products but, in general, the estimation obtained using these software considers all the different activities required to obtain the finished product, as defined by the ABC method (presented in the previous section). Therefore, it focuses on cost allocation to separate fixed costs, variable costs, and overheads, and is commonly based on three strategies:

- *Standard-based* – Production costs are allocated from databases or libraries, from which production process data can be selected.
- *Engineering-based* – It defines the necessary resources based on the formulas that describe the operations to be completed and the corresponding cycle time.
- *Intelligent Emulation* – It uses particular algorithms, similar to those used in CAM, through which the production process is reconstructed, obtaining an extremely accurate cost estimation.

Of these estimation strategies, standard-based and engineering-based require specialist knowledge in choosing the type of machine and settings for those particular operations, affecting the accuracy of the estimation itself. The choice of the estimation strategy depends primarily on the software developer, whose business knowledge and level of automation guide the selection. Among these, some are based on the ABC method, others are able to read the 3D CAD file, automating much of the product cost estimation process (PCE). In general, software based on automated estimation belong to Automated Cost Estimation (ACE).

In most cases, software based on the ABC method are preferred due to the high flexibility provided by this method in manufacturing operations and management of complex products. Once the operator has configured all the parameters (e.g., the machine type, input parameters, material, etc.), the software automatically estimates the hourly rate and cost for each activity involved. Although very accurate in the simulation, with a level of precision directly proportional to the accuracy of the input parameters accuracy, the ABC approach is time-consuming and requires a significant level of experience.

On the other hand, ACE types are easier to use since they use 3D CAD mathematics as input information. In this way, the software automatically defines an optimal manufacturing path and process, based on the information provided in the CAD file. Only a small set of variables is required by the user: the type of material, the types of manufacturing operations, and the annual volumes (batch size).

For both ABC and ACE software, the estimation results are provided through specific visualization tools, as well as to analyse the effects of different production strategies with respect to production volumes.

These software are growing in diffusion, becoming more complete, easy to use and effective for many industrial applications. Today several PCM are available: aPriori® (aPriori®), Costimator® (MTI Systems), DFM Concurrent Costing® (Boothroyd Dewhurst), Micro® (Micro Estimating Systems), Teamcenter® Product Costing (Siemens), SEER® (Galorath), SolidWorks® Costing (Dassault Systèmes®) (Ehlhardt, 2014). The most common are briefly summarized to identify their main structure and differences:

- *aPriori® (aPriori®)* – It is considered a computer modelling simulation software and belongs to the ACE software group. As with most simulation software, it consists of several main elements, first of all the mathematical formulation, i.e., the rules for estimating the cycle time: for each feature, it calculates how long it will take to be produced. It achieves the estimation of costs by combining data from 3D model geometry together with data from the factory VPE (virtual production environment), i.e., the digital version of the factory. VPEs correspond to specific libraries, including labour, square meter costs, energy prices, and overhead costs, depending on the production location and the parameters selected. Thanks to its model-based structure, aPriori® can perform advanced simulations, through the automatic recognition of semantic annotations, including product tolerances, surface treatments, and welding specifications. Moreover, it allows VPE customization, to achieve realistic and detailed production costs.

- *Teamcenter® Product Costing (Siemens)* – Product costing is part of the Teamcenter® product life cycle management (PLM) system. It belongs to the ABC software group, which analyses the production costs using an extensive database, covering several production regions as well as different manufacturing and equipment options. In this way, it represents the entire cost structure of the products (e.g., material prices, work centers, BOM's and routings), allowing design-to-cost calculations and comparing different design strategies. It provides tools to see the impact of conceptual changes on costs early in the life cycle and suggest alternative design solutions, through the identification of cost drivers and cycle times.
- *DFM Concurrent Costing® (Boothroyd Dewhurst)* – It is considered a hybrid tool since, as with the previous software, it enables model-based cost calculations from 3D CAD models but also allows manual input for the definition of manufacturing operations. It combines these options with built-in libraries and databases, from which identify the major cost drivers associated with manufacturing and finishing parts. In addition, it is complementary to Design for Assembly (DFA) software from the same developer, through which to integrate the reduction of assembly operations.
- *SolidWorks® Costing (Dassault Systèmes®)* – This cost estimation tool is a built-in module of the SolidWorks® 3D CAD software. This allows for increased level integration, providing a direct link between 3D models and associated costs and enabling real-time evaluation of design alternatives. However, its capabilities are severely limited, compared to the other software analysed: having a small, structured database, it provides estimation only for sheet metal and machined parts.

Aim of the work

2.1 Research gap

The previous chapter describes the main structure of the Engineering design systematic approach, focusing on the core activities of the Dimensional Management and the Cost Management, i.e., DfT and DtC approaches. In particular, the evolution of techniques and tools for design optimization has led to important innovations and design strategies. In general, all these innovations move towards the realization of a whole Concurrent Engineering approach, to improve and optimize the product development process. On the one hand, concepts such as Computer-Aided technologies, Model-Based Definition, and techniques of DfX are well-known and have been refined over the years, constantly evolving. On the other hand, advanced improvements for tolerance and cost design optimization are relatively new and, in general, their evolution is currently in progress.

Therefore, despite the growing potential given by the use of all these techniques, methodologies, and technologies, a profitable application in industry is hampered by several factors, as summarized in the following paragraph.

The result is that today most manufacturing companies are still unable to take full advantage of the proposed research innovations. As regards the automotive companies, in particular those belonging to top-class automotive, it is possible to follow the structure of the systematic approach provided by Pahl and Beitz (2013). These industries can be classified into two categories, depending on their approach to product design and development: “Traditional” design and “Advanced” design.

- *“Traditional” design* – These companies, typically with low-medium production rates, still rely on the traditional approach, as shown in Figure 18. According to this approach, after the definition of product requirements, i.e., the result of the primary goals definition, and the selection of materials and process technologies, the 3D CAD models of components and assembly are created and then, through the iterative use of CAE simulations to check the requirements, the overall design is validated (in some cases supported by the use of MDO platforms). At this stage, 2D drawings are executed from complete 3D models, which are necessary for the production and the assembly phases. Product tolerances are selected during this phase to provide the compliance of the real product concerning the functional requirements: most of the time, tolerance specification is based on the engineer’s experience, empirical data from previous projects, and trial-and-error tolerance selection. Therefore, tolerance stack-ups are only analysed before the production stages, after the complete definition of the 3D component geometry. Corrective actions are necessary only in case of non-achievement of the product requirements, otherwise the product is integrated into the process through the implementation of strategies, changes, and additions to make the product effectively feasible: in this phase, manufacturing process simulations are executed to set the production process and the first cost estimations are provided to identify the achievement of the economic requirements (i.e., target cost). Then, after the first prototypes, the production can begin, monitored by quality and inspection assurance. Consequently, since the processes of DM and CM are limited to the final phase of product design, DfT and DtC practices cannot be applied as design optimization methodologies. This is also due to the fact that, for both tolerance analysis and cost estimation, traditional approaches and tools are applied rather than Computer-Aided and advanced ones. In particular for tolerancing, generally linear one-dimensional methods are applied for tolerance analysis, with RSS and Worst-case calculations. Furthermore, the tools adopted manage the information relating to tolerances in a generic way: there is no distinction between geometric and dimensional tolerances, nor between the method for considering the effects due to the parts and the assembly process.

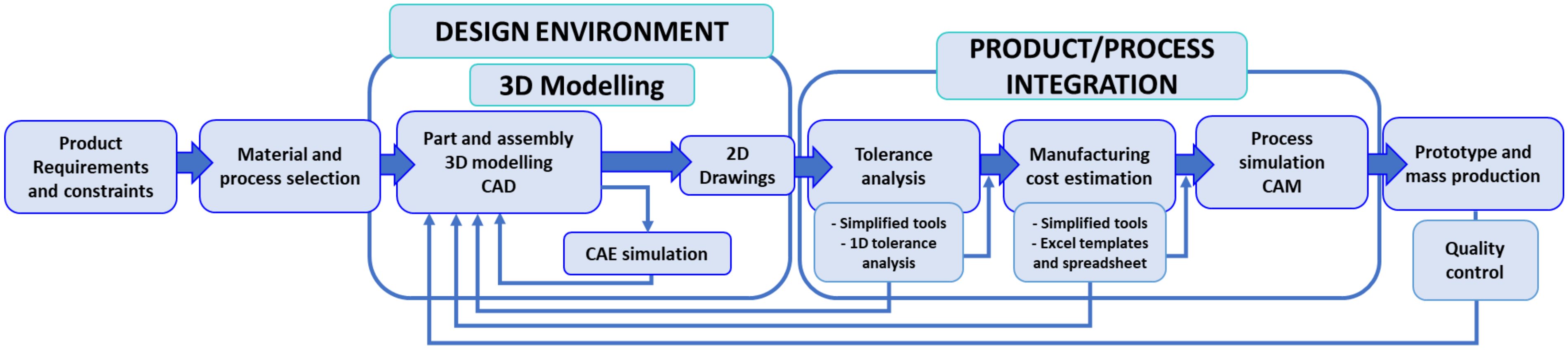


Figure 18. "Traditional" design process

Although simpler to manage and requiring fewer investments in technology and organizational and methodological changes, this approach is significantly lacking in integration and, therefore, in the possibility of design optimization. The analysis is performed by external tools, with respect to the design environment, resulting in difficulties in analysing quick changes in the 3D models, and complications in managing and sharing data between modelling and simulation tools. In addition, due to the simplification provided by these traditional approaches, the loss of information can lead to approximate results, far from reality, especially with complex assemblies and a large number of components.

- *"Advanced" design* – These companies, more structured and focused on medium-high rates of production, benefit from a more advanced product development process. The main structure of the approach follows the same phases described above, but in this case, as shown in Figure 19, they generally adopt advanced Computer-Aided tools for DM and CM activities. This is especially true for tolerance analysis, where CAT software is frequently used to better manage product complexity through more detailed tolerance analysis. This means increase realism of the simulations, thanks to: 3D stack-ups, integrating both dimensional and geometrical tolerances; advanced modelling of assembly operations and constraints; better customization of the system capability, providing probability distribution for each tolerance; customization of functional measurements (i.e., functional and assembly requirements) in terms of typology and acceptance limits. By eliminating 2D drawings, this approach exploits the integration capabilities of CAT tools with CAD software to share a common environment. Since geometric modelling, geometrical product specification and tolerance stack-up analysis occur in the same design environment, all information is stored in the same 3D CAD model improving data management and limiting scattering risks, getting closer to the MBD approach. However, CAT tools are generally applied to improve tolerancing activities but are rarely used in the embodiment design phase, as a real optimization tool. This is mainly due to the overall difficulties of changing mindset in the design approach and the drawbacks of the lack of integration with other simulation software (i.e., cost estimation software). As a result, the potential of CAT tools is not fully expressed and, consequently, DfT is only partially addressed in the design process: the degree of application depends on the level of investment in technological evolution and, above all, on the ability of companies to evolve their organizational and design approach. The same happens for the CM activity, with the additional drawback of the lower diffusion and awareness of advanced cost estimation tools. As these tools are relatively new and no fixed standards have currently been defined, these tools are partially applied by companies: they are mainly used to evaluate the cost of already defined products, to optimize manufacturing processes rather than product design (i.e., DtC practice).

Only in some cases, especially for a limited number of specific components, these tools are applied to evaluate the best solution with respect to different manufacturing processes.

As a result, the DfT and DtC approaches are not yet fully expressed due to the lack of integration between the tools, not allowing an integrated view of the tolerance effects on manufacturing costs. Consequently, multidisciplinary optimization of product design is still hampered, requiring both a change of mindset and the definition of a fully integrated design methodology for design optimization, to better exploit the new capabilities of integrated and advanced simulations.

As for “advanced” design companies, this category is very heterogeneous since each company may have different abilities to invest in high-tech tools and apply advanced design methodologies. However, common issues and critical factors can be identified as the main obstacles to the design evolution towards CE. These factors, summarized in the following paragraphs, belong to different phases and activities of product development, and their combined effect is causing an overall difficulty for manufacturers in applying the aforementioned innovations.

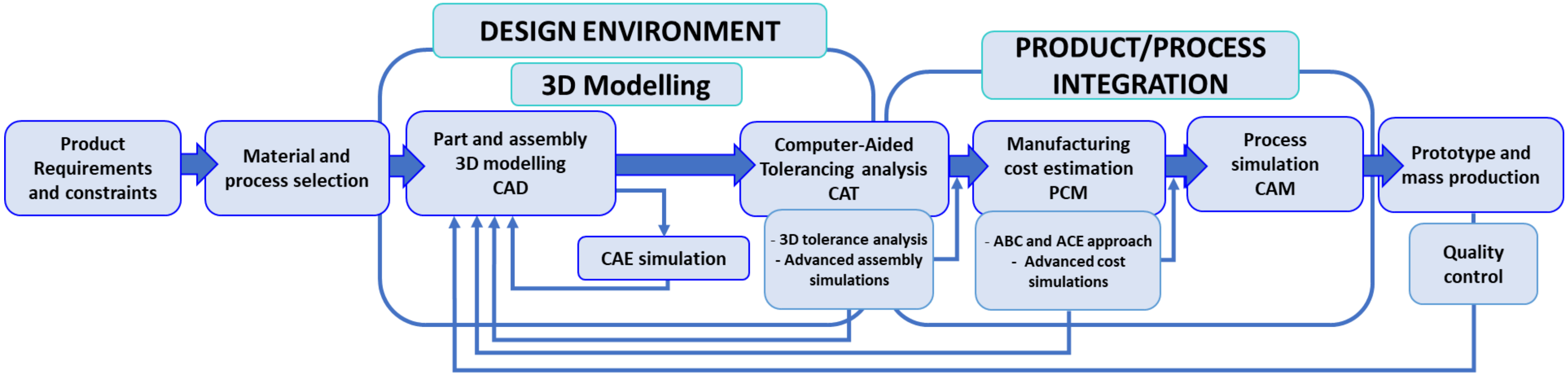


Figure 19. "Advanced" design process

Tolerance specification process

Tolerance specification is the first phase of tolerancing activity (Figure 20), consisting of the identification of the product tolerance scheme, to reflect product requirements through the definition of the dimensional and geometric variations allowed: product functionality is translated on component geometry by applying the Geometric Dimensioning and Tolerancing (GD&T) symbolic language (Henzold, 2006).

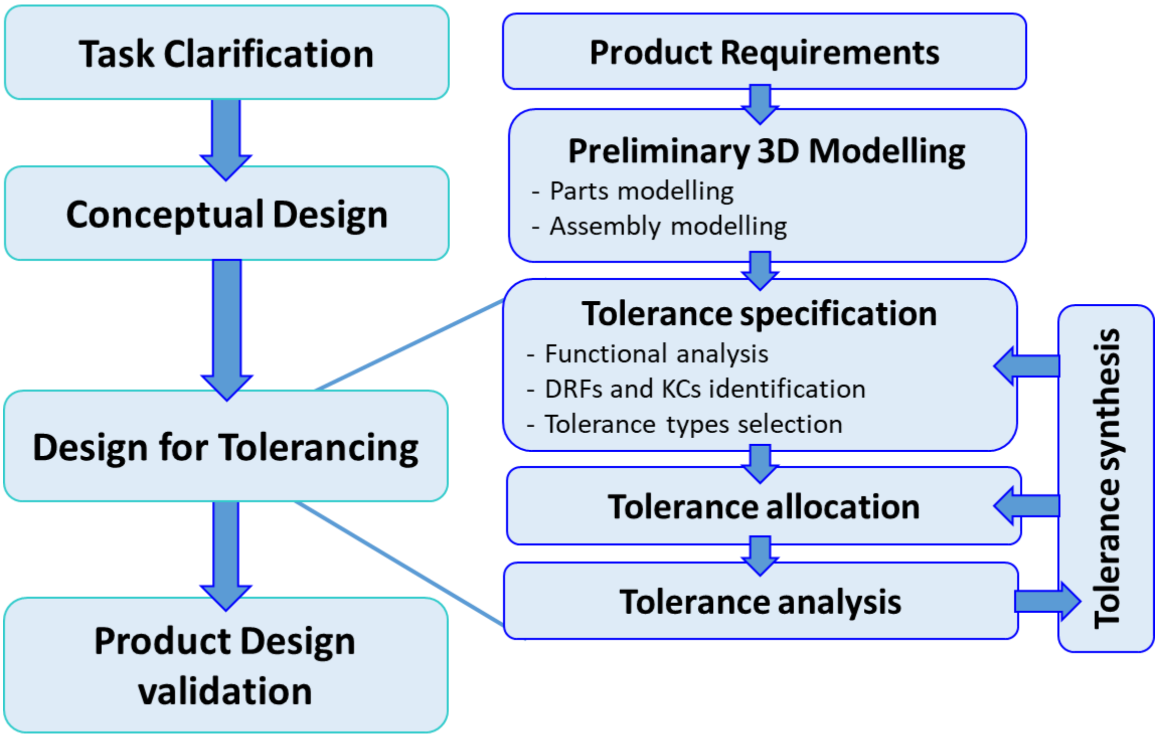


Figure 20. Design for tolerancing (DfT)

As pointed out by the literature, the tolerance specification process is still a challenging activity (Sun and Gao, 2020), as it may be very difficult to apply GD&T schemes to geometrically complex industrial products: the identification of the correct tolerance model, including the DRFs selection and the assignment of dimensional and geometric tolerances on product geometry, and the choice of values and types, require a lot of knowledge and experience to face the conflicting requirements (Haghighi et al., 2015) in compliance with rules and standards. This results in difficulties in implementing GD&T standards on real components due to ambiguities and potential errors, as different engineers can select, for a given product, different tolerance schemes, types, and values based on their knowledge and experience. As a consequence, the DfT approach cannot be systematically applied since the definition of a proper tolerance scheme directly affects the subsequent phases of tolerance allocation and analysis and, therefore, the ability to achieve the optimal tolerance design.

This difficulty is due to an intrinsic complexity of the task, but also to the lack of support by Computer-Aided technology during this phase: a systematic and CAD-based procedure must be defined to address current issues (Feeney et al., 2015). Moreover, the definition of a clear and unambiguous approach for Computer-Aided tolerance specification could improve the widespread use of 3D semantic annotations, i.e., the PMI, hence a more robust application of the MBD practice (Hallmann et al., 2019).

Model-Based Definition

MBD is the key approach to enable the transition to digital manufacturing: if a company moves towards a more complete implementation of model-based engineering and data interoperability, there is no interest in using manual techniques. However, its industrial application is still challenging (Li et al., 2016). According to the literature (Chen, 1996; Schleich and Wartzack, 2017; Ramnath et al., 2019), the main issues are related to the lack of representation standards for PMI within CAD tools. This results in the following consequences:

- Possible ambiguities in “representation” and “presentation” of PMI within CAD software.
- Manufacturers currently adopt different standards and file formats.
- GD&T is not completely inserted within the 3D models and not always assessed according to ASME and ISO standards.
- Decreased interoperability and integration between tools due to limited computer interpretability and data associativity.
- Missing establishment of a methodological approach for PMI integration into product design.

Consequently, ensuring consistent interpretation and presentation of PMI across different engineering applications is still a major challenge (Feeney et al., 2015; Hedberg et al., 2016): this also affects CAx tools (e.g., CAD, CAE, CAT, CAM, PCM etc.) themselves, reducing possibilities of integration and, therefore, of full exploiting their potential. Even if researchers are working on interoperability and data transfer issues (Hallmann et al., 2019) and on the definition of frameworks for enhancing MBD across the product life cycle (Morse et al., 2016), methodological, organizational, and “cultural” barriers are the main obstacles rather than the technical ones (Fang et al., 2016; Goher et al., 2019).

Computer-Aided Tolerancing

The use of Computer-Aided Tolerancing (CAT) tools is an important step in changing the design mindset towards CE and MBD, enabling more powerful design optimization. There are several advantages over traditional methodologies (i.e., manual, experience-driven and trial-and-error), mainly:

- More accurate 3D tolerance analysis, including both dimensional and geometric tolerances compliant with international standards.
- More realistic model of variation for complex products, combining rotation and translation effects and different distribution types.
- Better integration with CAD software, thanks to the direct link between 3D CAD model and CAT data and result analysis, automatic model update when changes are made, and information sharing through PMI, if available.
- Easier and more detailed analysis of the effects of specific design choices, from tolerance specification to assembly sequence and constraints, enabling more robust design.

However, despite the wide capabilities provided by these software, some important limitations still hamper their widespread implementation (Fischer, 2011; Qin et al., 2018):

- 3D software is more complex than simpler linear tools, as all component 3D features must be correctly tolerated according to GD&T and both assembly sequence and constraints must be modelled correctly.
- Despite their compliance with ISO/ASME standards, some tolerances are not supported, such as the form tolerances.
- Modelling of a 3D non-linear stack-up takes a long time compared to the simplified 1D linear tolerance stack-up.
- CAT tools require 3D CAD models to perform the analysis, requiring additional work in cases where these models are not available.
- CAT software application requires specific skills; therefore, training is essential for the correct use of the tool.

As reported, the main drawbacks are related to the need for a different approach in the design phase and a deep knowledge of GD&T by the engineers (Sigurdarson et al., 2018). In addition, even though CAT tools are directly linked to CAD models, they do not consider the effect of tolerances on production costs: the methods integrated into CAT tools are not yet capable of providing quantitative cost information, including manufacturing and tolerance costs (Qin et al., 2018; Hallmann et al., 2020a). Moreover, integration with PCM is still unavailable, limiting the analysis of tolerance effects to functional requirements only. Combined with the complexity and the required skills, this limits the implementation of CAT software in industry, resulting in an unexpressed potential for integration capabilities and advanced design optimization.

Product Cost Management

As remarked in the dedicated section, PCM tools allow a realistic estimation of manufacturing costs, providing a Computer-Aided approach to enhance the DtC approach. Thanks to their capabilities, PCMs are becoming a promising alternative to traditional methods for cost estimation, addressing an important role in MBD and design optimization. However, these software are relatively new and their diffusion is limited: the main obstacle to the PCM implementation is the lack of a standardized approach regarding these software. This results in the following drawbacks:

- PCM tools are applied in different phases, engineering departments, and for different purposes.
- PCM tools available on the market are very heterogeneous, with different interfaces, required actions, modelling structure, functionalities, and calculation strategies.
- Depending on the specific software, the estimation capabilities are significantly different (e.g., possibility to automatically provide process alternatives, identify critical geometries, import PMI, consider tolerance effects on costs, etc.).
- Cost estimation with PCM tools is more advanced than traditional techniques, but also more complex as it requires a lot of data from the user (e.g., 3D geometries, material specifications, production process and capabilities, etc.).
- PCM application requires specific skills for both modelling and analysing cost estimation, therefore training is essential for the correct use of the tool.
- PCM practice throughout the manufacturing industry is not systematically defined.

Consequently, PCM applications during product development are still limited to the final stages of the design process, to quantify the cost implication of engineering changes, as a final verification of the economic targets (Agyapong-Kodua et al., 2014). Indeed, only at the end of the design phase do the engineers have definitive data and manufacturing information (Shehab and Abdalla, 2002; Sanz-Lobera et al., 2016). Furthermore, although PCM tools consider the tolerance effects on costs, they provide information only on the economic impact of tolerances, not on the functional effects. As already highlighted, the lack of direct data exchange between PCM and CAT models has limited their combined application to simultaneously optimize cost and performance and, therefore, apply DfT and DtC approaches.

Tolerance-cost optimization

Tolerance-cost optimization is becoming the milestone of the DfT and DtC approaches. As DfT and DtC aim to identify the optimal tolerance design to address both functionality and cost effectiveness, tolerance-cost optimization provides a practical application of this approach. The key factor that enhances tolerance-cost optimization is that it addresses all major phases of the tolerance design process, leading to an integrated strategy for design optimization. As previously analysed in the dedicated section, literature pointed out the most important areas of tolerance-cost optimization: over the years, many researchers have proposed effective improvements to each of these elements. However, as reported by well-established reviews, the main obstacle to the profitable application of tolerance-cost optimization in the industry is its complexity (Hallmann et al., 2020a): the high number of interdisciplinary parameters, difficult modelling of the relationship between influencing factors, and lack of detailed information on the processes are the main issues. Above them, three critical areas can be identified in the methodologies and strategies addressed by the literature, namely, data and parameters sharing, flexibility to application complexity, and integration of simulation tools/environments.

- *Data and parameters sharing* - Missing classification standards, lacking integration between simulation tools, and limited availability of data during the early phases of design lead to reduced interoperability and inconsistent results (Sanz-Lobera et al., 2010).

- *Flexibility to application complexity* – Literature models generally suffer from over-simplifications and assumptions, limiting their industrial application. In addition, important modelling factors of tolerance analysis such as three-dimensional effects, geometric tolerances and the use of well-known standards (i.e., ASME-GD&T and ISO-GPS) are often neglected (Hallmann et al., 2020a).

- *Integration of simulation tools/environments* – Lack of integration of tolerance-cost optimization approaches with available Computer-Aided tools, in particular CAT and PCM tools. Scientific contributions of Computer-Aided integration in tolerance-cost optimization frameworks are limited in number and most of the time their industrial implementation is difficult (Li et al., 2016; Sigurdarson et al., 2018). Furthermore, MDO platforms are not implemented in the literature for tolerance-cost optimization, as these software are relatively new and do not yet relate to CAT and PCM tools.

Among these issues, the last is the most critical: to simulate the problem correctly, especially for geometrically complex systems, integrated software tools are needed, as well as the definition of specific modelling strategies. Therefore, a clear, easy-applicable, and systematic framework for tolerance-cost optimization is required, based on high knowledge of the different disciplines (tolerancing, manufacturing processes, optimization, cost estimation etc.) and provided with indications about the information required (i.e., input-output relations), the techniques and tools to support each operative step.

2.2 Research goal

As highlighted in the previous section, the combined effect of the aforementioned factors led to the failure to apply research innovations for product design optimization. Most of the time the limiting factor is methodological and organizational rather than technical: an important number of companies is already using Computer-Aided tools and advanced techniques, but the lack of an integrated and multi-disciplinary approach limits their effective application and, therefore, their potential. As these companies could considerably benefit from a complete implementation of these innovations in the industrial context, an innovative methodology is needed, starting with the optimization of existing processes to overcome organizational boundaries and, above all, with a fundamental cultural change. Consequently, this methodology has to address the following goals:

- Overcome the limitations of the design process currently adopted in industry, proposing a convenient and effective application of research strategies and techniques.
- Structure a design process based on the development of digital models with high information content (data and know-how), to increase their change and updating, minimizing errors and data scatter during the design activities.
- Improve design optimization, using advanced simulation tools and integrating frameworks to optimize tolerances, to achieve product quality, functionality, and (manufacturing) costs requirements.
- Effectively predict the performance of the final product from the early phases of design, reducing development time and cost.

With this in mind, the present doctorate research aims at defining a new integrated design methodology for product/process design optimization. By developing a systematic framework, DfT and DtC approaches can be integrated, leading to an effective combination of DM and CM practices. In this way, product design optimization can be further enhanced, as can CE and MBD practices. Therefore, the methodology aims at two main goals: to integrate the production process into the product design process, through the centralization of the information necessary for the tolerance design within the CAD models; to increase the accuracy of the analysis, avoiding dimensional simplifications using integrated techniques, simulations and optimization tools.

With the aim of providing a systematic methodology for more effective industrial implementation, the research focuses on the automotive sector, specifically top-class automotive. As the evolution of technologies and materials and the increase in production rates are leading to modifications in the design processes, several case studies are considered to stress the methodology and prove its suitability for practical application.

Computer-Aided integrated approach for Tolerance-Cost Optimization

3.1 Proposed methodology

The proposed methodology aims to establish an integrated approach for product/process design optimization. The main objective is to provide a comprehensive method for the industry, especially automotive companies, as an evolution of the current design process. For this reason, the systematic structure and integration of software are the key points for industrial implementation: each step of the method must be directly applicable, provided by specific operations and corresponding tools to effectively predict the effects of cumulative variation in geometrically complex systems. Thus, it is possible to achieve the goal of multi-disciplinary tolerance design optimization, including DfT and DtC approaches within a structured Computer-Aided integrated environment, exploiting their integrational capabilities and addressing the aforementioned limitations.

According to the main phases of the product development process, the methodology is applied after the definition of the product requirements and the selection of the material and manufacturing strategies. It employs a different formulation of the product development process: compared to the traditional method, product/process integration begins directly in the design environment, by anticipating tolerancing and costing activities. Product tolerances become design variables, such as for product geometry and nominal dimensions, to be considered for design optimization: combined assembly and cost simulations provide a comprehensive understanding of the impact of tolerances on both functional and economic requirements, enabling both DfT and DtC. In this way, geometric modelling, geometrical product specification and tolerance-cost optimization occur in the same design environment. Indeed, all the information is stored in the same 3D CAD model, improving data management and limiting the scattering risks, approaching the MBD philosophy. Moreover, since all tolerance design activities are implemented in the 3D environment, the 2D drawing representation is no longer essential, allowing the sharing and the use of the same CAD models during the subsequent product development phases.

To achieve this purpose, the Computer-Aided integrated approach for Tolerance-Cost Optimization is defined and developed according to the current design process, innovations and techniques from the scientific literature, and international standards and regulations. This results in a systematic framework for product/process design optimization, as reported in Figure 21, consisting of two main phases: 3D modelling and annotation, and tolerance-cost optimization. These phases are composed of subsequent steps, to which the corresponding Computer-Aided tools are assigned to convert each of them into a clear sequence of practical activities and operations.

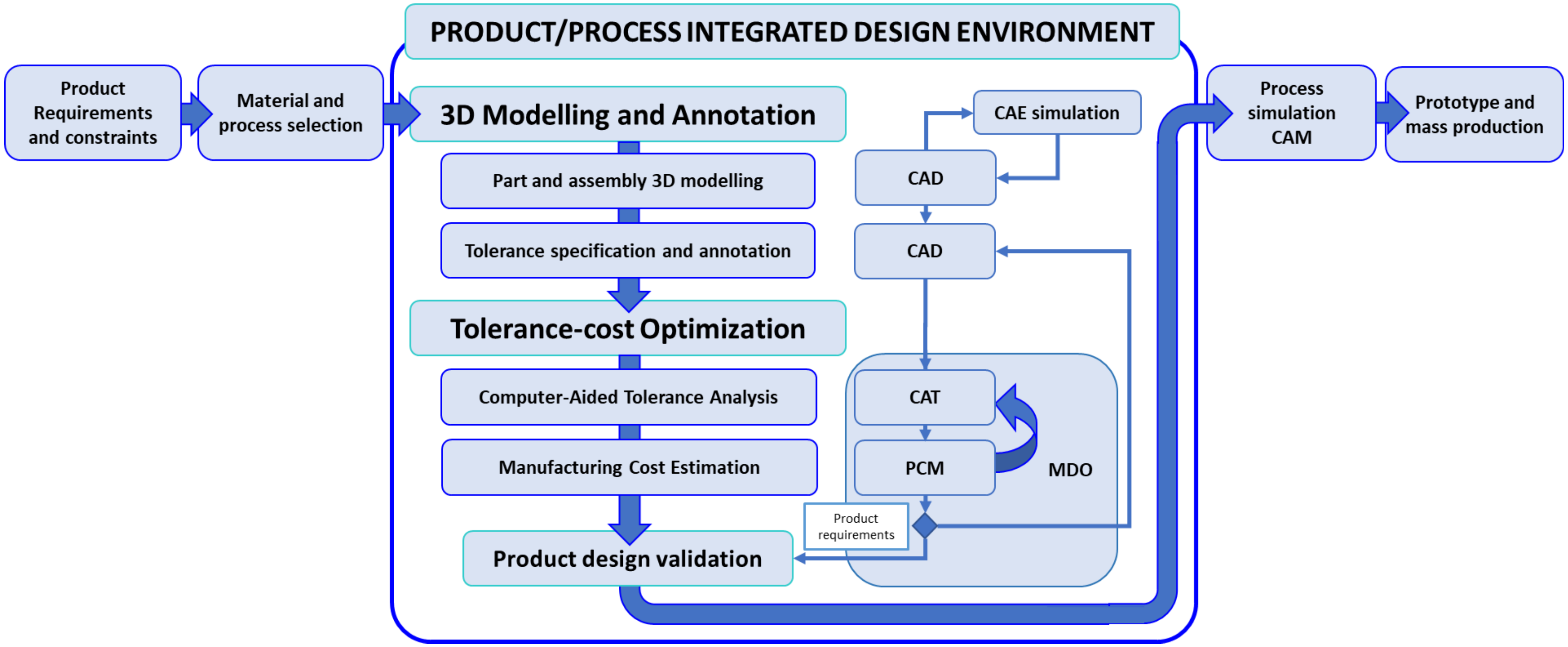


Figure 21. Computer-Aided integrated approach for Tolerance-Cost Optimization

Step 1 - 3D modelling and annotation

This step aims at implementing tolerance information within the 3D models of the product, providing the starting models and information required for the following optimization phase. In this way, the integration of 3D dimensioning and tolerancing leads to the achievement of two main objectives: to increase the information content of digital models and to improve the tolerance specification and annotation process. Compared to the typical workflow of product design definition, this phase consists of:

- *Part and assembly 3D modelling* – Preliminary 3D models of components and assembly are created in the CAD software environment. These models follow the prescriptions provided in the previous phases, through the translation of the main product requirements on the geometry of the components. Therefore, this phase comprises the definition of both part geometry and product structure, including the assembly sequence and constraints. Before completing the translation by means of product tolerances, the 3D models are first analysed through CAE simulations to verify the main technical requirements. Iterative use of CAE provides validation of the overall product geometry and dimensions, which can be addressed with product and process specifications. Since the need for CAE simulation for product design is directly dependent on the typology of the products and aiming to focus on tolerance-cost design optimization, this PhD research work does not aim to implement CAE simulation within the proposed approach (it will be addressed as further development, as pointed out in the final chapter of the work).

- *Tolerance specification and 3D annotation* – The specification of tolerances completes the process of translating requirements into product geometry, addressing information about functionality, assembly, and manufacturing. A systematic framework for tolerance specification is provided to reduce subjective decisions and ambiguities: starting from the 3D model geometry, it is broken down into hierarchical steps and converted into practical operations within the CAD model. In this way, the tolerances are inserted as 3D semantic annotation, i.e., the representation PMI, including functional analysis, functional features selection (KCs), DRFs identification and GD&T scheme definition. Consequently, the first tolerance values can be allocated directly on the 3D models, as a starting configuration to then be optimized.

As result, the 3D models record all information regarding geometrical product specification, from the feature geometry and dimensions to the dimensional and geometric tolerances. Therefore, the 3D models are provided with the correct representation of the product to be used efficiently in the next phase.

Step 2: Tolerance-Cost Optimization

The second phase focuses on the integration between modelling and simulation approaches, providing the integrated structure for tolerance-cost optimization. According to the state of the art in tolerancing and costing activities, and with reference to the technologies available for manufacturing companies, the modelling procedure is formalized in terms of operational steps and input-output required for each, as reported in Figure 22.

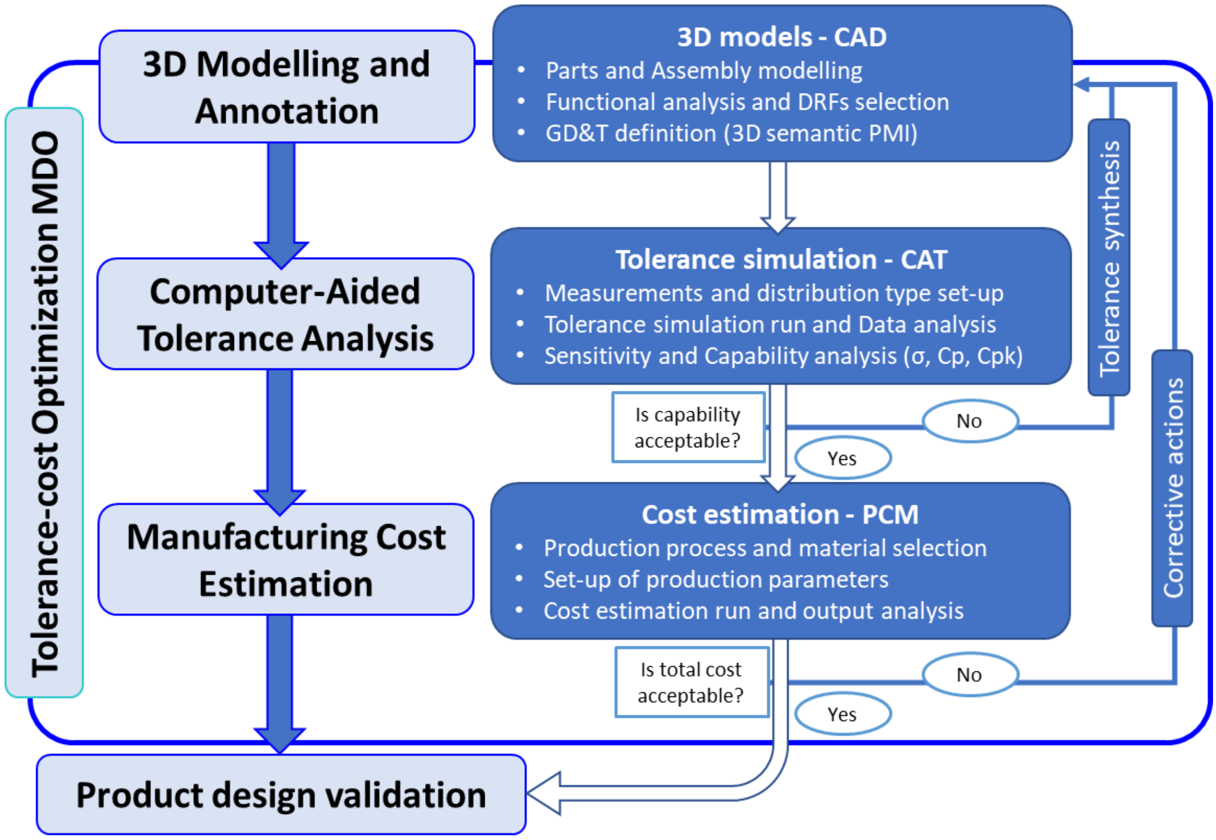


Figure 22. Tolerance-Cost Optimization

The 3D models of the components and assembly, provided with all the information needed in the previous step, are imported as input for both tolerance analysis and cost estimation models. Therefore, this second step consists of:

- *Computer-Aided tolerance analysis* – Key element of the proposed methodology, the use of Computer-Aided tolerancing addresses all the limitations of conventional methods for tolerance analysis, enabling advanced 3D simulations. A general procedure for Computer-Aided tolerance analysis is identified and provided to formalize the modelling approach regardless of the particular CAT software. The tolerance analysis model is developed directly from component and assembly models: GD&T schemes, including DRFs and KCs, are fully characterized providing distribution types, as well as assembly sequence, joints, and constraints. The measurements are defined to reproduce functional and assembly requirements, i.e., the tolerance stack-ups obtained by selecting the measurement control points. Then the tolerance analysis is executed and the simulation results are compared with the product requirements and the process capability values (cp, cpk, σ): if the output values are not acceptable, a synthesis of tolerances is needed, modifying the tolerance values and, if necessary, GD&T types and DRFs scheme.

- *Manufacturing cost estimation* – To provide a direct correlation between tolerances and costs, the cost estimation deals with a model-based approach, from which to identify each cost factor. Therefore, a PCM-based approach is structured to formalize the simulation procedure. 3D CAD models of components and assembly are imported, providing the main inputs for the estimation: parts geometry, assembly configuration and constraints, and product tolerances. In addition to these data, the specifications of the materials of the components and the manufacturing process are provided, according to the selection already made in the dedicated phase (i.e., material and process selection). Then, production parameters are set, including production rate and location, process capability etc. After that, the cost estimation is executed, identifying the manufacturing costs associated with each operation related to each component and feature: the estimated costs (i.e., component cost, assembly cost, annual and total production costs) are checked and analysed against economic targets. If necessary, corrective actions are applied: since the methodology focuses on tolerance optimization, changes in tolerance values are evaluated, and, if necessary, on GD&T types and DRFs scheme.

To provide the optimization of product tolerances, simulation models are integrated within a Multi-Disciplinary Optimization (MDO) environment: CAD, CAT and PCM models are linked, and simulation inputs and outputs are related to product objectives and constraints. The tolerance-cost optimization is structured and, after selecting the proper optimization algorithm, the automatic iteration of the simulations is provided: the tolerances are iteratively updated and several configurations are simulated. The process of simulation and comparison with respect to the functional and economic targets of the product is repeated iteratively, and the optimal configuration of tolerances can be identified as the best trade-off.

As a result, the process of product design is completed and validated by achieving the optimal tolerance design.

As described, the proposed methodology enables DfT and DtC by means of a Computer-Aided framework, through the integration of tolerancing and costing activities in the product design process. The definition of this product/process integrated environment requires a multi-disciplinary design approach to support engineers by providing a clear, systematic, and model-based method: in this way the combined implementation of Computer-Aided tools is established, as well as the formalization of well-known engineering practices.

Therefore, the methodology development has been divided into several phases, to address the issues highlighted in the literature concerning each specific area. Given the central role of the tolerance activity, the first part of the research work consists of defining and evaluating the tolerance design process:

- CAD-based tolerance specification and annotation
- CAT-based modelling approach

The research activity then focuses on the process of integrating tools and their implementation:

- PCM-based modelling approach
- CAT-PCM software integration through MDO
- MDO assessment through PMI integration

For each phase of development, a systematic modelling procedure is formulated and applied to simplified case studies, according to the state-of-art and combined with the selected software.

This aim is reflected in the next chapter, where the industrial implementation of the methodology, applied to an automotive engine, is divided into two corresponding steps: CAT-based tolerance analysis and tolerance-cost design optimization.

3.2 Phase 1: CAD-based tolerance specification and annotation

Following the main steps of the tolerance design process outlined in section 1.2.2, the first phase of the proposed methodology consists of the tolerance specification and annotation phase. The key element to providing an unambiguous geometrical product specification is the compliance with tolerancing standards to correctly apply GD&T symbolic language. As pointed out by the literature, the tolerance specification process is a demanding activity, and the definition of a clear and systematic practice is necessary to reduce subjective decisions and ambiguities. For this reason, a Computer-Aided framework for tolerance specification is provided for the systematic selection of optimal GD&T schemes and types (Petruccioli et al., 2021b). Moreover, this framework becomes the enabler for the whole Computer-Aided tolerance-cost optimization method itself since it directly impacts the result of the design activity.

The main steps of the tolerance specification are formalized in the framework, providing a hierarchical order and guidelines to drive the selection of DRFs scheme and functional features on 3D CAD models: the integration capabilities between the GD&T-based approach and the parametric 3D CAD modelling is exploited through the use of semantic annotations on 3D models with PMI. In this way, this framework aims to overcome some of the current limitations of MBD practice: it allows the generation of 3D models capable of showing the user all the part features as if they were drawings. Therefore, 2D drawings are no longer indispensable (almost during product/process design definition), and the integration of the geometric information of the 3D model with the GD&T annotations (i.e., Datums, geometric and dimensional tolerances, etc.) provides files reduction and less data dispersion, a major issue in all fields of engineering.

Following the GD&T rules, the process that defines the correct tolerance model is composed of specific steps (Figure 23), described as follows:

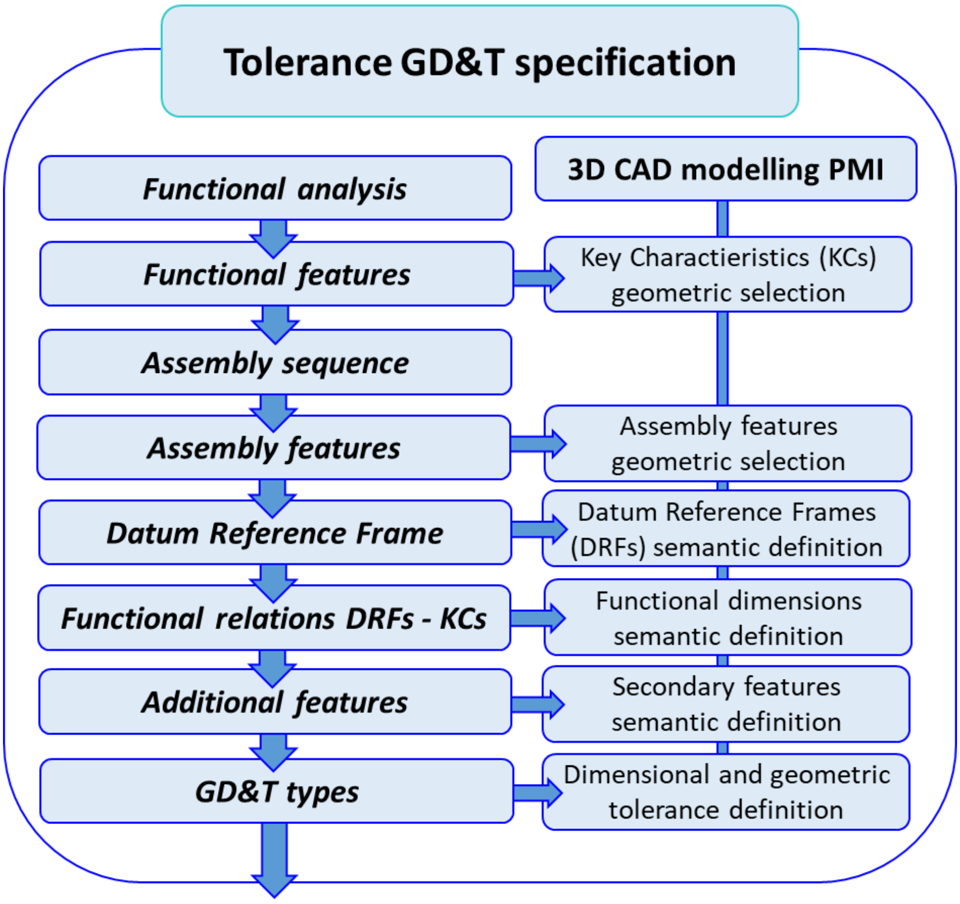


Figure 23. Tolerance GD&T specification workflow

- *Functional requirements analysis* – The requirement list is analysed and the functional targets and technological requirements to be met (e.g., position of features, geometrical conditions, gaps, flushes, etc.) are extracted, isolated and quantified (when necessary), for simple identification of geometrical elements. This fundamental phase mainly influences the final result of the design activity.

- *Identification of functional features* – The geometric elements that influence functional requirements are identified as KCs and selected in the 3D model. KCs selection is handled in PMI 3D environment, to be subsequently characterized with tolerances. If multiple requirements have to be checked, KCs can be grouped by function type.

- *Assembly sequence definition* – Both functional requirements and basic parts geometry are evaluated to identify possible assembly operations and assembly order. As different assembly strategies constrain the DOFs of the parts differently, the final result can be severely affected. Therefore, different solutions can be considered, to be compared and validated.

- *Identification of assembly and manufacturing features* – Assembly features are identified and selected from the assembly sequence. If necessary, manufacturing features, e.g., surfaces to clamp or to position the part for machining operations, can be identified and selected as well. As for the functional features, assembly feature selection is handled in PMI 3D environment.

- *Definition of DRFs* - The Datums are identified as reference elements of the tolerance scheme, from which to locate the other features that require tolerance control. According to the GD&T rules (Henzold, 2006), the selection of Datums follows a hierarchical order, known as the order of precedence, to uniquely define the component positioning and locate the reference system for functional dimensioning (i.e., define the orientation and location of the tolerance zone). Therefore, the DRFs have to be concurrently defined (the 3-2-1 rule is generally considered for planar Datum features) and qualified following this order. In addition, to identify the correct selection of DRFs, manufacturing operations can be considered to define the most realistic order of DRFs. Then, the DRFs are inserted into the 3D models as semantic PMI, on the geometrical features previously selected.

- *Definition of functional relationships between DRFs and KCs* – Once the DRFs have been entered, the KCs can be characterized with respect to the DRFs, with identification of the functional dimensions between the features. Consequently, the structure of the 3D tolerance model is enriched with the definition of the tolerance chains of the functional features. These functional dimensions are entered in the model as PMI, to be completed with dimensional tolerances.

- *Identification of additional features* – Secondary features to be located and tolerated can be selected and added to the PMI environment, if necessary.

- *Selection of dimensional and geometric tolerance types* – Finally, dimensional and geometric tolerances are assigned for each selected feature to be controlled. The tolerance types are identified to properly characterize the KCs with respect to their nominal geometry or the set of DRFs. Tolerances are entered into 3D models as PMI to complete the tolerance model.

The resulting 3D tolerance model reflects design intent, part functionality and assembly operations. Tolerance allocation is the next phase of DfT, and it can be easily handled directly on 3D models: tolerance values are related to PMI tolerances previously defined. Then, the 3D models with tolerance schemes are ready for the next tolerance design phases, in particular the subsequent CAT simulation. The workflow provides a clear separation between functional features identification and assembly features identification phases. In fact, the correct process of functional analysis must concern only the feature necessary for the fulfilment of the product functions (i.e., functional requirements): only these features must be identified as KCs. Then, the analysis of the assembly sequence is performed, and the assembly features belong to the specific assembly sequence: they can change considering a different order of assembly operations or a different type of constraints between the components.

Therefore, multiple assembly features can be identified for the same KCs. However, in some cases, some assembly features correspond to some KCs. For this reason, even if the separation between functions and assembly can be difficult, the separation between the corresponding phases is necessary to avoid any ambiguity.
As a result, the framework returns the 3D CAD models compliant with the GD&T rules, recording all information related to the geometrical product specification, from feature geometry and dimensions to dimensional and geometric tolerances. By following the framework, engineers can act systematically and sequentially during product specification, reducing the probability of errors in the GD&T application: it clarifies the function of each geometrical element, its relationship with other features and the type of control it requires. Furthermore, thanks to PMI semantic annotations, the 3D models are provided with the correct representation of the product to be used efficiently in the next phase, allowing the automatic sharing of all manufacturing information.

General mechanical assembly

To assess the tolerance GD&T specification workflow, it has been applied to a simplified case study, a general mechanical assembly (Figure 24). This case study is representative, in terms of functional requirements and assembly operations, of many industrial products, such as gearbox and engine block assemblies. Moreover, the definition of the tolerance specification model for this assembly should provide a common GD&T scheme to reuse for several products with similarities, providing savings in development time and costs. The method is implemented using a specific tool from CatiaV5® CAD software by Dassault Systèmes®, CatiaV5® "3D Functional Tolerancing and Annotation" module. As with most of the 3D annotation modules provided by CAD software, it is able to define and manage the specification of tolerances and annotations both for single parts and 3D assemblies, and both as 3D presentation and representation (Gaunet, 2003).

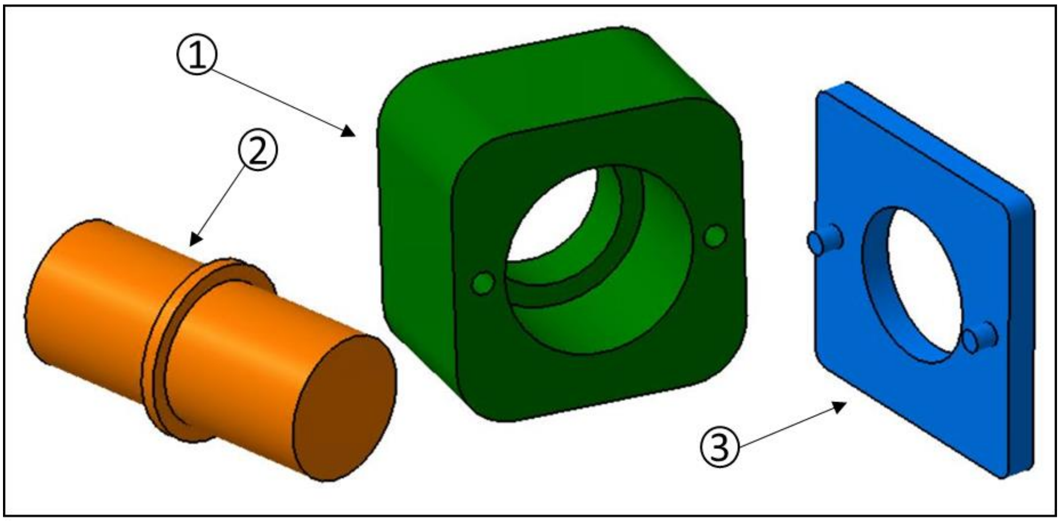


Figure 24. Mechanical assembly: 1 support; 2 shaft; 3 plate

The mechanical assembly considered consists of three main components: a support, a shaft, and a plate, respectively referred to as #1, #2, and #3, as in the Figure. The assembly has been chosen to be considered as an industrial product ready for the starting phase of DfT, the tolerance specification stage: the functional requirements must be translated as tolerance scheme of the components, already modelled in their basic geometry. To be as general as possible and provide a reference model, not all the additional components needed to complete the assembly are considered.

- *Functional requirements analysis* – As with all mechanical transmission assemblies, the main function of the selected case study is torque transmission through shaft rotation. The support has to locate the shaft to match the required geometric position with respect to the external components (i.e., secondary shafts and gear wheels, not considered here for simplification purposes). The plate has the function of closing the case, providing the correct position of the hole to match shaft rotation and avoid oil leakage (the gasket is not considered for simplification purposes). Therefore, the main function of the assembly is the correct positioning of the shaft to ensure the conditions for torque transmission.

- *Identification of functional features* – As a result of the previous step, functional features are identified on each component as KCs (Figure 25a).

- Support: internal cylindrical surface for support-shaft relative rotation (clearance fit); planar surface for the plate-support interface.
- Shaft: cylindrical surfaces for shaft relative rotation with respect to the support and the plate (clearance fit).

- Plate: internal cylindrical surface (central hole) for plate-shaft relative rotation (clearance fit); planar surface to close the case.

- *Assembly sequence definition* – Considering the assembly main function and the basic geometry of components, the assembly sequence is identified: the shaft is inserted into the support, it is aligned with the internal cylindrical surface and positioned on the support internal shoulder (bearings or thrust washers are not considered for simplification purposes). The plate is positioned on the support by contact between the two main planar surfaces. Then, ensuring the correct alignment with the shaft, the translations of the plate are blocked by inserting the first pin (i.e., representative of a screw operation) and finally the relative rotation is blocked with the insertion of the second pin.

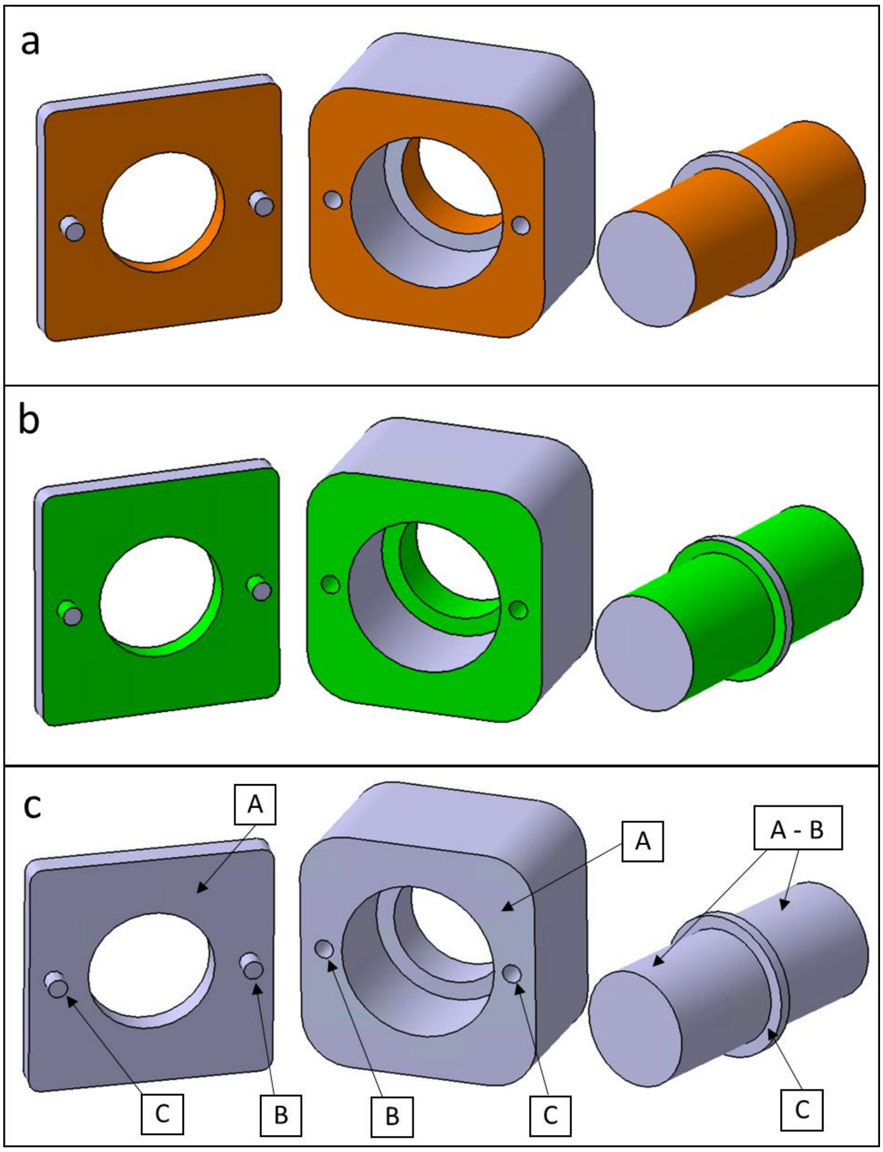


Figure 25. Tolerance GD&T feature selection phases: a. functional features (KCs); b. assembly features; c. Datum Reference Frames (DRFs)

- *Identification of assembly and manufacturing features* – As a result of the previous step, assembly features are identified on each component (Figure 25b).

- Support: as for plate-support assembly, planar surface for the plate-support interface, holes for the insertion of the pins; for shaft positioning, internal cylindrical surface for shaft alignment and internal shoulder for axial location.
- Shaft: the assembly features correspond to the KCs, with the addition of the shaft shoulder.
- Plate: as for the support, planar surface and pins for plate-support assembly, internal cylindrical surface for shaft alignment.

As with most industrial cases, some of the assembly features also belong to the KCs group.
- *Definition of DRFs* - The definition of DRFs must consider the features identified in the previous steps. In this case, the assembly sequence is centred on the support, on which the other components are assembled. The assembly interfaces between the components are divided into two independent areas (i.e., external features for the plate-support interface, internal features for shaft-support interfaces). Therefore, the choice of DRFs must be made considering these areas and the manufacturing operations: for the support, the internal features will be machined relative to the external ones (where it is held in position). Consequently, the DRFs of the components are identified with the following features (Figure 25c):

- Support: the contact surface with the plate is Datum A; the first hole is identified as Datum B; the second hole is Datum C.
- Shaft: as common for rotating components, the cylindrical surfaces are identified as the Common Datum A-B; the shaft shoulder in contact with the support is Datum C.
- Plate: as for the support, the contact surface with the support is Datum A; the first pin is identified as Datum B; the second pin is the Datum C.

- *Definition of functional relationships between DRFs and KCs* – Once defined the DRFs, the relationships between KCs and DRFs and between subsequent DRFs are identified:

- Support: Datum B must be qualified with respect to A, to control its orientation, as well as for Datum C, i.e., to control both the orientation and position with respect to Datum A and B; the internal cylindrical surface has to be located with respect to Datums; internal shoulder has to be oriented and positioned along the rotation axis. The position is done with respect to Datum

A while the orientation is done with respect to the internal cylindrical surface, to ensure the correct orientation of the shaft.

- Shaft: Datum C needs to be qualified with respect to Common Datum A-B, with orientation and axial position control.
- Plate: as for the support, Datum B and C must be qualified with respect to A and, for Datum C, to Datum A and B; the internal cylindrical surface must be located with respect to the Datums.

As described above, to correctly orient the internal shoulder of the support, the internal cylindrical surface has to be identified as a reference. Therefore, the additional DRF Datum D has been introduced.

- *Identification of additional features* – Considering the basic geometry of the reference assembly and the simple functions of the components, no additional features are required.

- *Selection of dimensional and geometric tolerance types* – As a result of the previous steps, the definition of the tolerance types is easily performed, corresponding to the identified functional relationships:

- Support: the dimensional tolerance is identified on the diameter of the holes (Datum B and C); the perpendicularity with respect to Datum A is assigned on Datum B; Datum C is controlled by a position tolerance with respect to A and B; Datum D is controlled by a position tolerance with respect to Datums A, B, C, by a diameter tolerance to match the dimensional tolerance with respect to Datum A, and by a perpendicularity with respect to Datum D.
- Shaft: the dimensional tolerance is identified on the cylindrical surfaces of Common Datum A-B; as regards Datum C, even if the perpendicular tolerance may be sufficient, a total runout tolerance with respect to A-B is preferred, as preferable for rotating components.
- Plate: the dimensional tolerance is identified on the diameter of the pins (Datum B and C); the perpendicularity with respect to Datum A is assigned on Datum B; Datum C is controlled by a position tolerance with respect to A and B; the central hole is controlled by a position tolerance with respect to Datums A, B, C and by a diameter tolerance to match the clearance fit with the shaft.

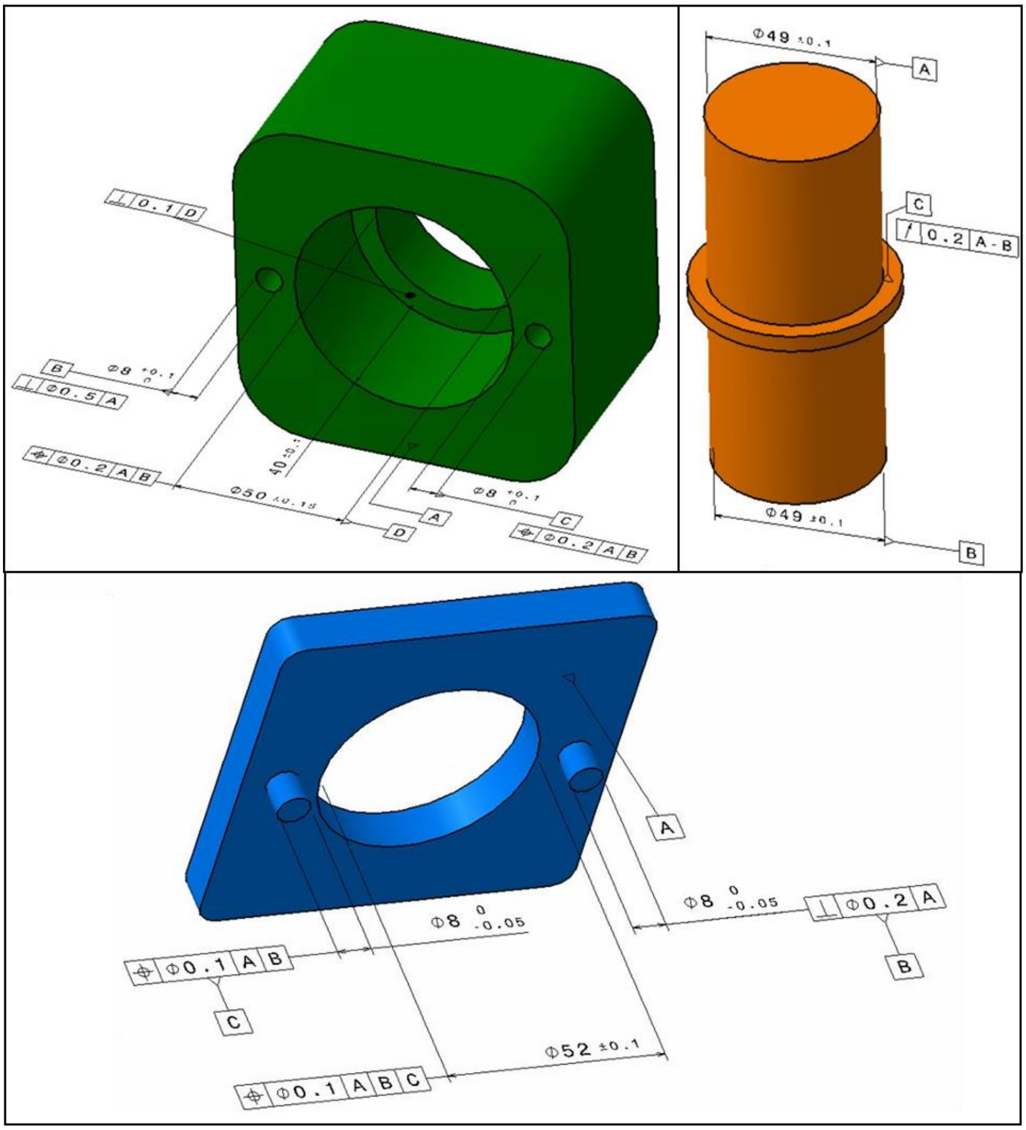


Figure 26. Tolerance GD&T specification model

As a result of the workflow, the tolerance model of the assembly is completed, with the GD&T specifications defined as PMI (Figure 26). Therefore, the semantic PMI is completed with tolerance values, which can be entered directly into the 3D models during tolerance allocation.

3.3 Phase 2: CAT-based modelling approach

Performing the tolerance analysis using CAT tools is the core activity to enable the DfT approach, allowing a more realistic model for dimensional variation simulation, especially for complex industrial products. Despite several advantages addressed over traditional methodologies, a general procedure can be identified to overstep the methodological transition. The formalization of the CAT modelling approach is provided to support engineers for the correct use of the tool even without particular skills, and regardless of the particular CAT software.

The CAT modelling approach includes several steps, reported below and in Figure 27 (Petruccioli et al., 2021a). Depending on whether the GD&T is implemented within the 3D CAD models as semantic PMI (as described in the previous paragraph) or whether it is modelled directly in the CAT environment, some of the first steps (i.e., functional analysis, tolerance specification and allocation) are already developed in the CAD environment. To be as general as possible, the following description considers GD&T modelled within CAT models: if tolerance PMI is available, it will be imported directly into the CAT model without additional actions.

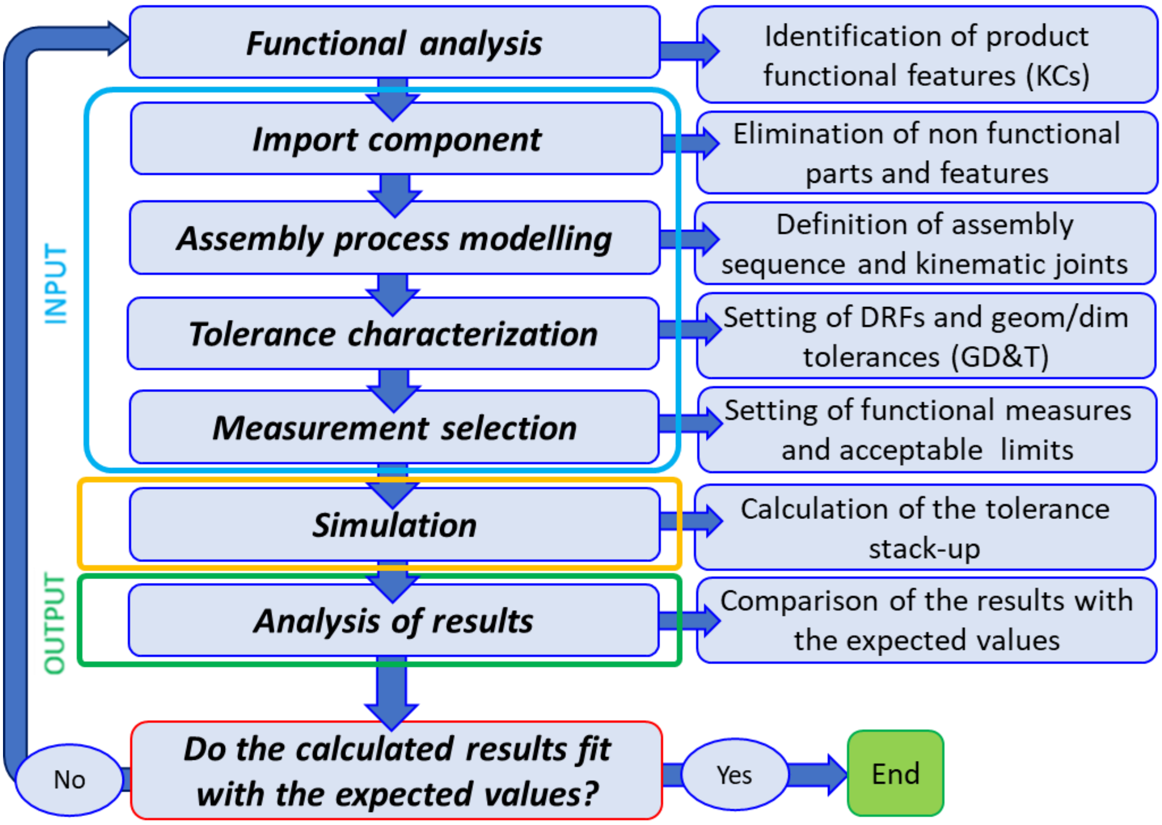


Figure 27. CAT modelling approach

- *Functional analysis* - The first phase corresponds to the functional analysis of the specific assembly, to understand the real engineering needs: what are the main features involved in the tolerance stack-up (and corresponding dimensions and tolerances); what is the correct assembly sequence to ensure the correct functioning of the model (from which to identify DRFs and coupling features); what are the features representing the functional measurements (i.e. product functional and assembly requirements). In addition, the assembled components are studied to analyse the possible contact and interface zones between the components: the areas between adjacent parts are highlighted to identify gaps or steps.

- *Import components* - Since most CAT tools work in parallel with CAD software, the 3D models must be imported into the CAT simulation environment: part geometries, assembly model (to import the relative positioning and sequence of components) and, if implemented, semantic annotations. Another important activity of this phase is the elimination of the non-contributing parts from the CAT model, to simplify the model and reduce its size: the analysis requires only the CAD models of the parts involved in the chain, all other parts are useless. Furthermore, only the functional surfaces need to be defined.

- *Assembly process modelling* - The assembly sequence is known from functional analysis and 3D models. The parts are connected with "joints" that describe the kinematics of the components in the assembly: clamping and fixing operations of the parts, with the corresponding constraining of DOFs. It is a critical step that assigns the assembly response and behaviour, as different connections can lead to very different results.

- *Tolerance characterization* – In this phase, all the tolerances involved in the stack-up must be entered into the CAD model and characterized: the selection of part features, the tolerance specification and allocation, and the selection of the tolerance statistical distribution types are executed to set-up the model and provide more realistic simulation behaviour. As noted, when PMI is available, this operation begins within the 3D CAD models, otherwise the operator must enter GD&T, including DRFs schemes and tolerances, directly into the CAT environment.

- *Measurement selection and set-up* - This phase is the core of the tolerance analysis since the functional requirements to be investigated are defined here in terms of measures (linear, gap, angular, etc) and acceptable limits. The choice of the measure type can have a big impact on the correctness of the analysis: a good tolerance stack-up model can give wrong results if the measures are incorrect. Therefore, points or directions are often needed to best set up the measurement. Once the proper features have been selected and the measurement set, the stack-up is closed and the model completed: it is now ready for simulation.

- *Simulation and analysis of results* - After running the simulation, the results are analysed and compared with the targets. Two situations may occur.

In case of success, the post-processing environment usually shows a list of the tolerances involved in the chain with their “weight” and “sensitivity”, to identify the main contributors to the variation. The weight indicates the variance contribution to the functional measure set, while the sensitivity indicates the slope of the response function. These indices indicate which tolerances should be changed to exploit the functional limits set in the measure, ensuring the quality objectives (σ, C_p, C_{pk} etc.).

In case of failure, there are mainly two options, depending on the distance to the target. A large inconsistency means that something is wrong in the model: usually, the cause is the inappropriate use of the kinematic joints. A small inconsistency requires a re-allocation: this means changing the process or modifying the functional limits, or acting on tolerance types and values, locator positions, and assembly strategy.

Simplified gear motor assembly

To implement the proposed methodology on complex industrial products, a CAT tool with a high integration level is chosen to develop the tolerance models: Cetol $\mathbf{6\sigma}$® V10.2 (developed by Sigmetrix, LLC) has been adopted among the CAT tools mentioned before. As reported in the first chapter on the CAT software description, it represents one of the most advanced solutions for the 3D statistical tolerance analysis, based on the Variational model and capable of solving non-linear problems. In particular, it is based on direct integration with the most common CAD software and allows the automatic reading of semantic PMI: in this way, it allows the complete development and assessment of the proposed methodology. During the research work, it has been applied in combination with both the CAD software Catia V5® by Dassault Systèmes® and CREO Parametric® 4.0 by PTC®: in particular for the CAT-based methodology, both the case studies have been implemented within Catia V5®.

To assess the CAT-based modelling approach before its implementation in the industrial case study, it has been firstly applied with respect to a simplified model, obtained from a real assembly of an industrial gearmotor (Petruccioli et al., 2021b). The original gearmotor is composed of the gearbox case, the cover, the rotating shafts and all the additional components (Figure 28).

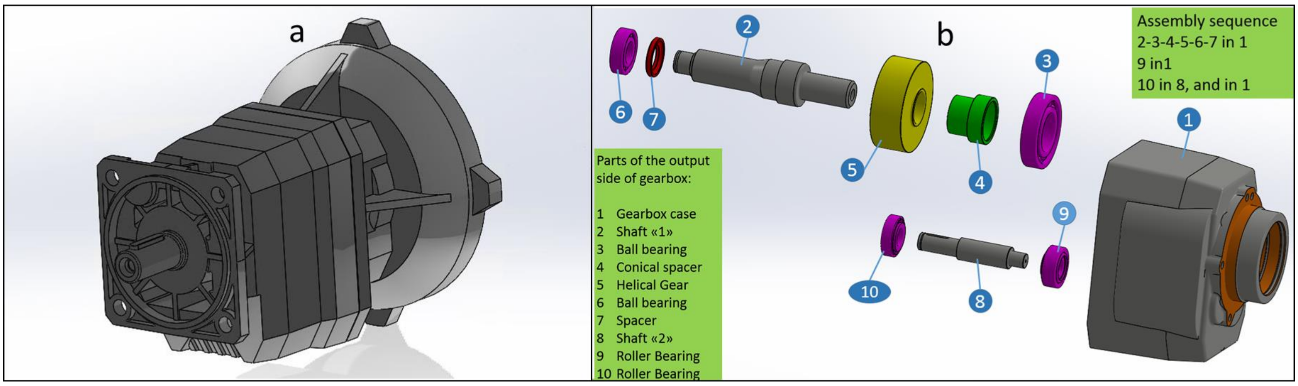


Figure 28. Gearbox assembly: a. original model; b. assembly sequence

- *Functional analysis* – Aiming at validating the modelling approach, the analysis has focused on the first functional requirement, i.e., the distance variations along with the X and Y directions between the first shaft and the second shaft (Figure 28b). In this case, the objective of the study is to identify the contribution of each tolerance to the measurement variation and to understand which tolerances have the greatest influence on functional requirements.

- *Import components* - The simplified model, shown in Figure 29, has been developed directly from the general mechanical assembly used for the tolerance GD&T specification assessment, consisting of the case (1), the cover (2), the primary shaft (3), and the secondary shaft (4). Modifications are made to replicate the base geometry and main dimensions of the real assembly. All unnecessary components are not considered and some of them (i.e., ball bearings) are included in the geometry of the main components. The components to be simulated are treated as rigid models, without distortion of the parts.

- *Assembly process modelling* – The assembly sequence, reported in Figure 28b, has been translated to the simplified assembly: the primary shaft (3) is aligned to the upper housing of the support (1) and positioned on the upper internal shoulder of the support. Then, the same operation is repeated for the second shaft (4). Finally, the cover (2) is positioned on the support (1), by means of the planar contact between the two main surfaces and the alignment between the cover pins and the support holes (i.e., representative of a screw operation), ensuring the proper alignment with the shafts.

- *Tolerance characterization* – The tolerance scheme of the gearbox assembly is very similar to that identified for the general mechanical assembly, both for DRFs, KCs, and tolerances: in this case, it consists of two shafts instead of one. Indeed, they share the same tolerance scheme: only the tolerance values are different, according to the specific dimensions and requirements. Particular attention is provided to the interface between the cylindrical housings (i.e., the bearing housings) of the support and the shafts since they directly affect the functional requirement (axis alignment).

- *Measurement selection and set-up* – Two measurements are set, the distances between the shafts along with the X and Y directions at the meshing gears (at a specified axial distance).

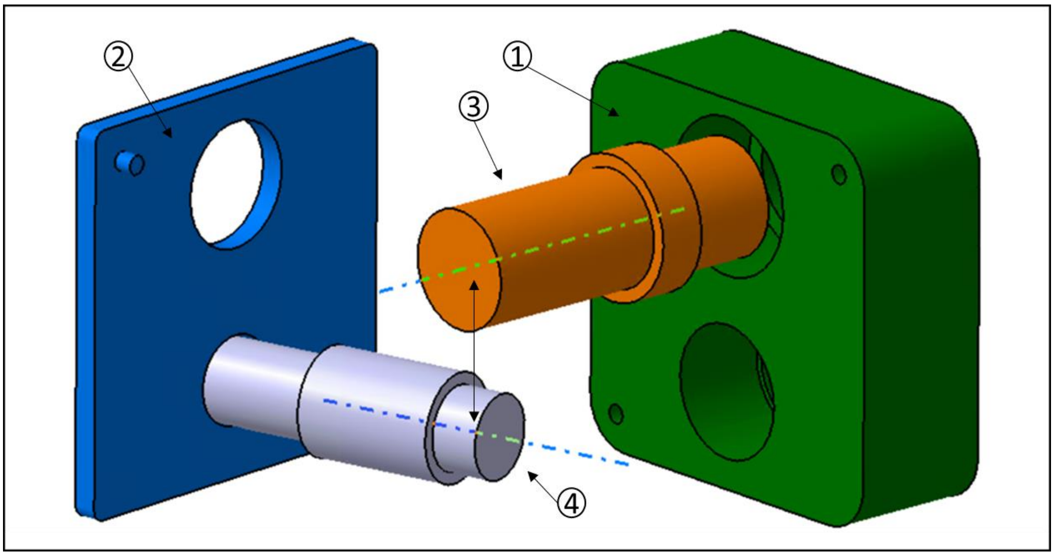


Figure 29. Gearbox assembly simplified model

- *Simulation and analysis of results* - The statistical analysis provides the distribution of the variation for both the X and Y axis. For the first measurement, ΔX1-2 (X DIRECTION), the main contributors to variation are (support = #1, plate = #2, primary shaft = #3, secondary shaft = #4):

- Position tolerance of the lower support housing (36.5%) (#1).
- Runout tolerance of Datum C (31.6%) (#3).
- Position tolerance of the upper support housing (29.5%) (#1).

For the second measurement, ΔY1-2 (Y DIRECTION), the main contributors to variation are (support = #1, plate = #2, primary shaft = #3, secondary shaft = #4):

- Position tolerance of the lower support housing (36.5%) (#1).
- Runout tolerance of Datum C (31.6%) (#3).
- Position tolerance of the upper support housing (29.5%) (#1).

As visible, the tolerance analysis shows the same contributors in both X and Y directions, justified by the fact that position and runout tolerances act with the same probability distribution along the radial direction for all cylindrical surfaces. The critical tolerances on which to act to optimize functional requirements have been identified. Therefore, depending on the comparison of the resulting measurements with the expected target values, two strategies can be adopted: if the targets are not met, it is possible to tighten the values of the main contributors to improve the assembly performance; if the targets are easily achieved and the process has a greater capability (i.e., it goes beyond the expected level), it is possible to relax the values of the main contributors, reducing manufacturing costs. In addition, the analysis identifies the least contributing tolerances, on which to act without significantly affecting the functional requirements.

Automobili Lamborghini V12 engine assembly

An industrial assembly from the automotive sector has been chosen as the second case study to apply the CAT-based modelling approach. In this case, the aim is to verify a real implementation of the method on a high-complexity industrial product. Since CAT analysis is one of the key activities of the proposed methodology for the tolerance-cost optimization, this step is of great importance: once its effective implementation has been proved, the integration with the other simulation tools is possible and, more importantly, suitable for companies.

For this reason, the case studies introduced here (the second fully described in the next chapter, with the implementation of the complete methodology) represent an excellent example of industrial products for which the Computer-Aided design optimization approach can be very advanced and appealing.

The industrial case presented is the high-performance V12 engine assembly currently produced by the company Automobili Lamborghini S.p.A. (Figure 30).

Figure 30. Automobili Lamborghini V12 Engine Assembly

Two case studies have been developed to verify and optimize two different requirements: guarantee the assembly of the parts composing the engine block assembly; optimize the tolerances between the engine block and the crankshaft to guarantee the expected performance while reducing the overall manufacturing costs. The common objective of the two case studies just mentioned is to achieve a clear understanding of the engine tolerances relating to the subsystems and individual parts: only in this way is possible to review them and possibly expand their values.

Since the case study related to the engine block assembly operation focuses on achieving high process capability (i.e., minimum number of rejects) rather than optimizing the trade-off between tolerances and production costs, it is the first to be addressed, requiring a full CAT analysis. Therefore, it represents the best-case study for applying the CAT-based approach.

V12 engine block assembly operation

The selected case study aims to verify the effectiveness of the assembly operations of the engine block (Petruccioli et al., 2021a). As in the previous case study on the CAT-based modelling approach, the CAT software selected is Cetol $\mathbf{6\sigma}$®, as the workbench of Catia V5® CAD software.

In this engine, the engine block is divided into two parts: the upper part called "cylinder block" and the lower part called "end plate". In the early manufacturing phases, these two parts are machined into a single component requiring a proper DRF: the usual procedure, in this case, is to choose a similar DRF for each of them, to ensure the best possible assembly of the parts. Moreover, a fixturing system is necessary first to allow correct positioning between the cylinder block and the bed plate, then to avoid their movement along the separation plane (critical conditions typical of high-performance V-Engines). For these reasons, a certain number of bushings (one for each stud) ensures the functional requirements described above.

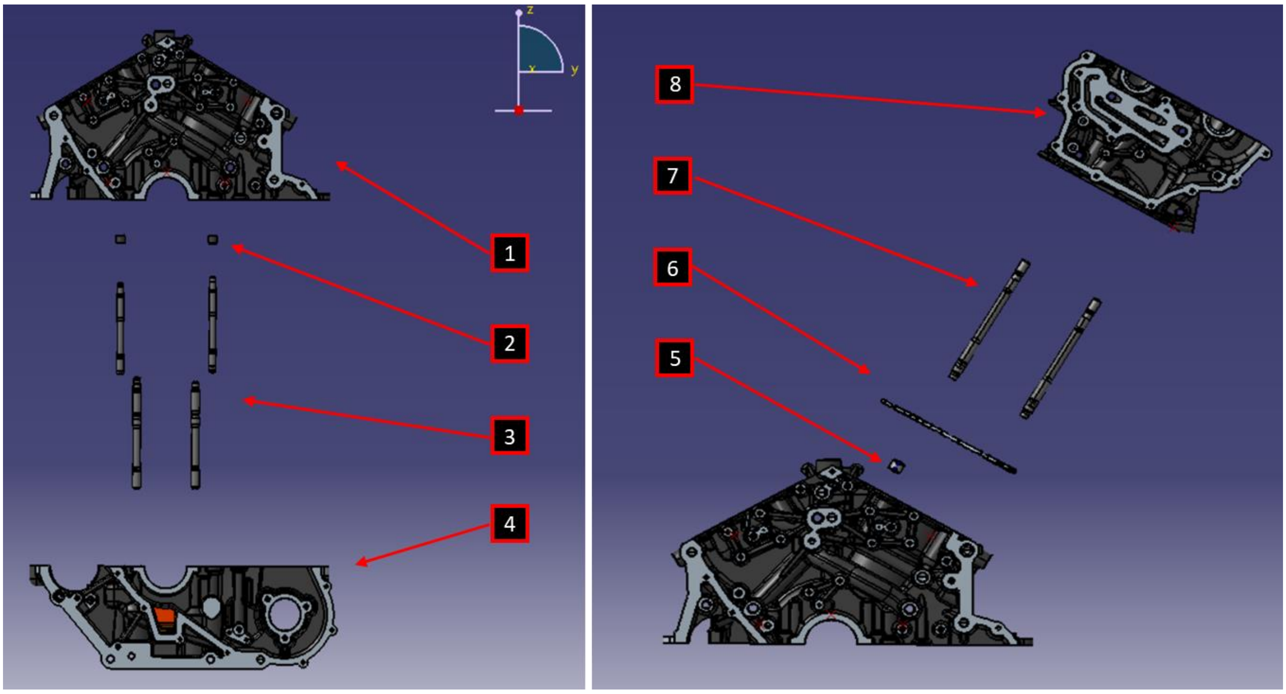


Figure 31. V12 engine assembly: 1. UC, 2. LC bushings, 3. LC studs, 4. LC, 5. Cylinder head bushings, 6. Head gasket, 7. Cylinder head studs, 8. Cylinder head

- *Functional analysis* – The V12 engine assembly consists of the following components, as shown in Figure 31: the engine block, divided into upper (UC) and lower crankcase (LC) (i.e., the cylinder block and the bed plate), the head gasket, the cylinder heads, and the fixture and positioning elements, i.e., the crankcase bushings and the studs. In particular, there are 14 bushings and 28 studs on the LC side, and 2 bushing and 14 studs on the cylinder heads side. The analysis focuses on the bolting operations between the upper (UC) and lower crankcase (LC) of the engine block, and between the cylinder heads and the UC. Since bushings and studs achieve the positioning and bolting operations of the assembly, respectively, their interface with the other components is crucial. In addition, the interface between the main components has a great influence on both component positioning and engine performance. For this reason, the main features of these areas must be very precise, requiring additional manufacturing operations to meet the functional targets.

- *Import components* – The assembly is imported into the CAT environment to ensure the correct relative positioning of the components. Non-contributing parts such as the head gasket and one of the cylinder heads were not considered in the simulation: the former is included in the UC as an additional thickness; the latter is not necessary as both cylinder heads share the same product specifications and assembly operations. The components to be simulated are treated as rigid models, without distortion of the parts.

- *Assembly process modelling* - The assembly sequence is identified: the UC is fixed (i.e., it is held in position by an external fixturing system) and the bushings are inserted in their housings on the UC (on both cylinder heads and LC sides) with interference fit, following a precise order. Then, the studs are inserted in their housings on the UC, following a prescribed order. Once these components are positioned, the LC and the cylinder heads are inserted. Bolting operations on the studs complete the assembly of the engine.

- *Tolerance characterization* - The DRFs for the components (Figure 32) are identified and modelled on the 3D models with respect to the assembly sequence. Starting from the UC and LC, the first reference, Datum A, is the separation plane between the parts. Then, considering the positioning function of the bushings, the holes corresponding to the two diagonally opposite external bushings are defined as Datum B and Datum C: B is qualified with respect to Datum A with a perpendicularity tolerance, C is qualified with a position tolerance with respect to Datums A and B. Then, a position tolerance with respect to Datums A, B, and C locates the other housings of both the bushings and the studs. All functional features are provided with dimensional and geometric tolerances to meet the previously defined functional requirements, inserted on the 3D models with respect to the DRFs. Finally, the model characterization is completed with the tolerance allocation: the starting tolerance values are selected according to the prescribed technical specifications and manufacturing process. The same is repeated for the other components. The cylinder head has the same type of DRFs and GD&T scheme (for whom that concerns the assembly operation) as UC and LC. Finally, bushings and studs are characterized by dimensional and geometric tolerances to control the cylindrical surfaces of interface with the main components, as well as their axial deviation: in this case the tolerance values are provided by external suppliers.

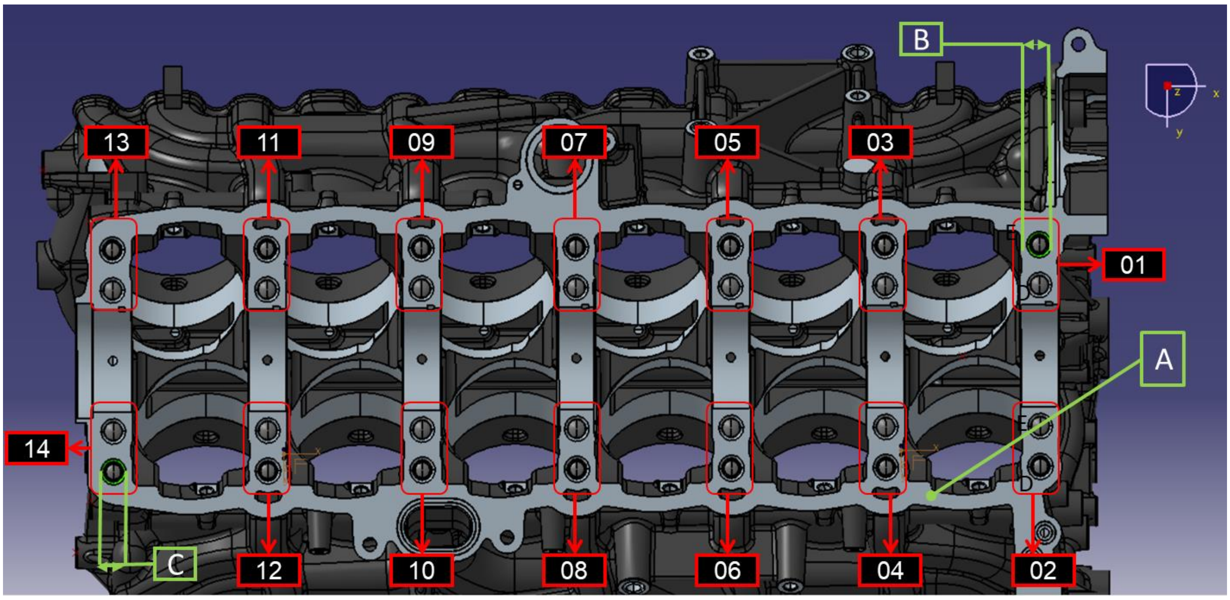


Figure 32. Datum Reference Frame (DRF) identification on the UC

- *Measurement selection and set-up* - The functional measurements (i.e., the responses to be checked in the tolerance stack-up analysis) are set correspondingly to the assembly functional requirements: the gap of both the bushings and the studs with respect to their housings in the engine components, i.e., between the cylindrical surfaces of the interface (Figure 33). In particular, the absence of collisions and physical interferences between the parts (gap < 0) is verified for all the measurements: the acceptability limits have been set for each measurement by assessing a target capability value of $\pm 3\sigma$ (corresponding to $C_{pk} = 1$ and a process Yield percentage of 99.73%).

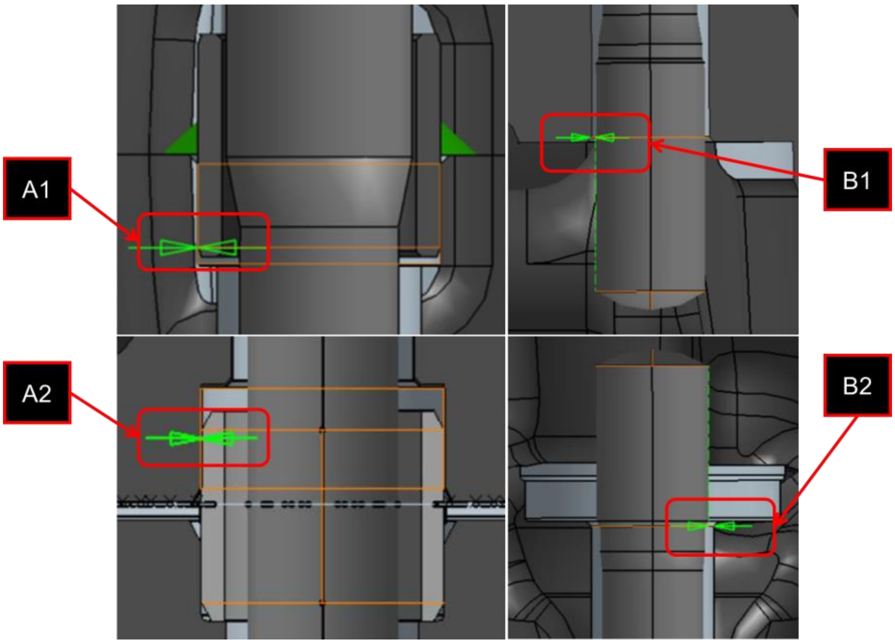


Figure 33. Functional measurements

- *Simulation and analysis of results* - The analysis of the simulation outputs provides the following results. These are classified into two groups, considering (A) the gap measurements between the bushings and their housings, and (B) the gap measurements between the studs and their housings, for both the UC-LC (1) and the UC-cylinder head sides (2).

- A.1 The target condition is not verified, with an average value of ±1.95σ (Figure 34). The sensitive analysis identifies the main contributors to variation: the position tolerance of the bushing housings on the UC, the position tolerance of the bushing housings on the LC, the dimensional tolerance of the external diameter of the bushings, and the dimensional tolerance of the bushing housings on the LC.
- A.2 The target condition is not verified, with an average value of ±1σ. The sensitive analysis identifies the main contributors to variation: the position tolerance of the bushing housings on the cylinder head, the dimensional tolerance of the bushing housings on the cylinder head, and the dimensional tolerance of the external diameter of the bushings.

Name	Value	Contribution (>=1%)
Pos. tol. of the bushing housings on the UC	Φ 0.03 / A	47.99%
Pos. tol. of the bushing housings on the LC	Φ 0.03 / A	33.32%
Dim. tol. of the ext. diameter of bushings	13.000 ±0.014	13.23%
Dim. tol. of the bushing housings on the LC	13.000 +0.034 +0.016	5.47%

Figure 34. Simulation outputs of A.1 measurements, with the main contributors to variation

- B.1 The target condition is fully verified, with a large safety margin and an average value of ±4.63σ (Figure 35). The sensitive analysis identifies the main contributors to variation: the position tolerance of the stud threaded seats on the LC, the position tolerance of the stud housings on the LC, the position tolerance of the bushings on the UC, the concentricity of the studs, and the dimensional tolerance of the stud housings on the LC.
- B.2 The target condition is verified, with a safety margin lower than B.1 and an average value of ±3.5σ, above the limit of acceptance. The sensitive analysis identifies the main contributors to variation: the position tolerance of the stud threaded seats on the cylinder head, the

dimensional tolerance of the stud housings on the cylinder head, and the concentricity of the studs.

Name	Value	Contribution (>=1%)
Pos. tol. of the stud threaded seats on the LC	Φ 0.20 / A|B	86.86%
Pos. tol. of the stud housings on the LC	Φ 0.20 / A|B|C	8.49%
Pos. tol. of the bushings on the UC	Φ 0.03 / A	1.85%
Conc. tol. of the studs	Φ 0.10 / A	1.60%
Dim. tol. of the stud housings on the LC	11.000 +0.100 -0.050	1.19%

Figure 35. Simulation outputs of B.1 measurements, with the main contributors to variation

The comparison between the measurement ranges and the functional targets, resulting from the output analysis, identifies two different scenarios. The outputs of A.1 and A.2 show a reduced capability of the engine assembly process compared to the target of $\pm 3\sigma$, therefore the tolerance ranges of the main contributors to variation must be tightened to improve the assembly performance. On the other hand, B.1 and B.2 show that the values of the stud-related tolerances are too tight, so it is possible to relax the tolerance values of the main contributors to variation, reducing the manufacturing cost of parts and achieving the expected production target. Hence, the simulation results lead to the following corrective actions on the tolerance values (Tables 1 and 2).

Table 1. Tolerance values of the main contributors need to be tightened (A.1 and A.2)

	Tolerance	Original value	Corrected value
A.1	Position tolerance of bushing housings on the UC and LC	0.03	0 with M.M.C.
	Dimensional tolerance of bushing housings on the LC	F7	E7
A.2	Dimensional tolerance of bushing housings on the UC	K6	P6
	Dimensional tolerance of external diameter of the bushings	+0.025 +0.012	js8
	Dimensional tolerance of bushing housings on cylinder heads	H7	E6
	Position tolerance of bushing housings on cylinder heads	0.05	0.03

Table 2. Tolerance values of the main contributors are relaxed (B.1 and B.2)

	Tolerance	Original value	Corrected value
B.1 and B.2	Concentricity tolerance of studs	0.1	0.3
	Position tolerance of stud housings on the LC	0.2	0.6 with MMC
	Dimensional tolerance of stud housings on the LC	+0.1 -0.05	+0.2 -0.1
	Dimensional tolerance of stud threaded seats on the LC	0.2	0.2 with MMC

After these corrective actions, the simulation shows the fulfilment of the functional targets (i.e., capability value of $\pm 3\sigma$) for both the bushings and the studs. This result is also due to the introduction of the Maximum Material Condition (MMC) and the relaxing of the tolerance ranges for the stud-related tolerances.

As a result, thanks to the CAT-based modelling approach the simulation of the engine block assembly operations gives a clear understanding of the assembly performance, providing corrective actions to meet the expected requirements. In particular, thanks to the sensitivity analysis and the analysis of the contributors to variation, this Computer-Aided approach provides important elements to identify the most influential tolerances and reference elements, with respect to the functional requirements of the case study. In this way, the tolerance design of the engine block assembly components is checked and validated.

3.4 Phase 3: PCM-based modelling approach

As underlined during the description of the proposed methodology, the fulcrum of the approach for tolerance design optimization is the application of Computer-Aided tools: in addition to the consolidated use of CAD software, the introduction of CAT software and the corresponding modelling approach is essential to enable advanced tolerance simulation and analysis. However, the only way to consider the impact of tolerances on production costs, in addition to their effect on functionality, is through the implementation of manufacturing cost estimation tools, the PCM software. Therefore, to exploit the model-based approach and enable an effective integration between the tools (described in detail in the next section), a PCM-based approach is structured to formalize the simulation procedure: this could be of particular interest since PCM tools are relatively new and their modelling practice is not yet systematically defined or standardized. In this way, PCM industrial implementation can be enhanced, supporting engineers during the modelling of manufacturing cost estimations of complex industrial products. As previously remarked, there are several PCM tools and their structure can differ significantly (see chapter 1, section 1.3.2). However, since the aim is to assess a model-based approach for cost estimation, starting from the 3D CAD model geometry, the modelling structure focuses on the ACE typology.

The proposed modelling procedure comprises several steps, reported in Figure 36: these steps are addressed in a hierarchical order, following a general and model-based approach. Depending on the specific software and the data already provided in the 3D CAD models (e.g., PMI, material specifications, etc.), some of these steps may be manually or automatically executed by the software and, in some cases, differently located. This also applies to product tolerances, which can be imported directly from 3D models when they are addressed as PMI or manually selected within the PCM modelling environment. In addition, as with most ACE PCM software, the cost estimation for multi-component products requires first modelling (and costing) each component. Then, a similar procedure is repeated for the whole assembly, automatically recognizing the previous individual estimations. The proposed framework reflects this approach: except for the first phase, the subsequent phases are divided into Component and Assembly modelling.

- *Import component* - The first phase consists in import all components and assembly into the PCM environment. As highlighted, the more 3D models are addressed with manufacturing specifications, the more the next steps can be provided automatically.

- *Production process* – Once the components have been imported, the main production technology must be chosen for each of them. In some PCM tools (i.e., the present research work uses aPriori®

as a reference tool) the selection of the primary process group is done manually by the operator, as it affects the following phase of material and secondary process selection.

- *Product material* – The material is selected for each component. In general, PCM tools have material databases, from which the proper material group is identified. Then, it is possible to compare the properties of the available materials and select the most suitable. In most cases, the software automatically excludes unavailable materials depending on the primary production process selected in the previous step. In addition, most PCM tools allow for material customization: it is possible to create new materials with custom properties (especially useful with build-in materials).

- *Product tolerances* – Not all PCM software allow manual entry of product tolerances, but ACE PCMs, based on 3D CAD models, enable tolerance selection: since their estimation comes from the component geometry and features, manufacturing tolerances can be addressed and considered during cost calculation. If semantic tolerances have already been entered in the 3D models, they can be directly imported from the CAD, otherwise they can be inserted manually.

- *Production parameters* – Once the main process group has been selected, additional process information can be set. In particular, as with most PCMs, the manufacturing plant location can be selected: in this way, the software identifies the cost factors relating to the specific area (corresponding to different built-in databases and libraries). In addition, process-related parameters can be set and, if needed, customized: process capability, machine selection and parameters (e.g., machine overhead time cost, times to set up the batch, parts orientation).

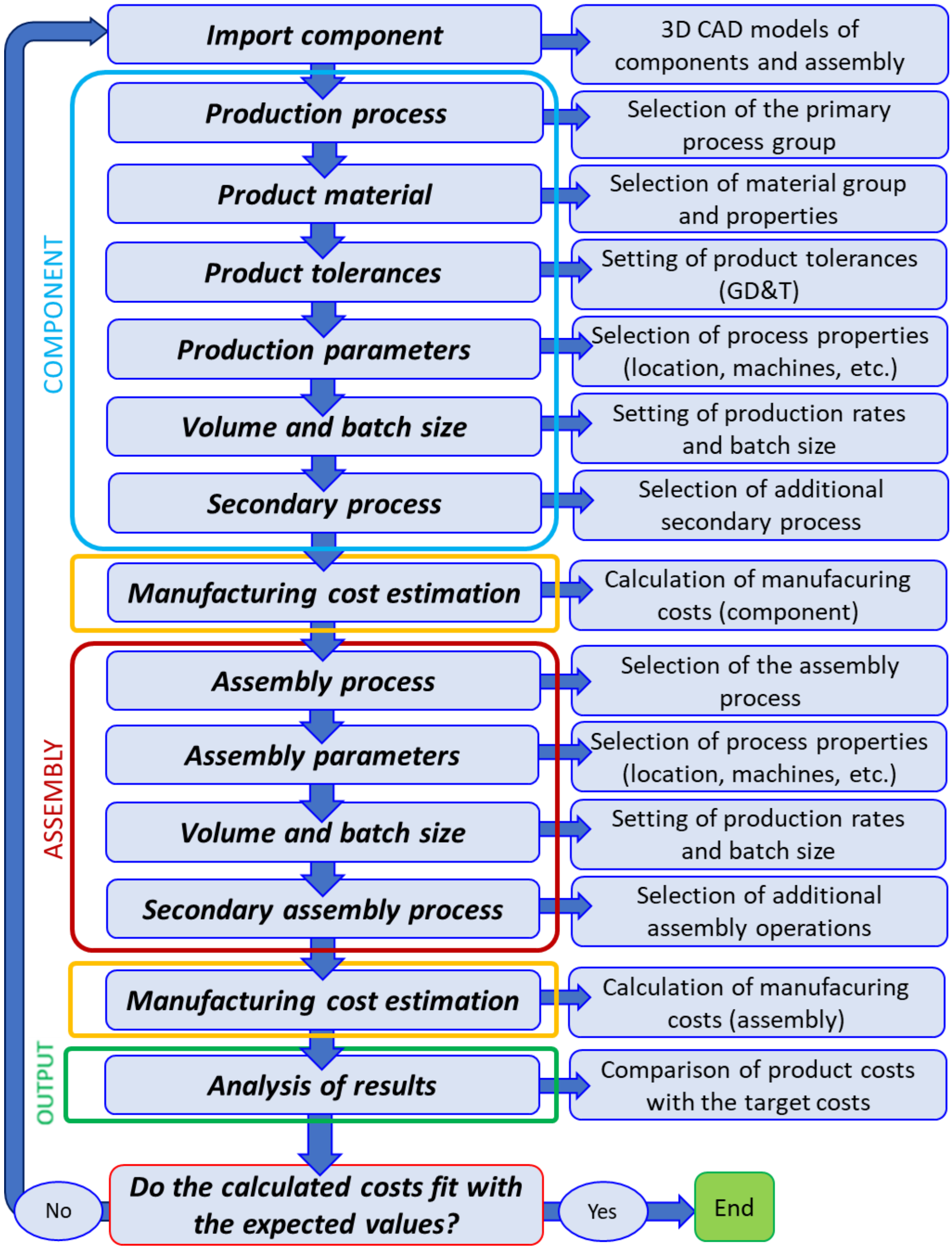


Figure 36. PCM-based modelling approach

- *Volume and batch size* – The dimensions and number of the batch have to be defined, as well as the total or annual production volumes. This affects how production cost drivers are distributed across each manufactured component and, consequently, the final price.

- *Secondary process* – If necessary, additional manufacturing processes can be added. Most of the time PCM tools, starting from the component geometry and the primary process group, automatically provide the sequence of operations and add additional processes to obtain the final geometry and specifications. However, in some cases, the user can manually add secondary processes, such as machining operations, thermal treatments, etc. Also for these processes, it is possible to set and customize several parameters.

- *Manufacturing cost estimation* – Once the above parameters and settings have been defined, the software performs the cost estimation providing the cost of the component in terms of total variable cost, piece part cost, amortized investments etc. In general, each cost factor is shown with information about its source: material, labour, overhead, logistics, machining operation etc. This phase completes the modelling of the component: once repeated for all components, it is possible to move to the assembly modelling.

- *Assembly process* – Once imported into the PCM environment, the assembly sequence and contact areas of the components are automatically evaluated from the 3D models. Then, as with the individual components, the assembly must also be provided with the selection of the assembly process. Most PCMs automatically calculate the type of assembly process and operation based on the assembly and its components. However, the user can manually select the most suitable process, among those available (generally some of them are automatically excluded by the software): in general, pick and place, bolding, sealing, bolting welding, riveting etc.

- *Assembly parameters* – The setting of the assembly parameters is related to the specific assembly process and operations: in some cases, it is necessary to select the areas (features, orientation etc.) in which to apply the specific joints (e.g., for welding operation, the identification of welding lines on components geometry).

- *Volume and batch size* – The batch size and the total or annual production volumes must also be assigned for the assembly. Most of the time this consists of the same production rate of the components, but in some cases it can be different (when considering components used for different products).

- *Secondary process* – If required, additional assembly processes can be added, depending on the primary assembly process selected: cleaning processes, inspection processes, etc.

- *Manufacturing cost estimation* – Once the assembly process modelling has been defined, the manufacturing cost estimation is executed and the assembly cost is provided. As for the components, the product cost is described showing each cost factor: in this case, among these factors, the cost of the individual components of the assembly is reported, to identify the most expensive operations, geometries, etc.

- *Analysis of results* - After running the cost estimation, the results are analysed and compared with the economic targets. The cost of each component is analysed, as well as the total production cost of

the product. If the economic targets are met, the product design and the manufacturing process are validated.
Conversely, if the objectives are not achieved, there are mainly two options, depending on the gap to be recovered. When the difference with respect to the target cost is small, corrective actions can be made to some production parameters, specific geometric parameters or specifications, i.e., the product tolerances. Otherwise, more substantial actions must be provided on product/process design, changing the overall product geometry, manufacturing process or materials. In this work, since the methodology is focused on optimizing the tolerance design, corrective actions are provided to reduce manufacturing costs through modifications to the tolerance values and, if necessary, to the types of GD&T and the DRF scheme.

General mechanical assembly

The formalization of the PCM modelling procedure allows for easier implementation of these tools for product design. However, before applying this methodology to complex industrial products, a simple case study has been considered. For all the implementations reported in this research work, the ACE software aPriori® (developed by aPriori®) has been adopted among the PCM tools mentioned above. This software has been chosen for its completeness, in particular in terms of model-based capabilities: it allows both a detailed analysis of the model geometry and the reading of semantic tolerances. In addition, it covers a wide range of manufacturing processes and materials thanks to its detailed libraries and databases. During the research work, it has been applied in conjunction with both Catia V5® software by Dassault Systèmes® and CREO Parametric® 4.0 software by PTC® CAD: in particular, both the case studies for the PCM-based methodology have been implemented within Catia V5®.
For this purpose, to assess the PCM-based modelling approach before its implementation in the industrial case study, it has been firstly applied concerning the general mechanical assembly (Figure 37), already introduced in section 3.2 for the CAD-based tolerance specification and annotation assessment: please refer to this section for the functional and assembly sequence analysis, as well as for the definition of DRFs and GD&T schemes.

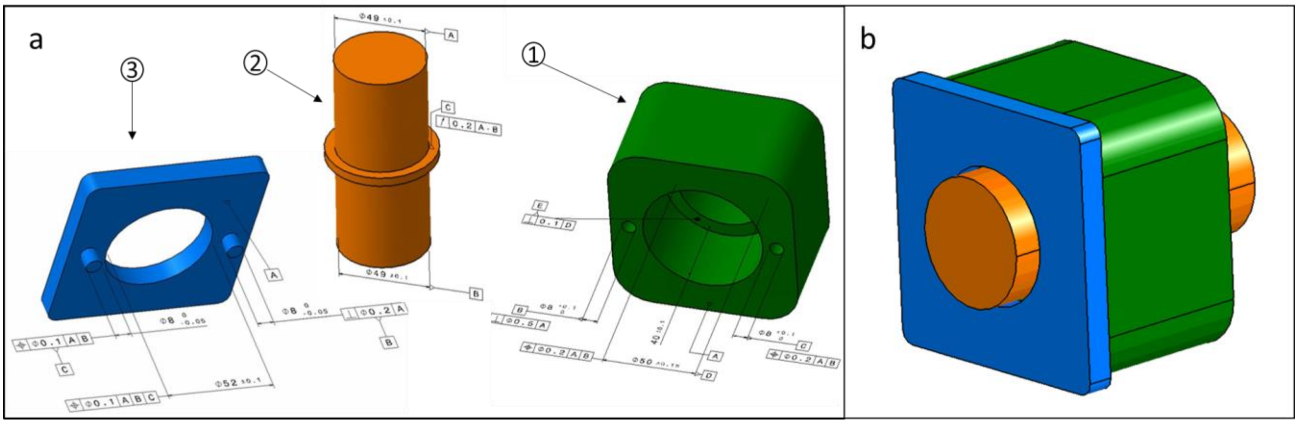


Figure 37. General mechanical assembly: a. GD&T specification; b Assembly

- *Import component* - All components and assembly are imported into the PCM environment.

- *Production process* – The main process group is selected for each component: casting-die process for both the support and the plate, stock machining for the shaft.

- *Product material* – The material is selected for each component: ANSI 6012 aluminium alloy for the support and the plate, ANSI 1008 alloy steel - cold worked for the shaft.

- *Product tolerances* – Since the GD&T scheme and specification have already been introduced within the 3D models as PMI, the modelling procedure for cost estimation consists in automatically reading the tolerances instead of entering them manually in the PCM environment. For aPriori®, the product tolerances are grouped in the Geometrical Cost Driver (GCD) relations, through which the software identifies the features that require additional machining operations to achieve the required specifications.

- *Production parameters* – Considering the general intent of this first case study and the simplicity of its geometry, only the manufacturing plant location has been selected (i.e., aPriori® VPE), considering the production located in western Europe: once selected, the software automatically identifies the corresponding cost factors.

- *Volume and batch size* – In this case a small production rate is considered, with 3.000 units per year, considering a total production of 2 years. The same production rate is selected for all components and the assembly.

- *Secondary process* – Thanks to the simple model, no additional processes are manually selected. Instead, the software automatically provides additional processes based on the geometry and specifications of the components.

- *Manufacturing cost estimation* – The estimation of the manufacturing cost for each component is performed, with resulting costs of € 6.23 for the support, € 12.17 for the shaft and € 2.74 for the plate, as reported in Figure 38.

- *Assembly process* – According to the assembly sequence and the geometries of the components, in this case the assembly process consists of simple pick and place operations. For most complex case studies, such as the V12 assembly used for CAT simulation, the fixture components must be included and modelled correctly. The software automatically calculates the assembly process by identifying the mating surfaces and joint types.

- *Assembly parameters* – In this case, as with the individual components, only the manufacturing plant location has been selected as western Europe.

- *Volume and batch size* – As already highlighted, the same production rate is considered for the whole product, i.e., 3.000 units per year and 2 years of total production.

- *Secondary process* – No additional processes are manually selected.

- *Manufacturing cost estimation* – By calculating the assembly process and the aforementioned parameters, the manufacturing cost estimation for the assembly provides a cost of the assembly operations of € 0.47 for each assembly, as reported in Figure 39.

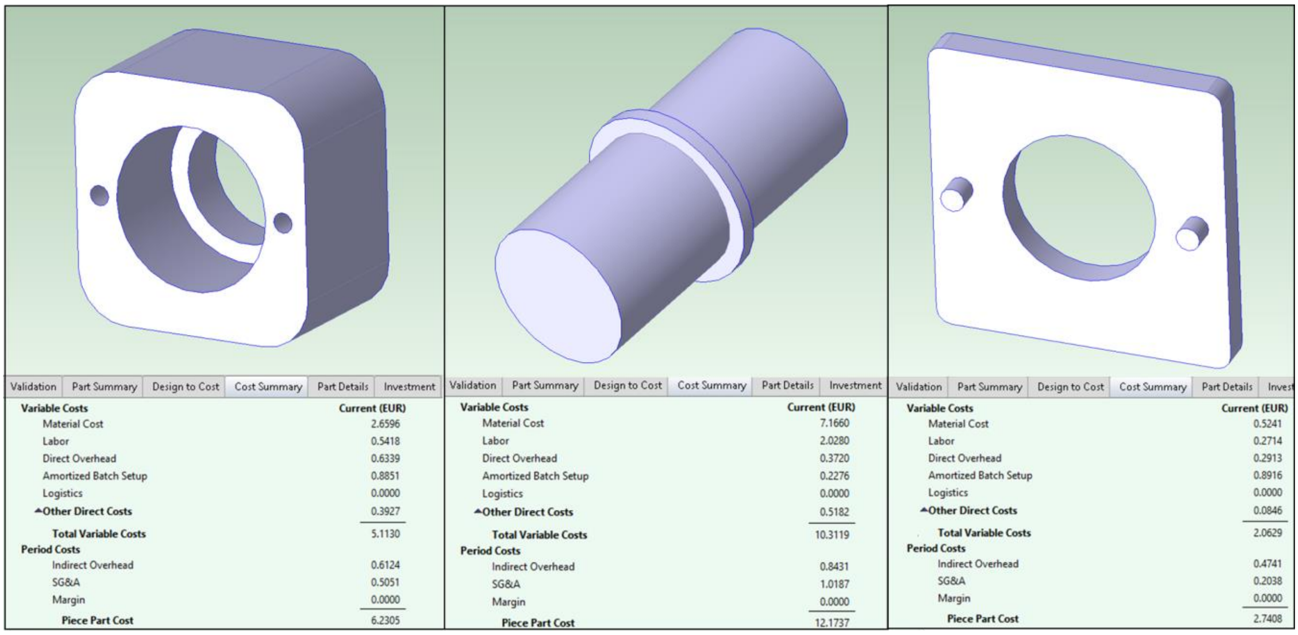


Figure 38. Component-level manufacturing cost estimation

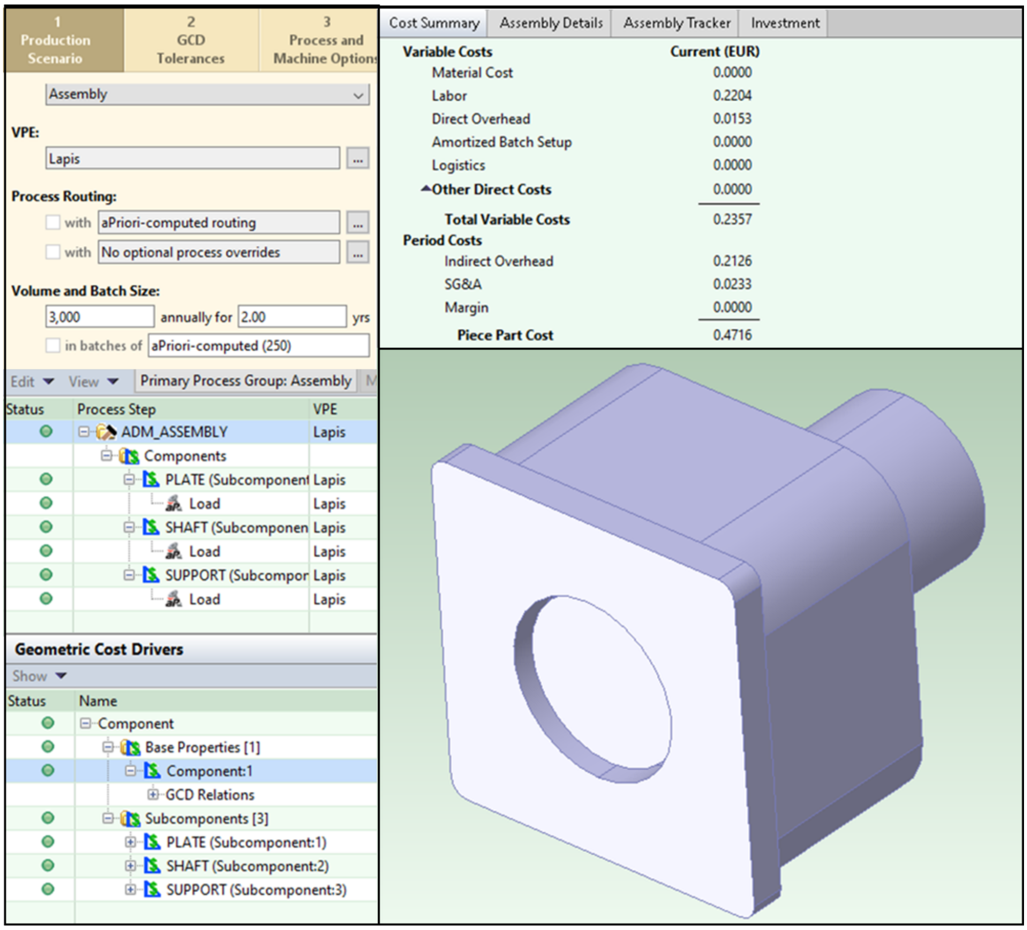


Figure 39. Assembly-level manufacturing cost estimation

- *Analysis of results* – The cost estimation for the whole assembly provides a total cost of € 21.61. Considering the aim of this case study, i.e., the assessment of the PCM-based modelling approach, no cost target is provided. However, to verify the ability of the system to react to variation of tolerances, all tolerances values on the support are relaxed by 30 % from the starting configuration. The new calculation provides a cost reduction for the support of 18.9 %: from the original value of € 6.23 to the final value of € 5.05 (a variation of € -1.18), as reported in Figure 40. Since the assembly process is not affected by the variation of the tolerance values of the support (the same happens for the other components), the total product cost is reduced by the same amount, moving from the initial € 21.14 to the final € 20.43.

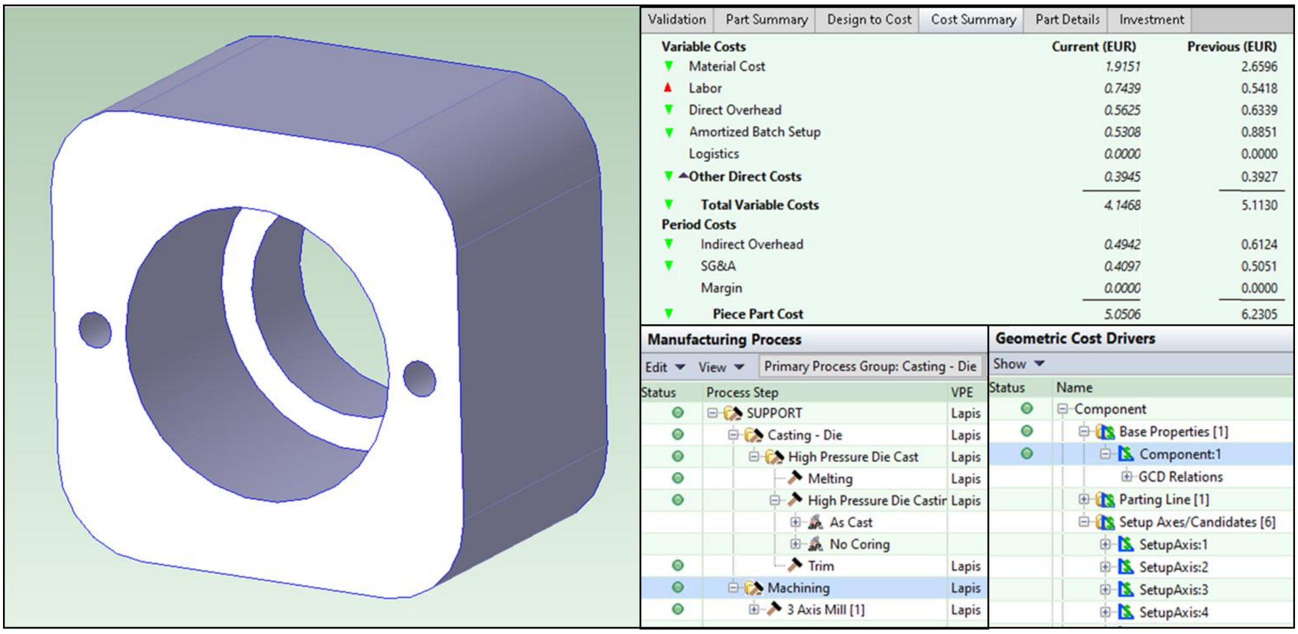


Figure 40. Cost reduction of the support (relaxation of tolerances)

As a result, the PCM-based cost estimation modelling procedure can provide tolerance effects on manufacturing costs. Therefore, it can be effectively applied to more complex industrial case studies and it is suitable for the next phase of integration with CAT tools for tolerance-cost optimization.

3.5 Phase 4: Tolerance-Cost Optimization (MDO)

The previous sections have provided the specific modelling approach for each main step of the proposed methodology: tolerance specification, CAT simulation, and PCM cost estimation. For each of them, the application on different case studies has led to the assessment of the modelling procedure, confirming the advantages of a model-based design approach through the use of advanced Computer-Aided simulations.

The last step of the methodology consists of the integration of the described approaches and tools in an integrated environment, enabling the tolerance-cost multi-disciplinary optimization. This means, starting from the general structure addressed by the literature (described in detail in the first chapter), converting each theoretical phase into a practical action (Figure 41).

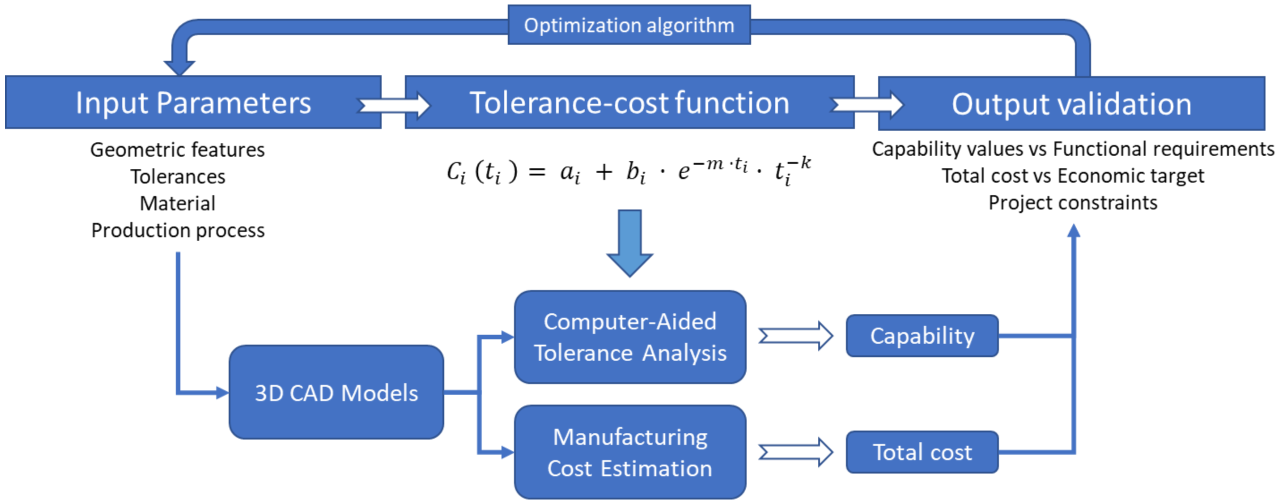


Figure 41. Tolerance-cost optimization generalized workflow

For this reason, it is necessary to assess two main tasks: to identify the proper strategy for the integration between CAT and PCM simulation models and for linking their data (input and output); develop the multi-disciplinary optimization structure, through the integration of tools to allow the automatic sharing and updating of tolerance information and the definition of the optimization strategy. Both of these tasks are critical for the achievement of the proposed methodology.

3.5.1 CAT-PCM software integration through MDO

Firstly, the CAT and PCM models are thoroughly analysed to identify both the file format and the main structure of the simulation models, and the typology and representation of the input/output data.

- *CAT software* - According to the literature and with respect to the main CAT software, the representation models commonly adopted are the EXPRESS model (established by the ISO for the implementation of tolerance information in computer systems) and the XML (extensive markup language) (Qin et al., 2018). Therefore, most CAT tools provide models according to these languages, through a model structure in which the tolerance schema of the product is provided in an object-oriented way (Zhao et al., 2006; Sarigecili et al., 2014): in particular, XML uses the tolerance information in CAD models to instantiate the schema. For both, the model is scripted within a tree structure, following the modelling procedure. The tolerance information is reported for each component section of the tree, with specific strings reported: associated feature, reference feature (DRF), tolerance type, nominal dimension, tolerance values (depending on the tolerance type, upper and lower limits for dimensional tolerances or single values for geometric tolerances), additional specifications (e.g., diametral tolerance zone, material modifiers, etc.), distribution type and parameters. The same happens for all modelling parameters, in particular for assembly joints and functional measurements. Finally, CAT simulation results are reported in the file structure following the same approach: for each measurement, capability indices (cp, cpk, σ, etc.) types and values, contributors list of tolerances and variance percentage values, etc. As for Cetol $\mathbf{6\sigma}$®, its structure corresponds to this general description, providing an XML-based model simulation file with a .cxm extension.

- *PCM software* – As with CAT, PCM ACE tools also start from 3D models, but their model structure is different from other simulation tools. As reported by the literature and the main PCM software developers, the model information in terms of cost estimation refers to built-in databases and libraries, from which the software automatically selects the most suitable and least expensive configuration (Ehlhardt, 2014). For this reason, in most PCMs (aPriori® included) the manufacturing model is represented by tables and spreadsheets on which, for each component, the corresponding commands for each model parameter are given and reported. The same happens for both the assembly and the components, providing all the model information in these spreadsheets and XML reports. In addition, the customization of the material and processes is generally related to the corresponding spreadsheets that can be imported into the software environment. Finally, cost estimation outputs are associated with CAD models by simulation spreadsheet and XML reports to be exported for post-processing or reporting operations. In the case of aPriori®, this modelling and structure logic is provided by an internal “watchpoint” mechanism, from which to generate spreadsheet (.xlsx) and XML reports. These are then populated with variable and attribute values during the modelling and estimation process.

As described, CAT and PCM software have different modelling procedures and structures. However, concerning product tolerances and specifications, both software require 3D models as a starting point, from which to import the component geometry (Figure 42): if semantic annotations are available, these too are imported and read automatically (covered in detail in the next subsection). This means that a simulation model is always provided: for the CAT model it consists of the .cxm file of the product (components and assembly) while for the PCM in the model spreadsheets, both for components and assembly. On the opposite, these models provide output file reports at the end of each simulation, in which the simulation results are reported with respect to product targets and requirements: this means respectively capability values for CAT and product costs for PCM, respectively. Once simulated, these outputs are analysed with respect to the functional and economic requirements of the product: for each configuration, the combined simulations must be repeated iteratively to identify the most suitable and cost-effective tolerance design configurations to achieve the targets.

Therefore, starting from a starting configuration of tolerances, an optimization algorithm is used to further investigate the design space to solve a multi-objective problem: the optimization problem is subject to design constraints, due to technological, functional, and economical requirements on parts and their manufacturing process (e.g., interference or gap between parts, dimensional and geometrical conditions, etc.). As a result, this constrained optimization identifies a feasibility region of the design space which contains all tolerance values capable of both meeting the optimization objectives and satisfying the design constraints.

To enable the tolerance-cost optimization and provide all the optimization capabilities required for the problem, the integration of CAT and PCM simulations must be developed in a multi-disciplinary environment, in which the connections between the software can be easily structured, and the design variables, objectives and constraints can be modelled effectively.

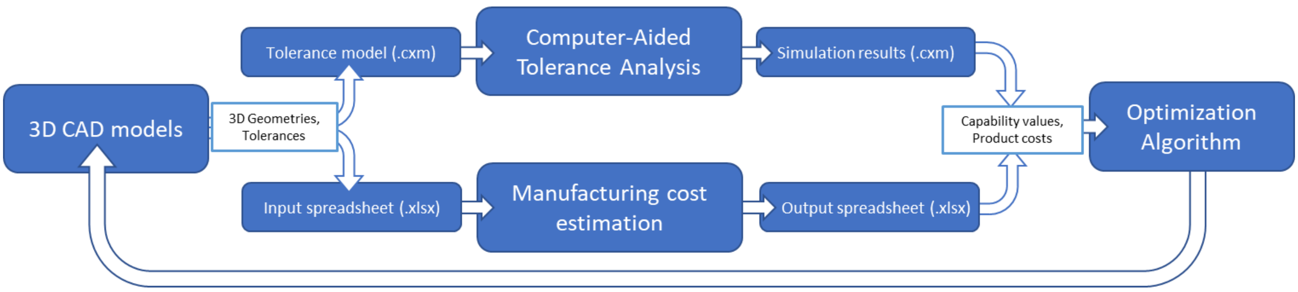


Figure 42. MDO input-output relations and data exchange

For this reason, the formalization of the methodology has been implemented within a Multi-Disciplinary Optimization (MDO) Platform. As briefly described in the first chapter, MDO platforms are very interesting for the development of multi-objective design optimization of systems, thanks to the integration of tools and advanced optimization capabilities. However, they are relatively new and most of their industrial applications focus on CAE simulation. Therefore, since MDO platforms still do not relate to CAT and PCM tools and they are not yet implemented for tolerance-cost optimization, the integration between CAT and PCM within the MDO environment must be fully defined and developed.

Among the MDO platforms available in the market, the modeFRONTIER® platform by Esteco© has been selected for the present work. As with most MDO platforms, its modelling environment is based on the use of nodes, from which the optimization structure and integration between tools are defined: each software file can be imported as a node into the environment and linked as convenient, introducing several nodes for variables and rules (also mathematical expressions) and defining objective values and constraints. Once the overall structure is modelled, the objective can be set as an optimization target. Finally, the optimization setting closes the model through the selection of the numerical method and algorithm for the optimization, including the Design of Experiments (DOE) definition, starting and ending conditions, iteration options etc.

Simplified engine assembly

The first implementation of the methodology aims to provide the preliminary structure of the tolerance-cost MDO environment. Focusing on the integration between CAT and PCM models, a simple model has been selected as a case study: an archetypal model belonging to an automotive engine assembly.

The original engine assembly (the V12 engine already introduced in section 3.3) is composed of a large number of components: the main components are the engine block (upper and lower crankcase), the cylinder heads, and the crankshaft. In addition, the assembly is completed by bearings, thrust washers, gaskets, and all fixture elements, i.e., the bushings and the studs.

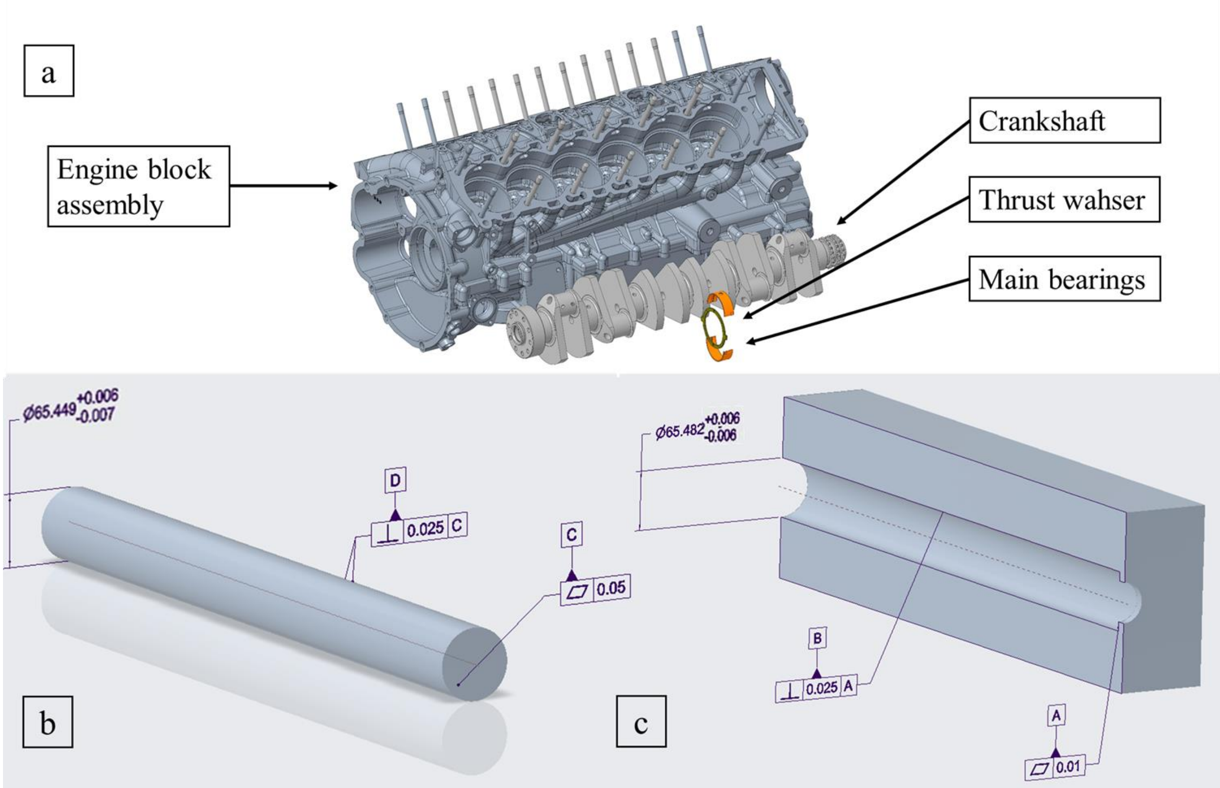


Figure 43. V12 engine assembly: a. original CAD models; b. simplified crankshaft; c. simplified engine block (section view)

With respect to the original model, the functional requirement to be optimized is the assembly of the crankshaft with the engine block to verify the functional radial gap between the crankshaft and the journal bearings. Therefore, focusing on the engine block-crankshaft assembly, all other components not involved in the tolerance stack-up are useless: only CAD models of the engine block, crankshaft, bearings, and thrust washer are required for the analysis (Figure 43). In addition, to abstract the case study and generalize this preliminary work, the components involved have been simplified with the integration of the bushings and the thrust washer in the engine block. For the same reason, the geometry of the main parts has been generalized to have only the functional features involved in the tolerance stack-up, i.e., the surfaces necessary for the assembly.

Considering the functional condition of the assembly, the target to be verified is the absence of interference between the crankshaft and the journal bushings. Consequently, the functional dimension to be controlled is the radial distance, which has been referred to as gap ≥ 0. Regarding the verification of the functional requirement, the process capability index C_{pk} is selected as the drive parameter for the optimization (Pyzdek and Keller, 2014), with a lower threshold value set to $C_{pk} = 1$.

Model definition

The integrated optimization model is developed to address the main steps of the Computer-Aided Integrated Approach for Tolerance-Cost Optimization, as illustrated in section 3.1. For this reason, the simplified model is analysed following this order, to enable the most suitable definition of the MDO structure.

- *3D modelling and annotation* - The first step of the model definition begins within the CAD software, in this case CREO Parametric® 4.0 by PTC®. The modelling of the simplified components (Fig. 2b and 2c) and the functional analysis are performed, as well as the definition of the assembly sequence. The position of the engine block is fixed and the other elements of the engine assembly are located with respect to it: it defines the position of the crankshaft by means of the journal bushings and the thrust washer. The functional elements of the coupling are the reference plane (which axially guides the crankshaft) and the main journal axis. These features are classified as DRFs: the reference plane is Datum A and the cylindrical surface (which defines the journal axis) is Datum B. Then, both dimensional and geometric tolerances are included in the model. However, given the high impact of 3D geometric deviations on the interface between the components and their relative positioning, the optimization focuses on the geometric tolerance of perpendicularity of Datum B with respect to Datum A, both for the engine block and for the crankshaft (for this part it is between Datum C, locating shoulder surface, and Datum D, rotational axis). Since the CAD software allows 3D semantic tolerance annotation through the GD&T Tolerances tool, the DRFs and tolerances are defined directly in the CAD environment: 0.025 mm is chosen as starting value for both the perpendicularity tolerances.

- *Computer-Aided tolerance analysis* – Tolerance analysis is performed on Cetol $\mathbf{6\sigma}$®. The 3D parts and assembly are imported into the CAT environment with their dimensions, geometric features, and GD&T specifications. Subsequent steps are required to set up the tolerance model, such as defining the kinematic joints and setting the tolerance distribution type, which has been assumed normal and centered. The functional gap between the crankshaft and the journal bushings (here the engine block cylindrical surface is assumed) must range from 0 to 0.025 mm: to analyse the area with maximum deviation the section opposite the reference plane is chosen as functional measurement. The results of the first simulation are shown in Figure 44. The standard deviation is ±1.06σ, relative to a C_{pk} value of 0.2578 and corresponding to the 70.96% of acceptable components: this first result is far from the target value of $C_{pk} \geq 1$, where $C_{pk} = 1$ means a value of ±3σ and a process Yield of 99.73%. Nevertheless, the sensitivity analysis confirms the perpendicularity tolerance as the main contributor to the functional gap.

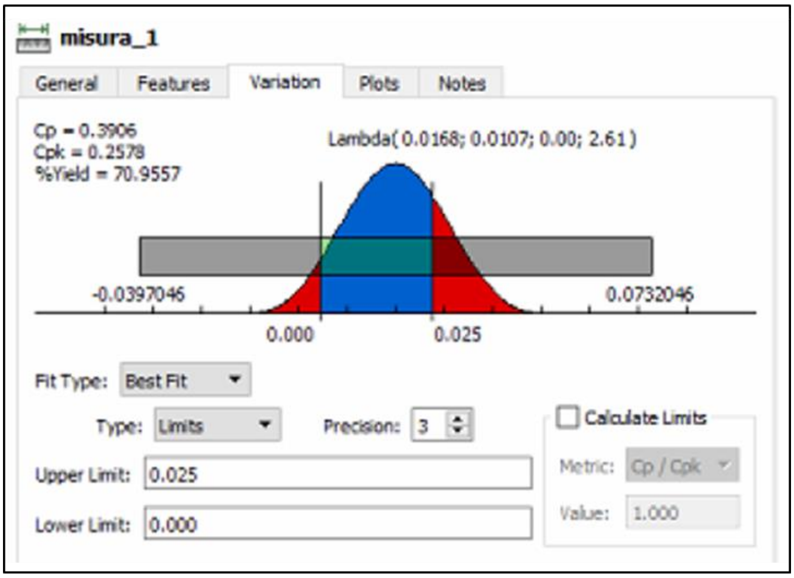


Figure 44. Tolerance stack-up simulation results

- *Manufacturing cost estimation* – Cost evaluation is performed with aPriori®. Following the PCM-based modelling approach, the components are imported into the software and their primary process and material parameters are specified: die casting and ANSI 6012 Aluminium Alloy for the engine block; machining operations and AISI 4140H Alloy Steel for the crankshaft. For both models, GD&T semantic annotations are imported as manufacturing tolerances. The volume and batch size are set as 5.500 annual units for 5 years, as well as the plant location is set in the US. The same options are assigned to the assembly model. The cost estimation for the starting tolerance configuration returns a total assembly cost of $ 429.74: $ 329.83 for the engine block, $ 97.50 for the crankshaft, and $ 2.14 for the assembly operations.

MDO framework setup

Once completed, the tolerance model and the cost model are connected to the MDO platform and the integration is set up according to the hierarchical order of the method, as reported in Figure 45.

- *Optimization variables* - Due to their central role, product tolerances are the first to be introduced in the MDO platform: the two perpendicularity tolerances (of engine block and crankshaft) are inserted as input variables (highlighted in orange in the Figure), called “OrthoA” and “OrthoC”, with the values set in the CAD model.

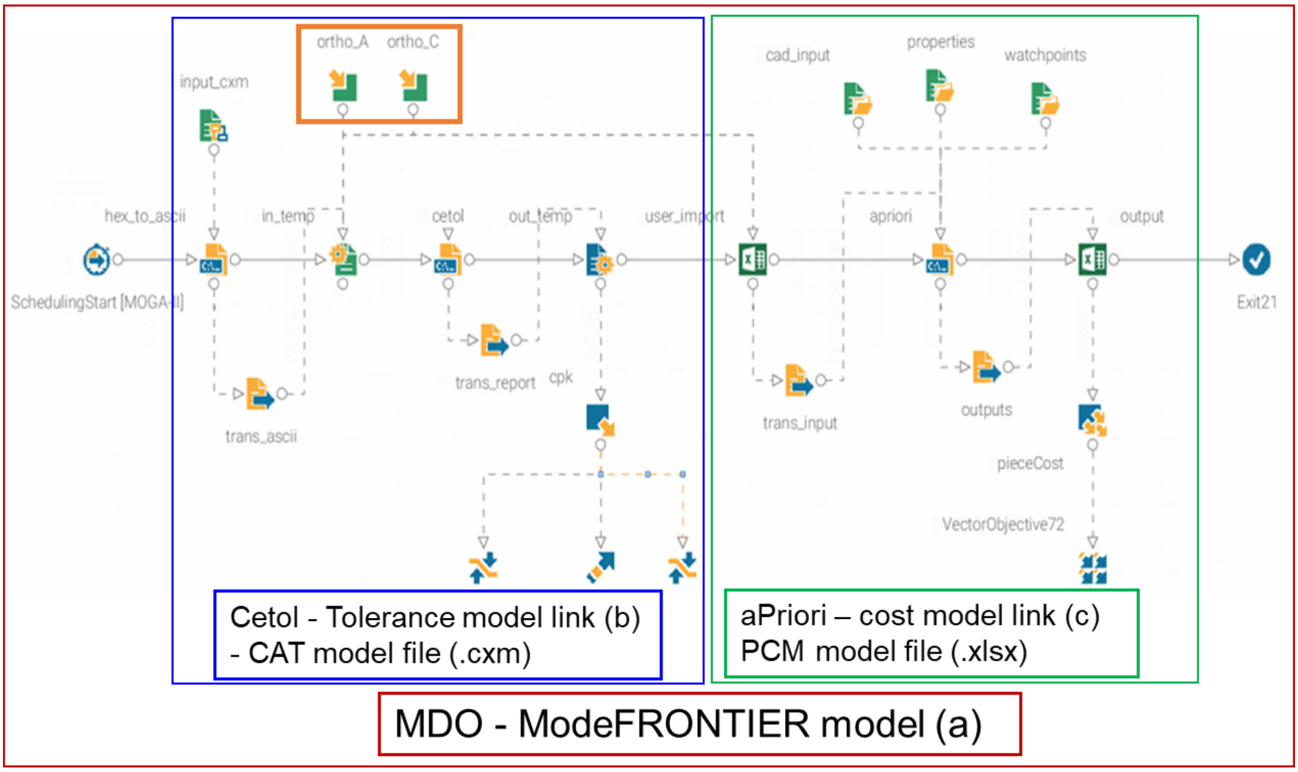


Figure 45. Tolerance-cost optimization model

- *CAT Tolerance analysis* - The CAT nodes are structured in the workflow (highlighted in blue in the Figure): differently from the built-in nodes for several software (CAD, CAE etc.), the CAT software requires as many nodes as the step required to address all the needed information. First, the CAT model (.cxm) is imported into MF as an input file: an additional transfer node allows MF to read the data from the Cetol input file. Then, an "input template" node associates the variables "OrthoA" and "OrthoC": this means entering the .cxm file and linking the simulation variables with the corresponding lines of code of the tolerance values. Subsequent nodes allow the simulations to run in "batch mode" (i.e., the MDO platform automatically executes tolerance and cost simulation), uploading the input parameters at each step. The last nodes manage the output variables of the CAT simulation: in this case, the C_{pk} value is extracted from the output file (.cmx) obtained from the simulation and then associated with the corresponding nodes of the functional objective (maximize C_{pk}) and with the constraints ($0.5 \leq C_{pk} \leq 5$).

- *PCM Cost estimation* – The nodes addressed to structure the cost estimation (highlighted in green in the Figure) reflect the differences between the PCM and the CAT models. First, the input spreadsheet file (.xslx) is imported into MF to integrate the cost simulation model with the optimization variables. Then, this node is connected to the next node, from which to set the simulation in "batch mode": in this way, the input variables within the cost model are constantly updated at each iteration. In the case of aPriori®, additional files are required to provide the cost estimation properties as well as the 3D CAD models (assembly, engine block and crankshaft). The system is now able to perform cost estimation. Finally, the output node is provided with the output spreadsheet file (.xslx) generated from the simulation of the first configuration: in this way it is possible to select and extract the output variables, i.e., the total cost, then associated with the objective node (i.e., in this case, the minimization of the total production cost).

Once the structure for CAT-PCM integration has been modelled, the final step comprises the selection of the optimization algorithm and rules, as well as the DOE algorithm type for self-iterative calculation. In general, MDO platforms allow to select different algorithms, providing a wide range of optimization strategies. The identification of the most suitable strategy strongly depends on the specific optimization problem: in the case of multi-objective optimization, the general practice is to start from the generation of DOE sampling points, from which an evolutionary algorithm further investigates the design space.

Since this preliminary work aims to set up the environment structure rather than execute advanced optimizations (object of the following case study), a simple strategy is adopted for the current case study: two separate optimizations have been performed, both 50 iterations. Two DOE strategies are considered to evaluate the experimental strategies: the deterministic algorithm Sobol DOE (Sbl-DOE), based on quasi-random low-discrepancy sequences and belonging to the group of global sensitivity analysis methods (Dimov and Georgieva, 2010), and the Random DOE algorithm (Rnd-DOE), based on the mathematical theory of random number generation (Wang et al., 2020). For both, the Multi-Objective Genetic Algorithm MOGA-II, belonging to the stochastic methods group, is chosen as the optimization algorithm (Zolpakar et al., 2020).

Optimization results

The optimization results (Figure 46) are analysed by comparing the economical and functional targets of each simulated configuration. These are divided into two groups: the green lines are the feasible configurations, which have achieved the objectives; the yellow lines are the unfeasible configurations, with values below the imposed limits.

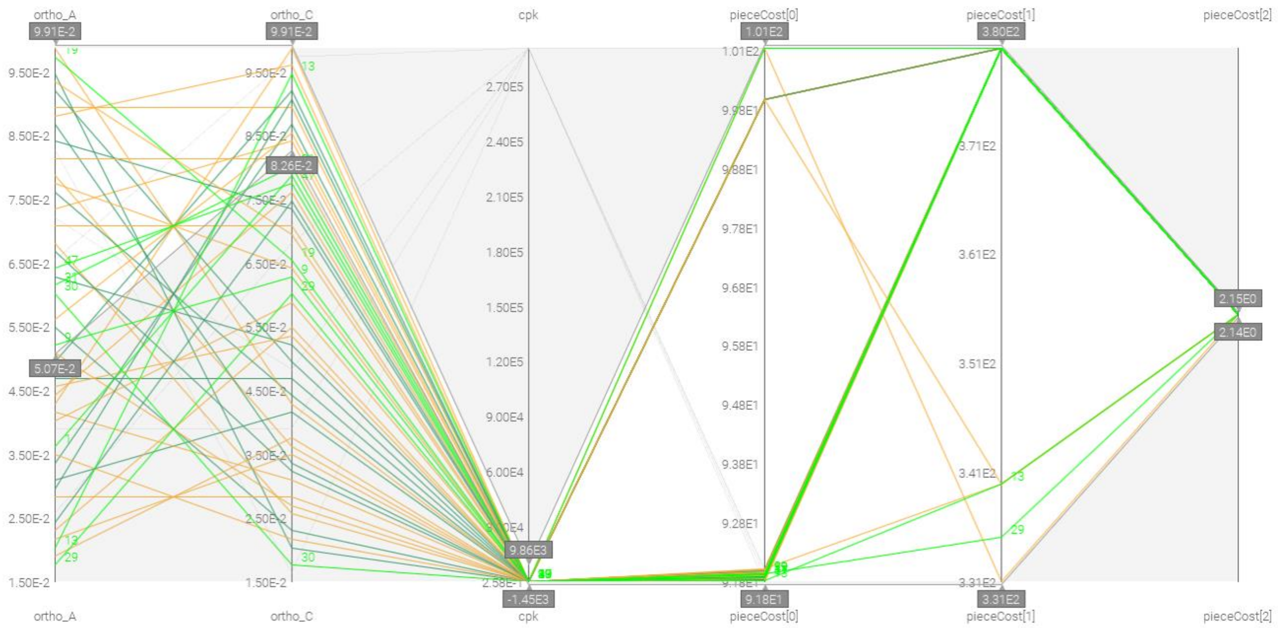


Figure 46. Optimization results

Considering the total number of 100 tolerance configurations, 20 and 23 feasible configurations are identified for Sbl-DOE and Rnd-DOE, respectively. Among these, the optimal configurations with C_{pk} value close to the target ($C_{pk} = 1$) are, respectively for the two groups, 2 and 7, reported in Table 3.

Table 3. Selected configurations close to the design targets: optimal configuration #13

N°	DOE algorithm	ortho_A	ortho_C	C_{pk}	Cost shaft	Cost block	Cost ass_op
13	Sbl-DOE	0.02	0.095	1.057	91.856	339.762	2.14
30	Sbl-DOE	0.06	0.018	1.057	100.874	379.671	2.14
1	Rnd-DOE	0.033	0.043	1.057	92.038	339.762	2.14
9	Rnd-DOE	0.047	0.027	1.057	100.010	339.762	2.14
15	Rnd-DOE	0.068	0.031	1.057	100.008	379.671	2.14
19	Rnd-DOE	0.049	0.033	1.057	100.007	339.762	2.14
29	Rnd-DOE	0.058	0.057	1.057	91.99	379.671	2.14
31	Rnd-DOE	0.076	0.097	1.057	91.849	379.671	2.14
47	Rnd-DOE	0.064	0.077	1.057	91.917	379.671	2.14

The best result is achieved by the configuration n°13 Sbl-DOE, with the optimal value of $C_{pk} = 1.057$ and the lowest production cost. In fact, with this configuration the perpendicularity tolerance has been reduced from 0.025 mm to 0.02 mm for the engine block, and relaxed for the crankshaft, from 0.025 mm to 0.095 mm. Consequently, compared to the initial cost of components, the cost of the engine block is increased by $ 10 while the cost of the crankshaft is reduced by $ 6. As an example, for other configurations the engine block costs $ 40 more. As a result, the overall cost of assembly, considering assembly operations, is increased by $ 4, 29, from $ 429, 47 to $ 433, 76, as reported in Table 4.

Table 4. Cost simulation output: comparison between initial values and optimized solution (#13)

	Initial cost	Optimized cost #13	Variation
Engine block	$ 329.82	$ 339.76	+ $ 9.94
Crankshaft	$ 97.51	$ 91.86	- $ 5.65
Assembly operations	$ 2.14	$ 2.14	$ 0
Total cost	$ 429.47	$ 433.76	+ $ 4.29
Annual cost (5500 units/year)	$ 2362085	$ 2385680	+ $ 23.6
Annual Scraps cost (5500 units)	$ 685863	$ 6506	- $ 679357
Total production cost (5 years)	$ 15239740	$ 11960930	- $ 3278810

Nevertheless, this increase in costs is largely offset by the huge reduction in the number of rejected components: compared to the starting condition, the reject rate is reduced from the 29.04% to the 0.27%, which means a process fallout of 2700 DPMO (defects per million opportunities), rather than the starting value of 290400 DPMO. This reduction means, over one year of production (5500 units per year) and considering a reject cost equal to the total assembly cost, a reduction of rejected parts of 1582 units, with a consequent cost reduction of $ 679357. As a result, through the integrated model it has been possible to find the optimal configuration to satisfy the functional requirements with the lowest increase of cost. In fact, compared to the CAT simulation alone, the integration with the cost evaluation has allowed to select from the set the best solution that respects the capability target ($C_{pk} \geq 1$).

3.5.2 MDO assessment through PMI integration

The previous subsection has provided the main structure of the MDO, achieving the integration between the CAT and PCM simulation models through the identification of the proper optimization strategy. The simplified case study has supported the development of this structure: the minimalistic approach used during the modelling phase of the case study gives the possibility to focus on the MDO model definition, in particular on the integration setup. However, the implementation of the methodology must be refined to improve its adequacy, through the assessment of tools that enable the automatic sharing and updating of tolerance information. In addition, the optimization strategy needs to be further investigated, increasing the complexity of the optimization problem.

With this in mind, the framework has been improved through a more systematic assessment of 3D semantic annotations, i.e., the GD&T PMI. Indeed, until now the use of PMI within the MDO structure has been limited: tolerance information supports the original 3D models needed to define the initial CAT and PCM simulation models. However, the optimization does not use PMI to update the tolerance values: since tolerance values are defined directly as MDO design variables, they enter directly within the CAT and PCM nodes, without acting on the 3D CAD models. This means that, even if the modelling procedure is faster, the optimization does not provide updated CAD models for each tolerance configuration: for example, the update of the PCM model acts by updating the tolerance values within the input spreadsheet rather than by updating 3D models.

Therefore, an advanced model is defined, where the PMI becomes the key element of the entire optimization, enabling a more effective optimization structure where the CAD models are constantly updated (Petruccioli et al., 2022). In addition, this can improve the automatic sharing of all manufacturing information between simulations. For this reason, the general framework of the proposed methodology (presented in section 3.1) has been expanded focusing on the central role of PMI, as reported in Figure 47. In this way, the CAD models are the starting point of each iteration: PMI tolerances are extracted directly from the models and selected as variables for multi-disciplinary optimization. The tolerance values drive the simulations during the optimization steps: at each step, the optimization algorithm updates the variables according to the global constraints and the defined objectives. Thanks to their link to the CAD models, these variables are automatically transferred to simulation models, where the system performs tolerance and cost simulations. Compared to the previous modelling structure, this provides not only the updating of the input variables but also the generation of 3D CAD models updated at each iteration. This means that, at the end of the optimization, the best configurations can be identified and the corresponding 3D models can be selected, with the optimized tolerance values already addressed as PMI.

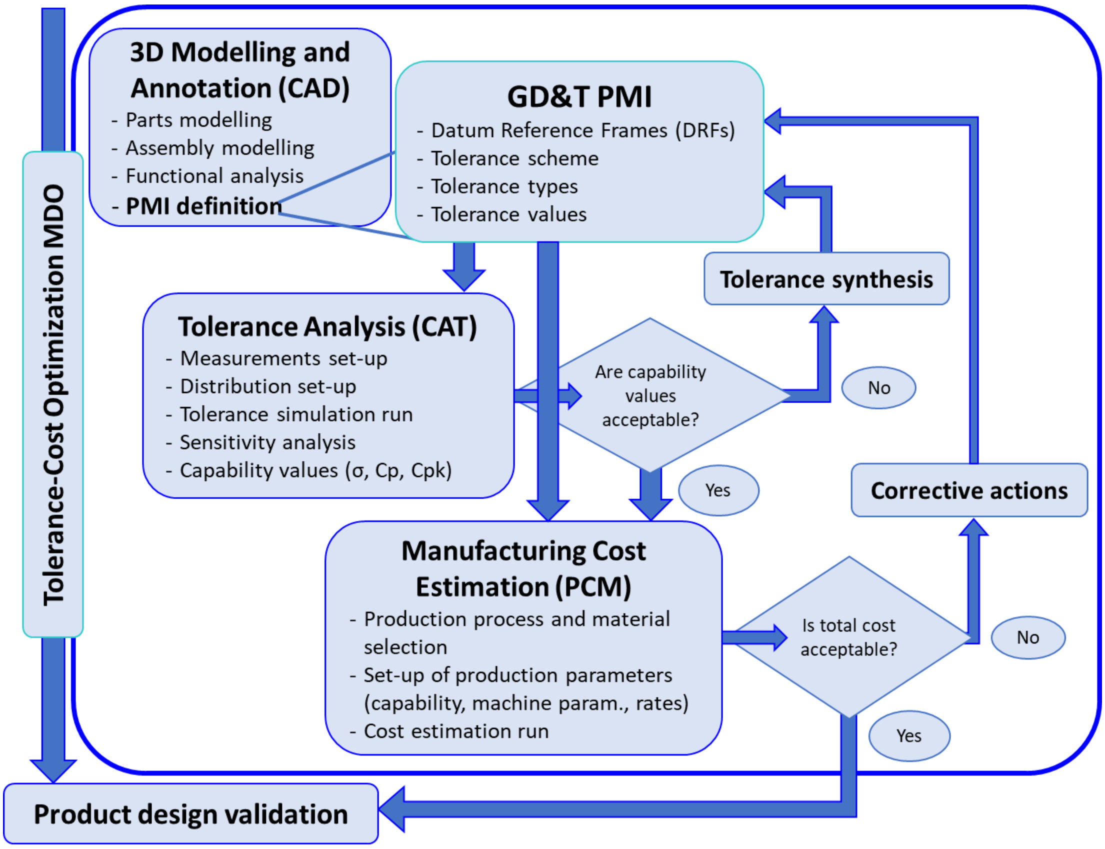


Figure 47. “PMI centred” Tolerance-cost optimization framework

General mechanical assembly

The PMI-based structure for MDO is assessed through the development of a second case study. Compared to the previous one, this case study aims to stress the optimization model through the implementation of PMI, a greater number of tolerance variables and objectives, and an increased number of evaluations. In this way, this case study provides the complete validation of the whole methodology, suggesting the final structure of the MDO environment and allowing its application to a real industrial product (subject of the following chapter).

The selected case study is an evolution of the general mechanical assembly, already introduced and adopted both for the tolerance specification and for the cost estimation modelling (in sections 3.2 and 3.4, respectively). The assembly model, shown in Figure 48a, consists of the three components, i.e., the plate #1, the support #2 and the shaft #3. Compared to the original assembly, the model has been modified in some of its components, to meet specific requirements: in particular, the shaft has been modified in its shape and its interface with respect to the support has been differently located (affecting DRFs scheme).

The tolerance-cost optimization of the assembly is modelled following the main steps of the Computer-Aided Integrated Approach.

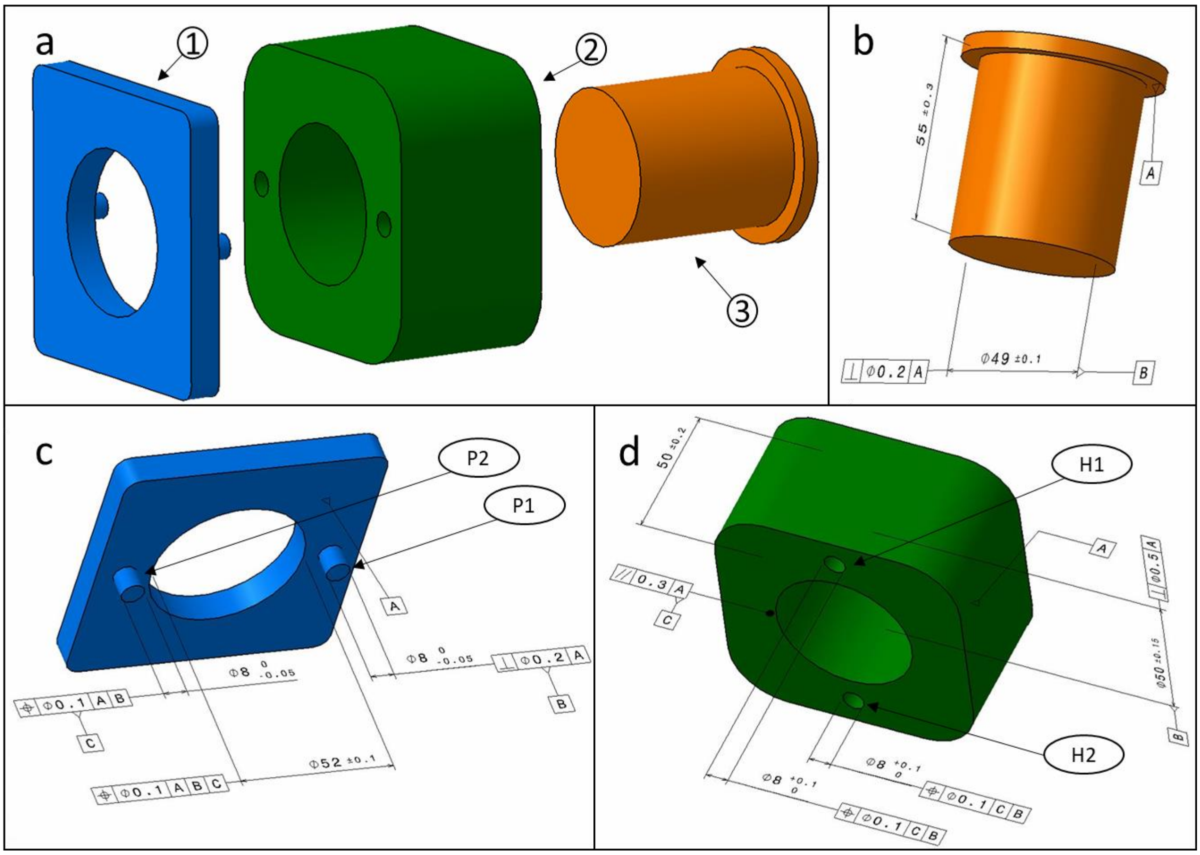


Figure 48. Mechanical product: Assembly (a), shaft (b), plate (c) and support (d)

3D modelling and annotation

- *Part and assembly 3D modelling* – As described in the previous sections, the modelling of components and assembly is performed within the CAD software Catia V5®. The main function of the assembly is the exact positioning of the shaft and the plate on the support: the functional requirement to be verified is the axis alignment with the corresponding radial gap between the shaft and the plate hole. In this way, the case study is representative of many industrial products, such as gearbox assemblies and engine block assemblies where the positioning of the main components on a case must allow the required performance. According to the assembly sequence, the shaft is inserted into the support, then the plate is positioned on the support through the two pins.

- *Tolerance specification and 3D annotation* – According to the tolerance specification modelling procedure proposed in section 3.2, the GD&T specifications are addressed with respect to the assembly sequence: the DRFs for the components are identified for each component, the functional features are selected, and the semantic annotations are inserted (see Figure 48b, 48c and 48d).

- Support: The contact plane with the shaft is the first Datum A; the hole axis is the second Datum B, controlled with a perpendicularity tolerance; the plane opposite to A is controlled by a dimensional tolerance and a parallelism tolerance; the plane, identified as Datum C, is used in conjunction with B to control the position of the holes (H1 and H2) for the assembly with the plate; all holes are controlled by dimensional tolerances.
- Shaft: The contact plane with the support is Datum A; the cylindrical surface, identified as Datum B, is controlled by a perpendicularity tolerance, dimensional tolerances on the main diameter and on the axial length.
- Plate: The contact surface with the support is Datum A; the first pin (P1) is identified as Datum B, perpendicular to A; the second pin (P2), the Datum C, is controlled by a position tolerance with respect to A and B; the central hole is controlled by a position tolerance with respect to A, B and C; all holes are controlled by dimensional tolerances.

Once the tolerance scheme has been defined, the first values of tolerances are chosen as the starting configuration to be optimized and inserted into the 3D semantic annotations. For pin/hole joints, a clearance fit is considered to avoid physical interferences.

Tolerance-cost optimization

- *Computer-Aided tolerance analysis* – The 3D models and the assembly are imported into the Cetol 6σ© CAT environment. Once the components are inserted according to the assembly sequence, the GD&T annotations are automatically read for each part. The tolerance model is then completed by defining the joints between the components and the tolerance distribution types. Finally, the functional measurement to be controlled by the simulation is identified: the radial gap Rg between the shaft and the central hole of the plate, whose range of acceptance is ±0.1 mm. In addition, as the assembly process directly affects the functional requirement, the gaps between pins and holes, H1g and H2g respectively, are checked as an assembly requirement to avoid interference. To check whether the process meets these requirements, the process capability index C_{pk} is selected as functional parameter to be optimized (Pyzdek and Keller, 2014). Referring to the automotive standard VDA 6.3 as a quality target, the target value is set at $C_{pk} = 1.33$, which is considered to be the minimum requirement for long term process capability. Then, the simulation with the initial configuration is run. As reported in Table 5, the stack-up simulation shows a low value of σ for Rg, corresponding to a C_{pk} of 0.62. H1g shows optimal capability, while H2g is strongly influenced by geometric tolerances. Tolerance main contributors to variation are identified (reported in Table 5).

Table 5. Tolerance simulation output (starting configuration)

Measurement	Value and range	Capability	Tolerance main contributors
Rg	1.5±0.1 mm	±1.87σ, C_{pk}= 0.62	⊥ (#3), ∥ (#2), Ø Datum B (#3)
H1g	0+0.2 mm	±4.17σ, C_{pk}= 1.33	Ø H1, Ø P2
H2g	0+0.2 mm	±1.71σ, C_{pk}= 0.45	⌖ H1 and H2, ⌖ Datum C (#1)

- *Manufacturing cost estimation* – Cost estimation is set up by importing 3D models of components and assembly into aPriori© PCM software. According to the PCM-based modelling approach, the primary process and material parameters are specified for each component: die casting and ANSI 6012 Aluminium Alloy for both the plate and the support; machining operations and AISI 4140H Alloy Steel for the shaft. Hence, 5500 annual units for 5 years are selected as production rate and the production location is set in western Europe. After this preliminary setting, the PMI manufacturing tolerances are imported and their corresponding geometric features are recognized, identifying the available operations to achieve the tolerance values. Then, the same manufacturing options are assigned to the assembly model, whose assembly process consists of simple pick and place operations. Finally, the estimation of manufacturing cost for the starting tolerance configuration is executed and the costs for each component are provided: $ 5.34 for the support, $ 8.24 for the shaft and $ 2.25 for the plate, for a total assembly cost, considering $ 1.90 of assembly operation, of $ 17.73.

MDO framework setup

Once the starting configuration has been set, the 3D models are inserted into the MDO optimization environment. Compared to the previous case study, the MDO structure has been modified to set the PMI as optimization variables, as reported in Figure 49.

- *CAD models and PMI* – Unlike the original structure, CAD models are the starting point of the optimization, providing both the input models and the optimization variables (highlighted in blue in the Figure). The 3D models of the components (.CATpart for Catia®) are imported into the MDO as individual nodes. It is not necessary to implement the assembly file (.CATproduct) as a node of the framework because it is included directly in the CAT and PCM models and linked associatively to the corresponding part models: therefore, updating the tolerance values within the components update the assembly automatically. Then, the PMI tolerances are extracted directly from the CAD models and selected as optimization variables: in this case, 24 tolerances to be optimized have been considered. For each tolerance, some variable parameters can be set, such as the introduction of allowable variation limits to avoid unfeasible values of tolerances or guarantee some specific coupling conditions.

- *CAT Tolerance analysis* - As for the CAT nodes (highlighted in red in the Figure), there are no modifications to their structure compared to the original framework. As usual, all optimization variables, in this case the PMI tolerances, are connected and associated with tolerances within the tolerance simulation model (.cxm). Similarly, the capability values of the simulation are extracted from the simulation output file (.cxm): as previously described, in this case three capability indices C_{pk} are evaluated, one for each requirement (Rg, H1g, H2g). For all of them, the functional objective is to maximize C_{pk} values, with a constraint of $C_{pk} \geq 1.33$.

- *PCM Cost estimation* – Compared to the original framework, the PCM model structure (highlighted in green in the Figure) is modified in the relative input nodes. Instead of linking the optimization variables to the input spreadsheet (.xlsx), the connection is made through the CAD models themselves. Since the optimization variables are updated directly in the CAD models, these are inserted as input into the PCM simulation node (i.e., for the "batch mode" simulation). There are no further changes to the PCM structure: at each iteration, the cost estimation is executed and the results are generated in the output spreadsheet file (.xslx). In this case, the production cost for each component is extracted and associated with the objective node (i.e., minimize the total production costs).

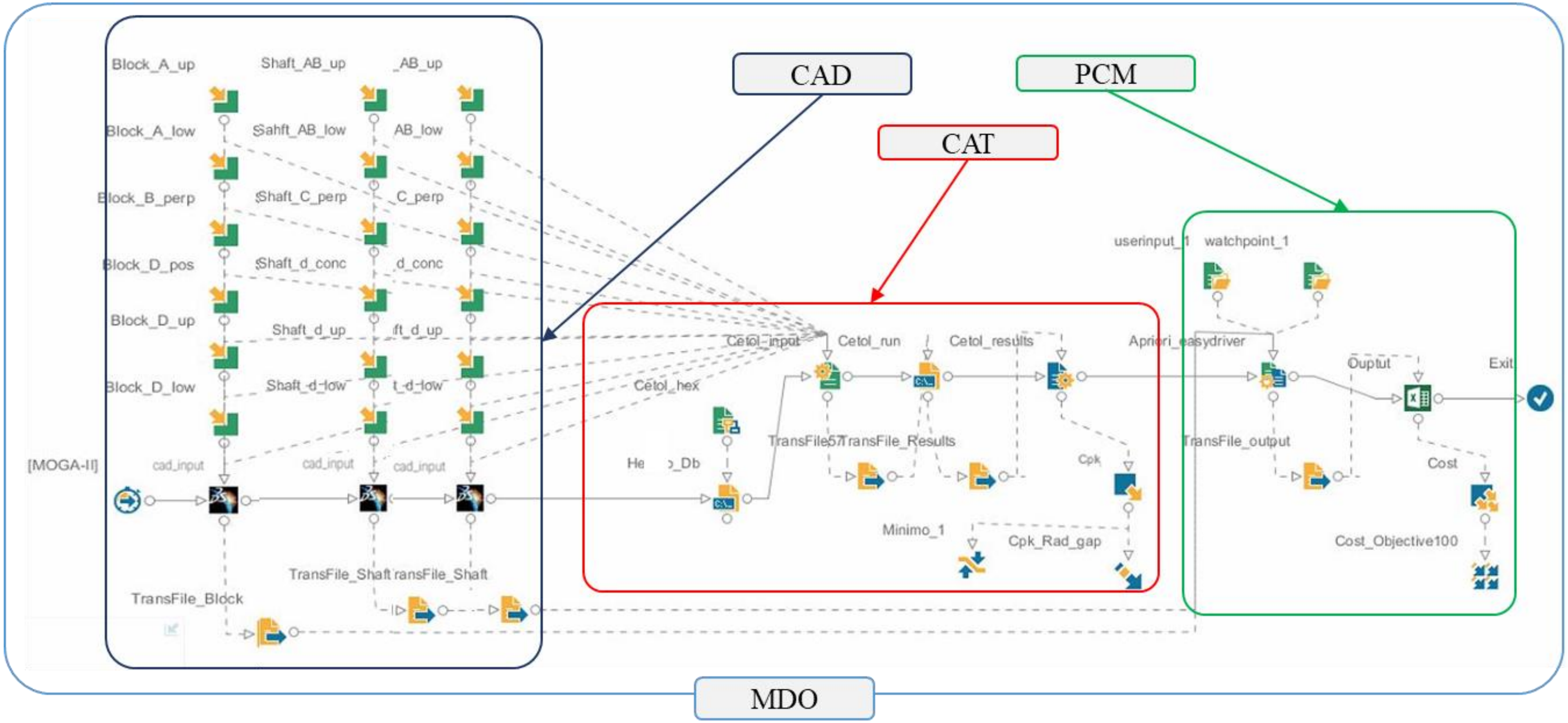


Figure 49. Tolerance-cost MDO framework

Optimization setting and results

Compared to the previous case study, the complexity of the problem has increased: the assembly comprises three components and 24 tolerances to simulate and optimize. Furthermore, three functional requirements (Rg, H1g, H2g) must be fulfilled, as well as the cost of each component must be minimized. To comply with the increased number of variables, models and objectives, the optimization strategy is properly selected. In this case, the pilOPT multi-strategy self-adapting algorithm is selected to evaluate an alternative to the MOGA-II algorithm: starting from a preliminary design, the algorithm generates new populations to reach the Pareto front, while satisfying the constraints (i.e., feasible designs). This means that PMI tolerances are updated with each iteration, exploring the available designs, and refining the optimal Pareto set with new values constantly transferred to the tolerance and cost models. To generate a first population, the deterministic algorithm Sobol DOE, already selected for the previous case study, is chosen. In particular, the DOE algorithm generates 50 configurations, from which the algorithm starts to generate optimized populations: a total set of 600 evaluations is programmed.

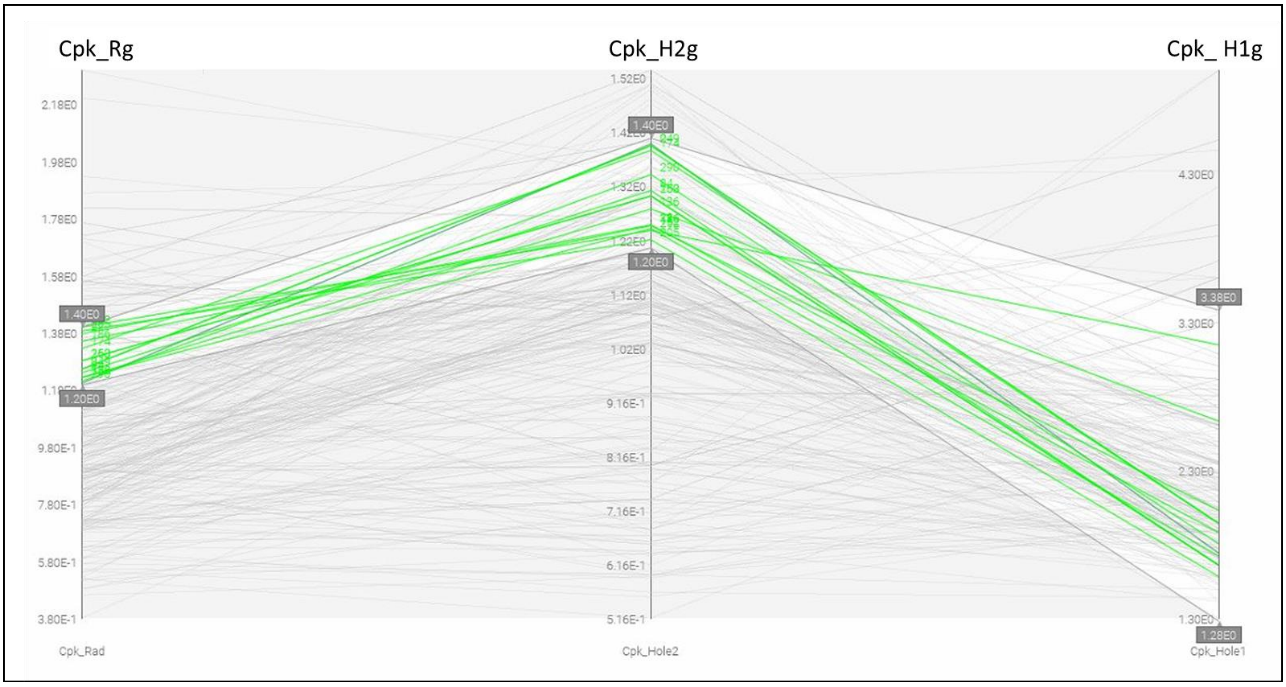


Figure 50. Optimization results

Considering the total 600 configurations, the simulation results provide a set of 16 feasible configurations (highlighted in green in Figure 50) in which the target value of C_{pk} is reached for both functional and assembly requirements. Among these, the optimal configurations are reported in Table 6: the least cost configuration is identified as the n°534, while the best C_{pk} (considering the lowest value among the three evaluated C_{pk}) is the n°446.

- Least cost configuration #534 – For this configuration, the assembly costs $ 19.06, which corresponds to an increase in manufacturing cost for both the support and the shaft, while the cost of the plate does not vary from the starting configuration. The cost of the assembly operations, of $ 1.90, is not affected in any case by the variation of tolerance values. The C_{pk} values of this configuration respect the functional requirements of C_{pk} higher than 1.33, with the lowest value of 1.37 both for the Rg and H2g measurements.

- Best C_{pk} configuration #446 – This configuration reaches the best value of C_{pk} (for the lowest of the three C_{pk} evaluated): it corresponds to the Rg measurement, with a value of 1.61. The high value of C_{pk} and the corresponding reduction in number of rejects compensate for the higher values of the manufacturing cost of the assembly, $ 21.52: in this case, the manufacturing cost is increased for all components.

Table 6. Simulation results: optimal configurations

ID	Cost (#1)	Cost (#2)	Cost (#3)	Cost (Tot)	C_{pk} (H1g)	C_{pk} (H2g)	C_{pk} (Rg)
446	$ 4.51	$ 6.80	$ 8.31	$ 21.52	2.11	1.67	1.61
534	$ 2.25	$ 6.61	$ 8.30	$ 19.06	2.67	1.37	1.37

As a result, the tolerance-cost optimization has provided two optimized tolerance configurations. To select the most suitable among them it is necessary to evaluate their capabilities through the trade-off between production cost and the cost of rejected parts. Consequently, the product design can be validated and the 3D models with optimized tolerance values can be directly selected and then used for subsequent product development phases.

The present case study has enabled the assessment of the proposed Computer-Aided Integrated Approach for Tolerance-Cost Optimization. Indeed, the MDO structure has been further improved by these modifications. Thanks to the use of PMI as optimization variables, data sharing and interoperability between Computer-Aided tools are exploited providing a reduction in the overall system complexity: the structure follows a more logical and systematic sequence of operational steps, the number of nodes is reduced, and the 3D CAD models are updated automatically. In this way, PMI becomes the enabler to integrate product design, manufacturing and inspection. Therefore, this increases the suitability of the MDO for its industrial implementation, as in the case study presented in the next chapter.

Tolerance-Cost Optimization of Automobili Lamborghini V12 engine

The previous chapter dealt with all the development stages of the Computer-Aided Integrated Approach for Tolerance-Cost Optimization. The simulations carried out for each area of intervention have provided modifications and refinements to the methodology, through direct application on several case studies. Thanks to these activities, the proposed methodology has been improved and its correctness evaluated, enabling its suitability for industrial applications.

For this reason, to verify the application capabilities and the advantages of the methodological approach, this chapter provides the implementation of the Computer-Aided Integrated Approach for Tolerance-Cost Optimization on a complex industrial case. The selected case study is the V12 engine assembly provided by Automobili Lamborghini S.p.A. (Figure 51), already introduced in section 3.3. The first case study has concerned the assembly of the parts composing the engine block, aiming to achieve a high process capacity. In that case, the objective has been achieved only using CAT simulations, through the minimization of the number of rejects. The second case study, on the other hand, focuses on a different objective: the optimization of the tolerances affecting the subgroup consisting of the engine block and crankshaft, to ensure the expected performance by reducing the overall production costs. Therefore, unlike the previous application, this case study requires the multi-disciplinary optimization of the engine tolerances to meet both functional and economic targets.

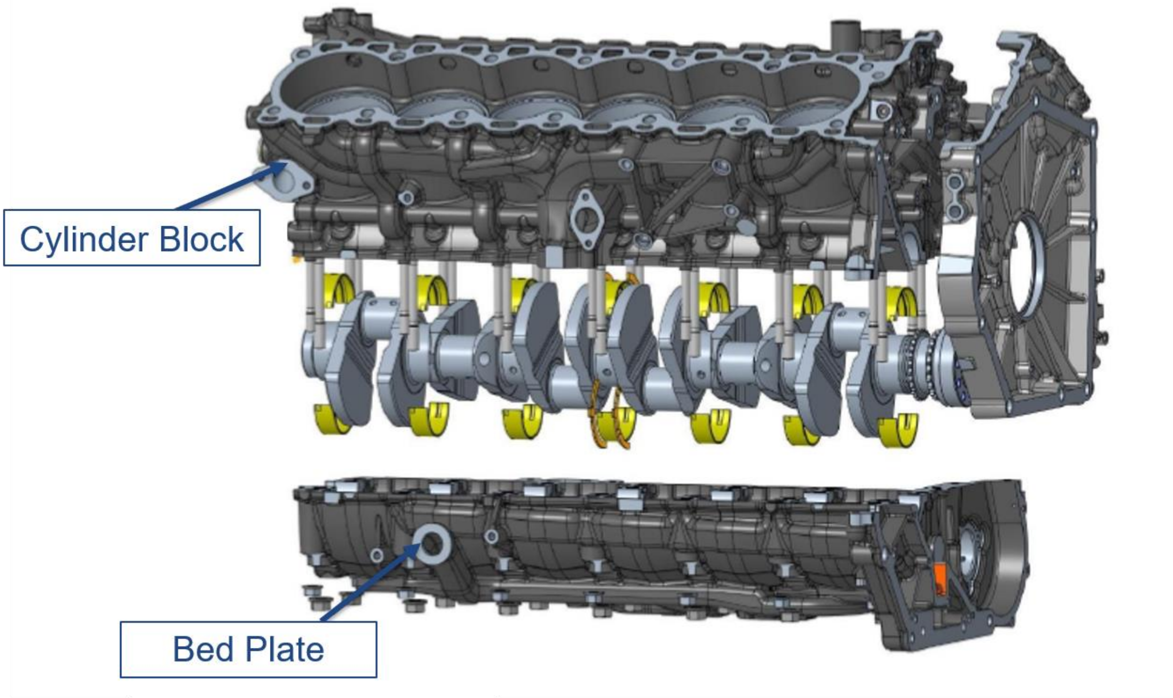


Figure 51. V12 Engine: cylinder block and bed plate

The activity follows the main phases of the Computer-Aided Integrated Approach. However, the tolerance analysis phase has been divided into two steps: after the 3D modelling and annotation phase, before starting with the integrated tolerance-cost optimization within the MDO environment, a CAT analysis has been performed. In this way it is possible to identify the most critical area of the assembly, i.e., the critical functional requirement, on which to focus the optimization objective, reducing the complexity of the optimization problem.

4.1 3D modelling and annotation

Part and assembly 3D modelling

This case aims to understand the tolerances to be assigned to the engine block, the crankshaft, and the other components involved in their coupling. In particular, the subject of analysis are the planes facing the engine block and the crank web shoulder. The goal is to optimize tolerance values both to achieve the required functionality and to reduce costs. The functional dimension is therefore the measure of the gap between the plane of the engine block and the plane of the crankshaft, as in Figure 52: this requirement applies to each cylinder. The functional requirement expressed by the company is to avoid contact between the two surfaces during the operating conditions, i.e., to avoid seizing. Since the nominal gap is equal to $gap = 1.385\ mm$, for simplicity the functional requirement is expressed in equal-bilateral symmetry tolerance equal to $gap = 1.385 \pm 0.200$, i.e., $1.185 \leq gap \leq 1.585$. It should be noted that the upper limit (1.585 mm) is not a specific request, but it is a convenient value to have an equal-bilateral symmetry tolerance, being close to an acceptable upper value. In this way, the functional measurement consists of a symmetrical acceptance window with respect to the nominal value.

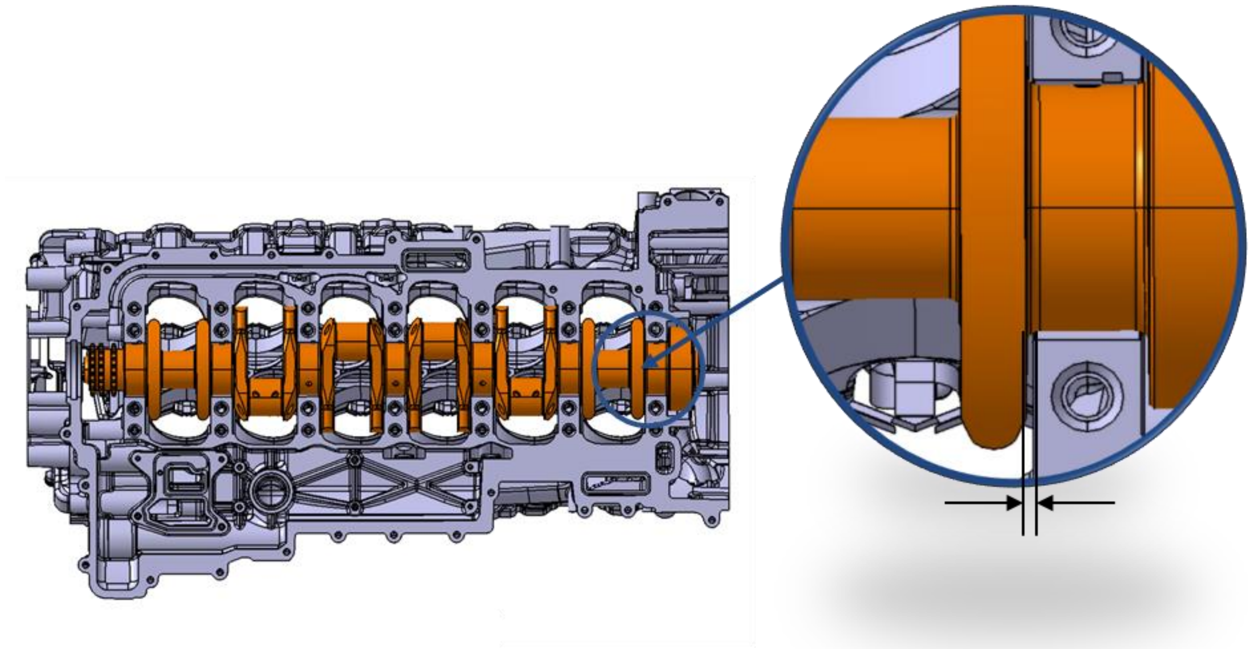


Figure 52. Functional requirement

The original engine assembly consists of a large number of components. As in the previous case study, the primary component is the engine block, divided into “cylinder block” and “end plate”, as shown in Figure 51. The other main components are the cylinder heads and the crankshaft. Additional components are bearings, thrust washers, gaskets, bushings and studs (the fixture elements).

Since the functional requirement concerns the engine block-crankshaft assembly, all other parts not involved in the chain or in the assembly sequence are not considered. Therefore, the analysis requires only the CAD models of the engine block, the crankshaft and the two thrust washers (Figure 53). In a first attempt, the main bearing was considered as an individual component, while in a second analysis it has been neglected because it did not significantly influence the results. Moreover, modelling of deformable components, such as the main bearings, would require a specific case study to be considered realistically: most CAT software does not comply with deformable models, providing only the simulation as rigid parts.

According to the assembly sequence, the cylinder block has been imported as the parent of the model, introducing a hierarchical order: it is held in position by an external fixturing system, therefore it is considered fixed. Following the engine assembly sequence, the two thrust washers are inserted, one for each engine side: in the real application there are four thrust washers, two per side, but here is not mandatory. In fact, these axial bearings are necessary for the axial position of the crankshaft (and consequently for the entire crank mechanism), so they enter in the chain. While the engine is running, the crankshaft can touch both sides. For this reason, in both cases one thrust washer per side is required to simulate the axial position: they are aligned with the main journal axis and positioned by contact with the central shoulder planes. Then, the crankshaft is inserted into the cylinder block, aligned with the main journal axis, and positioned by contacting the thrust washer of one side (later identified with Datum E side). Constraining the crankshaft without the main journal bearings may seem unreal because the crankshaft floats in the main journal axis of the engine block. However, the actual clearance between the main journal bearings and the crankshaft is so tight that any movement of the crankshaft would be negligible: therefore, considering the crankshaft coaxial with the main journal axis is a good approximation (this hypothesis has been validated through several simulations and by consulting the company). Finally, the bed plate, after inserting the bushings and the studs, is positioned on the cylinder block by means of the planar contact between the separating planes of the cylinder block and the bed plate, and then the alignment with respect to the two diagonally opposite bushings axis. Finally, the cylinder block and the bed plate are bolted together closing the assembly: in this way, all the DOFs of the bed plate are constrained, avoiding any relative movement between them.

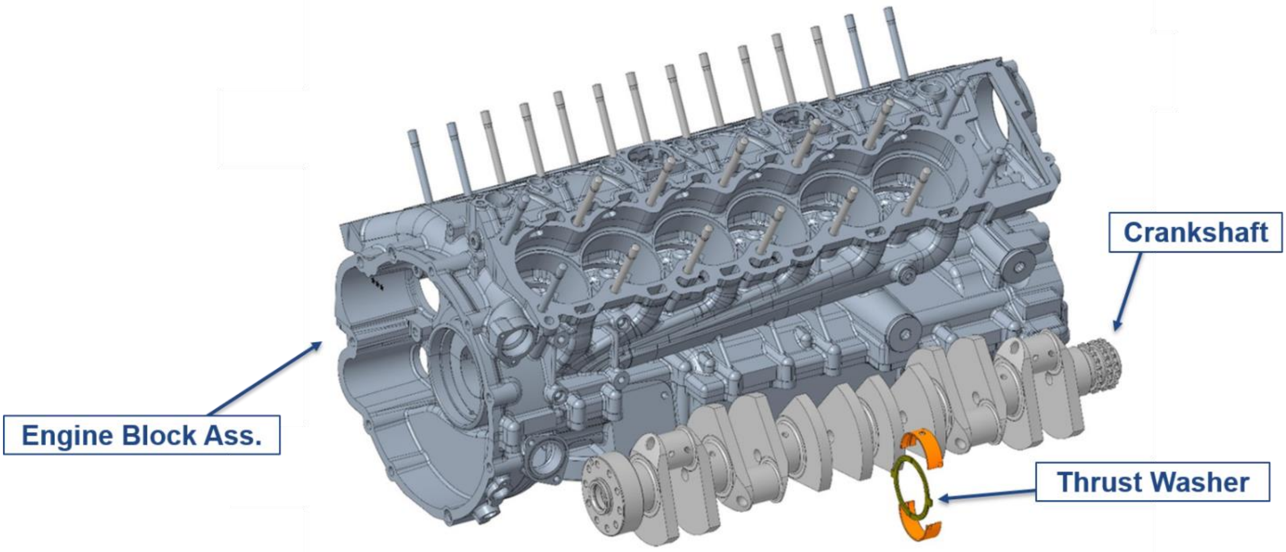


Figure 53. Engine components for the analysis

Tolerance specification and 3D annotation

The tolerance specification and annotation process follows the main steps discussed in section 3.2. According to the functional analysis of the product and the assembly sequence, GD&T schemes must be defined for each component, including all useful information: DRFs, functional features involved in the chain, functional features used to set the measures, dimensional and geometric tolerance types and values.

Following the Computer-Aided integrated approach, this phase has been carried out entirely within the 3D CAD environment, through the use of 3D semantic annotations: in this case, the CatiaV5® "3D Functional Tolerancing and Annotation" module. Therefore, the PMI has been addressed both for the selection of the DRFs and functional features (KCs) and for the definition of the GD&T types and the starting values.

Firstly, the DRFs system and the KCs are identified for each component:

- *Engine block (cylinder block and bed plate)* – As already shown in the previous case study, the cylinder block and the bed plate significantly affect the assembly of all other parts. Therefore, their DRFs system must also be considered for the current case study, as it mainly acts for the relative positioning of the other components. Therefore, the DRFs for the two parts are composed of the separating plane, Datum A, and the two diagonally opposite bushings holes, Datum B and Datum C, as shown in Figure 54. In this way, the DRF system A|B|C provides relative positioning between engine block components, constraining all DOFs: Datum A provides planar contact by constraining 3 DOFs, Datum B removes 2 DOFs, and Datum C the last remaining DOF.

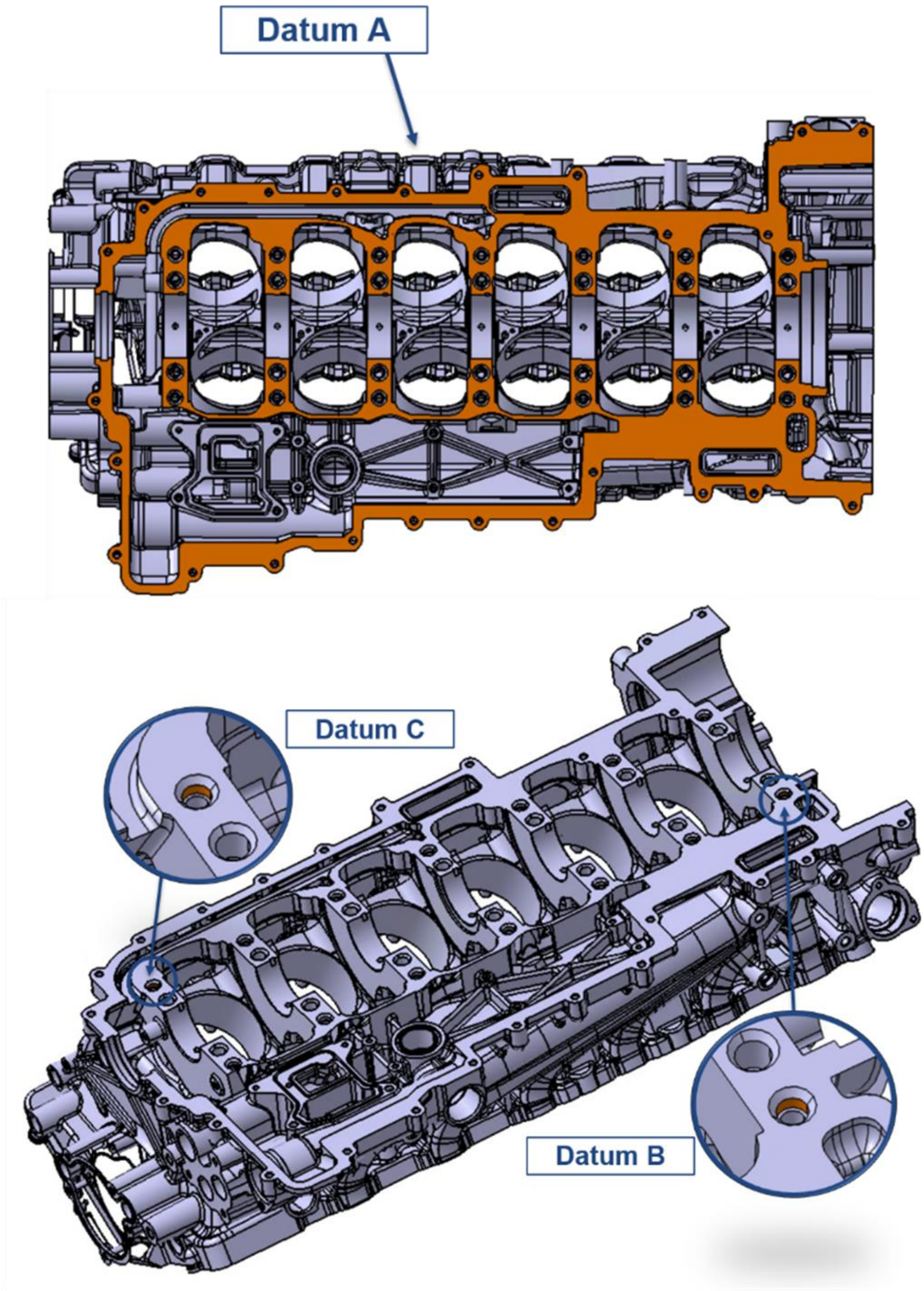


Figure 54. Engine block DRFs: Datum A, Datum B and Datum C

Unlike the previous case study, the other bushing and stud housings are not involved in the chain, as only the bushes B e C have been used to define the assembly conditions in addition to plane A. Furthermore, the assembly conditions between cylinder block, bed plate, and cylinder heads by means of fixturing elements have already been investigated, showing a good response of the fixture system.

For this reason, positioning errors between the two engine block parts are neglected in the present case study. This means considering the engine block components as an assembly, with the DRF A|B|C used as an assembly DRF. This hypothesis is supported by the manufacturing process, since once the two parts are assembled, different machining phases occur on the entire engine block: boring of the main journal supports, milling of the reference plane (i.e., the central shoulder plane, addressed as Datum E) which axially guides the crank mechanism, and many other operations.

Once the DRF system has been defined, the other functional features (KCs) are identified, defining the additional reference elements to be considered as additional Datums. In particular, since the correct positioning of the crankshaft is directly influenced by the main journal axis of the engine block, the related features must be addressed as reference elements: the main journal supports, obtained by boring operations on the engine block, define the main journal axis, identified as Datum D (Figure 55).

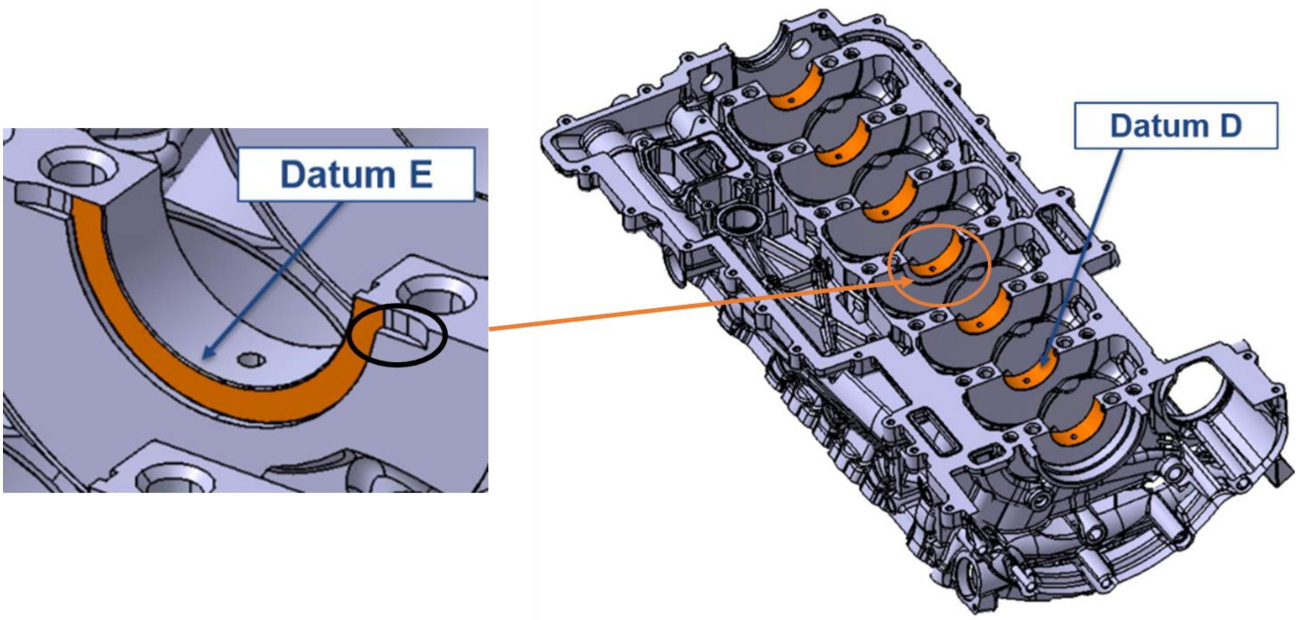


Figure 55. Engine block DRFs: Datum D and Datum E

The same happens for the central shoulder planes: these planes provide the contact areas on which to place the thrust washers. Since the crankshaft axial position is limited by contact with the thrust washers of both sides, these reference planes enter in the chain and primarily affect the relative positioning of the crankshaft with the engine block and thus the functionality under operating conditions. For this reason, these two reference planes are critical functional features (KCs): since these must be correlated by both dimensional and geometric tolerances, one of them is identified as Datum E. The choice of one side instead of the other is related to the assembly operations where, once the thrust washers have been inserted on both sides, the crankshaft is positioned axially with respect to Datum E. This affects only the assembly operation: during the operating conditions, the axial position of the crankshaft may vary within the range given by the contact with the thrust washers. In addition, the housing groove for the angular positioning of the thrust washer, comprising the two planes on the engine block (one of which is highlighted in black in Figure 55), has been considered as KC (i.e., is not necessary to consider them as a Datum since no other features are referred to them). Then, the remaining shoulder planes are identified and selected as KCs, since their positioning with respect to the Datums directly affects the functional requirements: these are the functional features that define the functional measurements, i.e., the distance from these planes on the engine block and the corresponding planes on the crank web shoulder.

- *Thrust washer* – The assembly sequence analysis has highlighted the role of the thrust washers for the correct axial position of the crankshaft. Since these components are commercial products, the DRFs for these components are directly related to their assembly features. As shown in Figure 56, the contact plane with the central shoulder planes is identified as Datum A. Then, since the inner ring surface is aligned with the main journal axis of the engine block, this feature is identified as Datum B. Finally, the two surface planes on the outer ring (shown in the Figure) identify Datum C as the mid-plane, to be aligned with the mid-plane of its housing groove on the engine block. In this way, the DRF system A|B|C provides relative positioning with respect to the engine block, constraining all DOFs of the thrust washer: Datum A provides planar contact, constraining 3 DOFs; Datum B removes 2 DOFs through concentricity between axles; Datum C removes the last DOF remaining via an angular constraint with respect to the engine block groove. The same operation is then repeated for the second thrust washer on the opposite side.

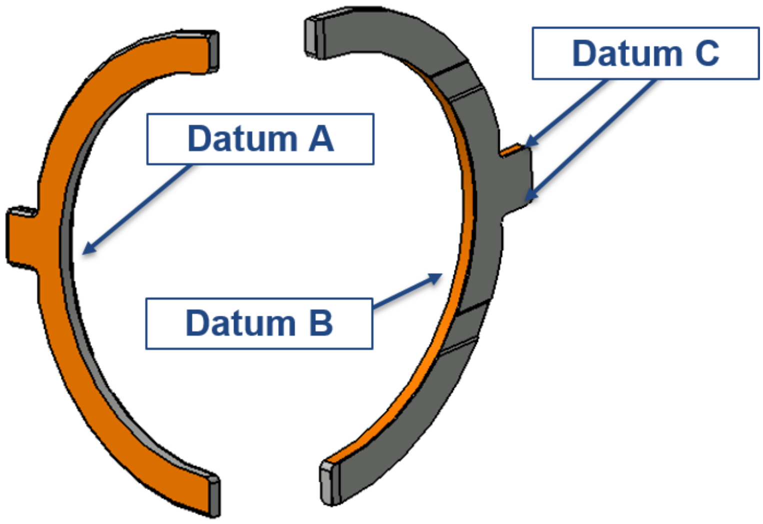


Figure 56. Thrust washer DRFs: Datum A, Datum B and Datum C

- *Crankshaft* – The last component to consider is the crankshaft. As already described, the functionality of the crankshaft during the operating condition of the engine is correlated to its correct position during the assembly operations: in addition to the geometric and dimensional deviations of the shaft and the main journal supports of the engine block (Datum D), orientation errors have an important effect. According to the manufacturing operations commonly addressed for rotating components, as well as the functional requirements and the assembly sequence, the component is characterized by a Multiple Datum (i.e., Co-Datum) A-B: this Datum is obtained from the two cylindrical surfaces of the two extremal main journal bearings, as reported in Figure 57. The choice of these features is due to the assembly operations, where these features are aligned with respect to Datum D of the engine block. Then, a second Datum C is introduced, provided by the central main journal bearing. This Datum is necessary to have tighter control over the orientation of the thrust shoulders (in addition to the axial run-out with respect to A-B), possibly in contact with the thrust washers during the engine operating conditions. As mentioned, these thrust shoulders (Right and Left, as shown in the Figure) ensure axial positioning of the crankshaft: two limit positions are possible, subsequently provided as “1°Misura” and “2°Misura” states. Conversely, this time the DRF system correctly constraints the model by removing 5 DOFs, leaving the residual DOF of shaft rotation around its axis. First, the Multiple Datum A-B provides the concentricity between the axes of the two cylindrical surfaces, removing 3 DOFs. Finally, the axial positioning of the crankshaft is removed, depending on the state considered, by the contact between one of the thrust shoulders and the feature of the closest thrust washer. Once defined the DRF system and identified the thrust shoulders as functional features, the remaining crank web shoulders are identified and selected as KCs, similar to the engine block shoulder planes. Indeed, their positioning with respect to the Datums directly influences the gap measurements.

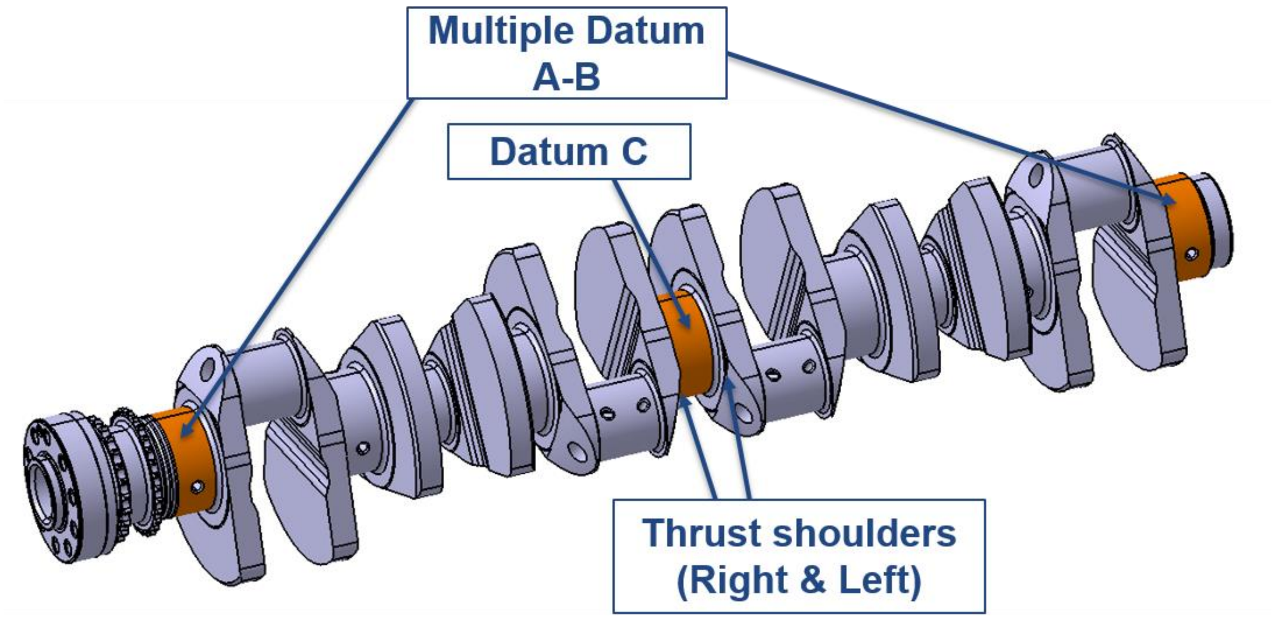


Figure 57. Crankshaft DRFs: Multiple Datum A-B and Datum C

After the identification of both DRFs and KCs for each component, the following phase consists of the qualification of DRFs and characterization of KCs through dimensional and geometric tolerances. The tolerance assignment and allocation phase has been carried out aiming of focusing on the specific functional requirements, i.e., the gap measurements. Therefore, the tolerances addressed here are the only ones to contribute to these requirements, i.e., to enter in the tolerance chain: the approach has been the minimalist one. Moreover, dealing with the limitation of the CAT tool of not supporting some tolerances, form variations have been neglected. Similarly to the previous steps, this phase has been implemented directly within the 3D CAD models, providing GD&T semantic annotations. As highlighted in section 3.2, this allows for a faster and safer characterization procedure.

- *Engine block* – The engine block is characterized by assigning the dimensional and geometric tolerances for both DRFs and KCs. According to the order of precedence and the functional relationships between DRFs and KCs, the tolerance specification gives the following results.

- Datum B: qualified with a perpendicularity tolerance with respect to Datum A and a dimensional tolerance on its diameter.
- Datum C: qualified with a position tolerance with respect to Datum A and Datum B and a dimensional tolerance on its diameter.
- Datum D: qualified with a position tolerance with respect to Datum A, B and C, and a dimensional tolerance on its diameter.

- Datum E: qualified with a position tolerance with respect to Datum A, B, and C; in addition, a perpendicularity tolerance with respect to Datum D is added with a tighter value than the position tolerance, to provide more precise control of planar orientation.
- The shoulder plane of the opposite side to Datum E is oriented by a perpendicularity tolerance with respect to Datum D and a dimensional tolerance between this feature and Datum E.
- All shoulders relating to the gap measurements are characterized by a position tolerance with respect to Datum A, B, and C. It is worth mentioning that, unlike Datum E, the milling of the shoulders occurs when the engine block is disassembled, therefore are tolerated as single components (cylinder block and bed plate separately) with respect to A, B, C, rather than with respect to Datum D.

In this way, all the features involved in the chain are considered. The tolerances are inserted into the CAD models as PMI, as shown in Figure 58. Once the tolerance scheme has been defined, the first tolerance values are chosen as starting configuration to be optimized and inserted into the 3D semantic annotations: these values have been provided directly by the company, as they are currently allocated to the 2D drawings of the components.

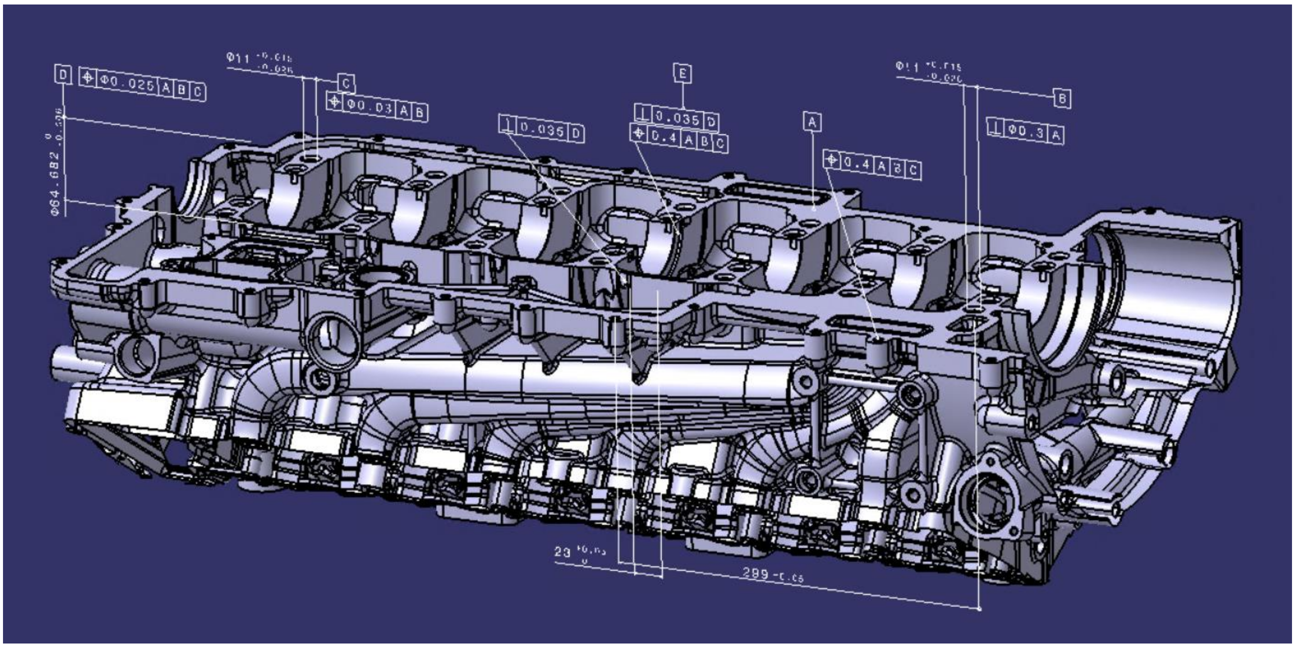


Figure 58. Engine block GD&T semantic annotations (PMI)

- *Thrust washer* – As for the engine block, dimensional and geometric tolerances are assigned for both DRFs and KCs.

- Datum B: qualified with a perpendicularity tolerance with respect to Datum A and a dimensional tolerance on the internal diameter.

- Datum C: the two surfaces define the position and orientation of the mid-plane, so they are controlled by a position tolerance with respect to Datum A and Datum B and by a dimensional tolerance on their nominal distance.
- In addition, a dimensional tolerance is considered to control the thickness of the thrust washer, as prescribed by the external supplier.

The tolerances are inserted into the CAD models as PMI, as shown in Figure 59. Finally, the first values of tolerances are chosen as starting configuration to be optimized, and inserted into the 3D semantic annotations: here, a general geometric tolerance ISO 2768-mK has been considered to define the starting tolerance values, except for what was provided by the supplier of this commercial part.

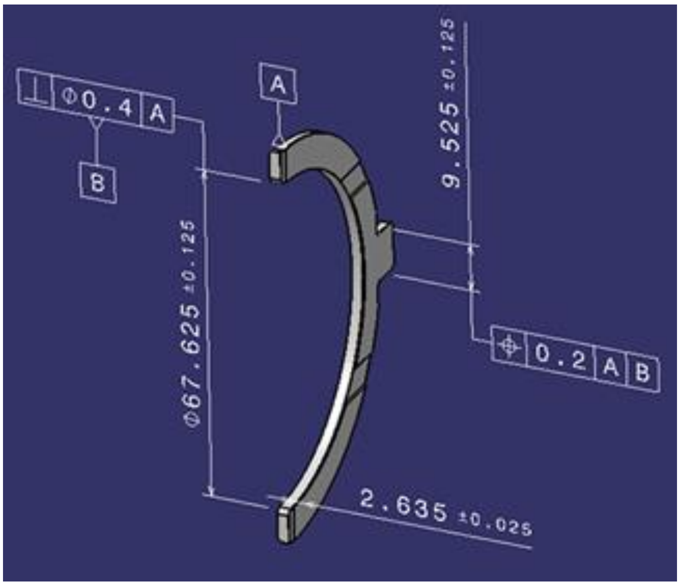


Figure 59. Thrust washer GD&T semantic annotations (PMI)

- *Crankshaft* – According to the identified DRFs and KCs and the manufacturing process for this type of components, the following dimensional and geometric tolerances are assigned to the crankshaft.

- Multiple Datum A-B: according to the dimensional tolerance prescribed on Datum D of the engine block, Datum A-B surfaces (as well as the other main journal bearings) are characterized with dimensional tolerances to match the required clearance fit ensuring the correct functional conditions.
- Datum C: it is qualified with axial run-out tolerance with respect to Multiple Datum A-B and, as for all main journal bearings, with a dimensional tolerance on the cylindrical surface.
- The central crank web shoulders are characterized by an axial run-out tolerance with respect to Multiple Datum A-B. In addition, a perpendicularity tolerance is added to have more

precise control of their orientation with respect to Datum C. Finally, their reciprocal distance is controlled with a dimensional tolerance.

- The other main journal bearings are controlled by an axial run-out tolerance with respect to Multiple Datum A-B and by dimensional tolerance on their cylindrical surfaces.
- The remaining crank web shoulders are characterized by an axial run-out tolerance with respect to Multiple Datum A-B, a dimensional tolerance to locate them with respect to the central shoulder and a dimensional tolerance to control the distance between two adjacent shoulders.

Once defined, the tolerances of all the features involved in the chain are inserted within the CAD models as PMI, as shown in Figure 60, as well as their first values allocated as starting configuration to be optimized. As for the engine block, these values have been provided directly by the company, as they are the values currently assigned to the 2D drawings of the components.

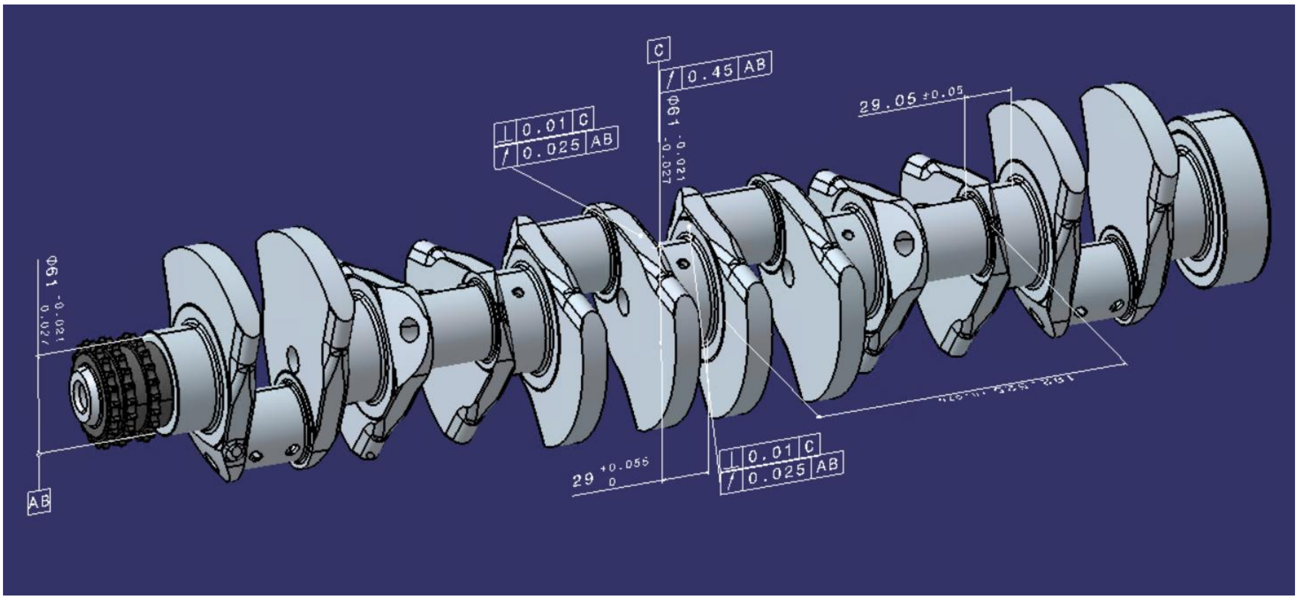


Figure 60. Crankshaft GD&T semantic annotations (PMI)

4.2 Computer-Aided tolerance analysis

As already mentioned, before applying the integrated tolerance-cost optimization on the engine assembly, a CAT analysis is performed to provide a general analysis of the functional requirements. Since the complexity of the optimization problem is high, considering both the geometry and the specifications of each component and the need to simulate two assembly states ("1°Misura" and "2°Misura"), it is important to clarify the critical condition. The identification of the most critical functional requirement of the assembly, with its corresponding critical features and tolerances, can help to optimize the entire optimization problem by focusing on the most influential factors.

Following the CAT-based modelling approach described in section 3.3 and considering the phases already developed in the CAD environment, the components are imported into the Cetol 6σ© CAT software: they are arranged according to the assembly sequence and the GD&T annotations are automatically read for each part. The tolerance model is then completed by defining the tolerance distribution types: in this case, the normal centered distribution is selected for each component.

Measurement selection

The selection and set-up of the measures is the most critical phase during the CAT modelling. In general, different types of measurements can be selected, depending on the functional requirements but also on the mastery of the CAT tool. In this case, ten gap measurements are specified (two of the twelve are not functional). To represent the real operating conditions of the engine, already described in the previous section, the two states "1°Misura" and "2°Misura" are created: with respect to the standard layout of the assembly, schematized in Figure 61, these two states are representative of the two limit conditions of the axial displacement of the crankshaft.

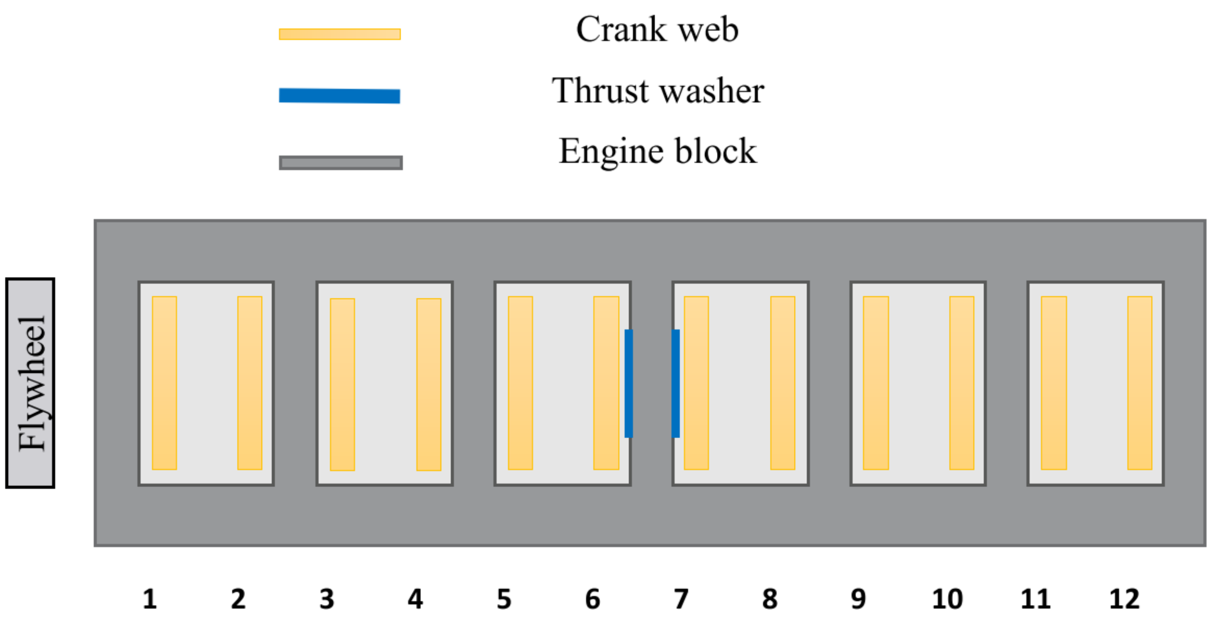


Figure 61. Standard layout - legend

Figure 62 and Figure 63 help to understand the two states and the surfaces selected for the measurements. The ten measures aim to identify the critical gap: after that, only the critical gap (with the corresponding state) will be modelled for the optimization of the tolerance values.

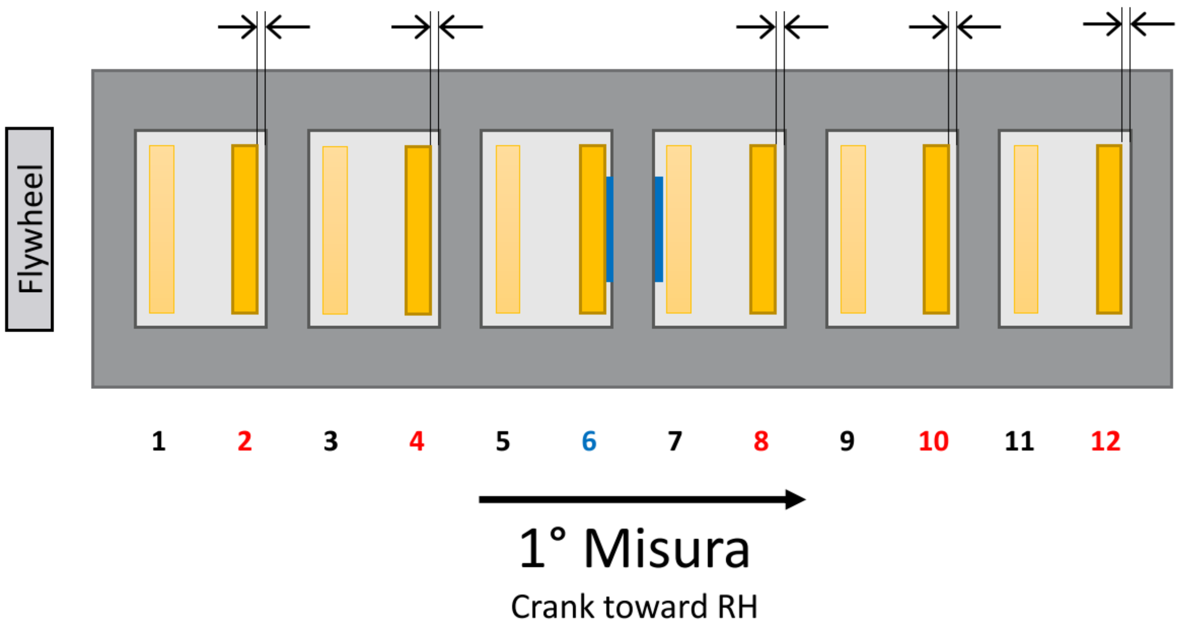


Figure 62. 1°Misura, crankshaft positioning

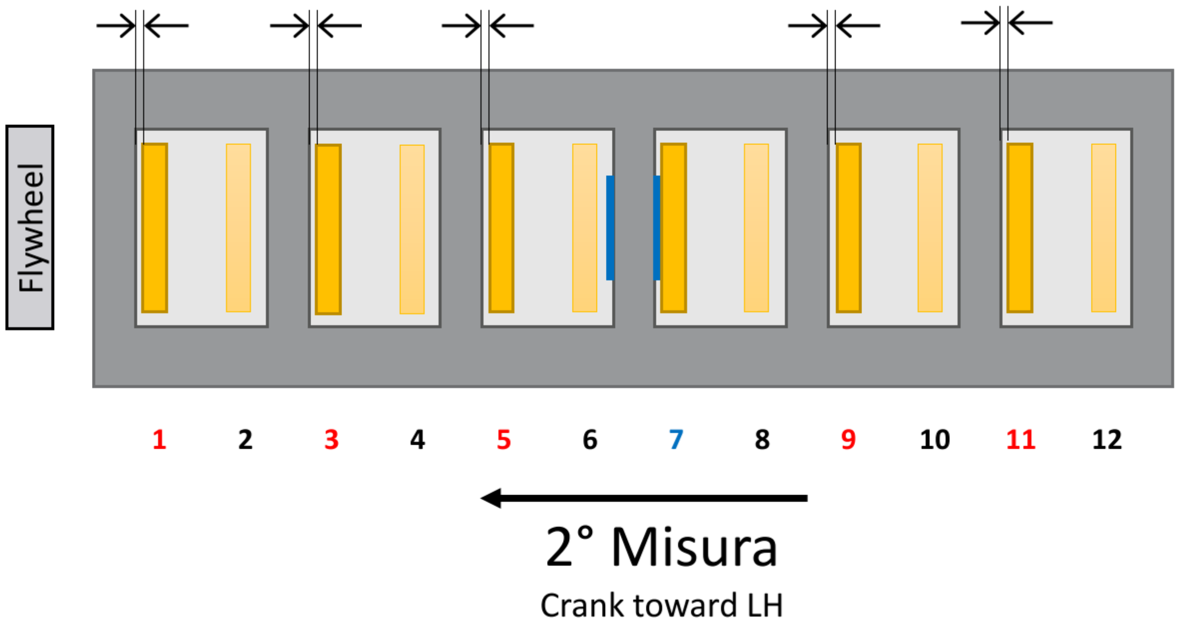


Figure 63. 2°Misura, crankshaft positioning

During the definition of the measurements, the functional requirements are inserted, i.e., the target value and the acceptance range: in this case a symmetric interval has been set from the nominal value calculated by the software, gap = 1.385 ± 0.200 (see Figure 64). The same procedure has been repeated ten times for each gap illustrated before, organized in the set of two states.

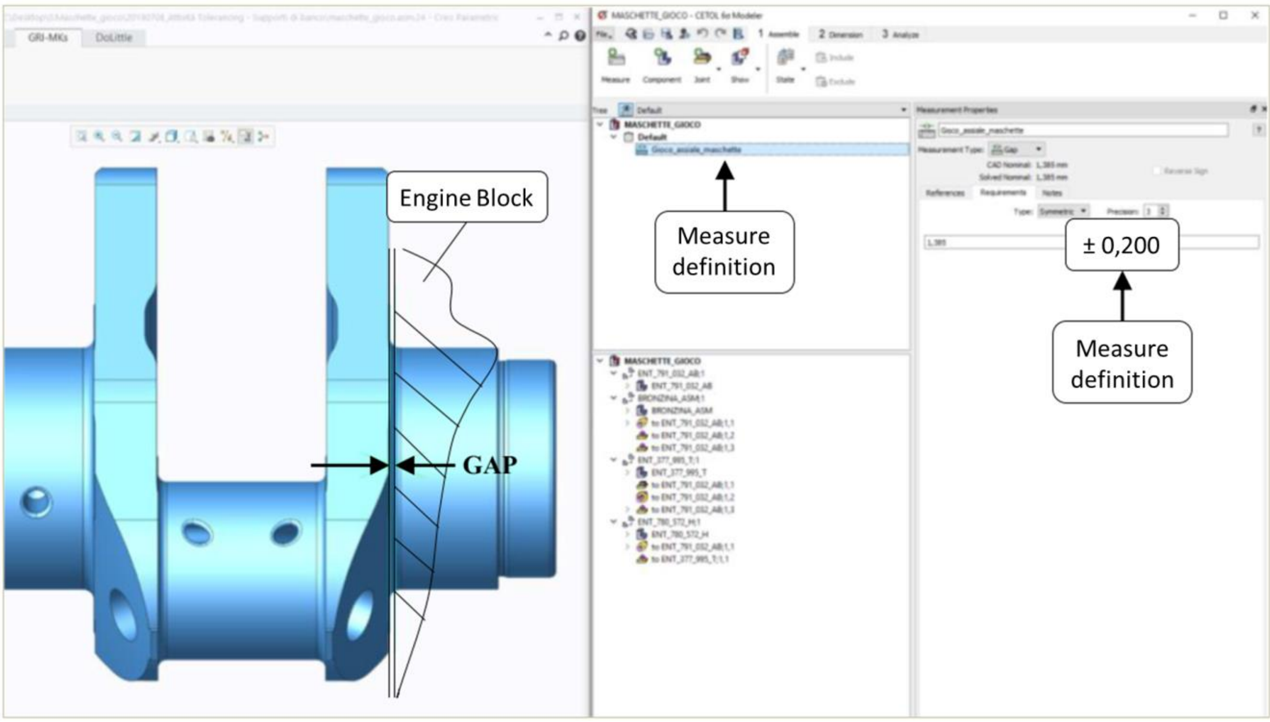


Figure 64. Functional limits specification

CAT simulations and firsts results

The tolerance simulation has been approached in two different steps. A first “complete” model is created containing all ten measurements to individuate the critical gap. From this model, a second “critical gap” model is derived including only the critical gap: this model will be considered for tolerance and cost optimization within the MDO environment to reach the optimal tolerance configuration for both functional and economic targets.

The 3D tolerance analysis allows to quickly calculate the critical gap simply by setting the ten measures and arranging them according to the σ value, replacing the more boring and inaccurate spreadsheet calculations commonly used by the company for tolerance management (1-D, WCA and RSS). The complete analysis has been performed using a quality metric according to VDA 6.3: a value of $C_{pk} = 1.33$ has been adopted for the tolerance distributions of all parts and therefore for the functional limits too.

Table 7. Tolerance analysis results: “complete” model

Name	State	Nominal	Tolerance	C_{pk}
Gap_1	2°Misura	1.385	± 0.200	1.341
Gap_2	1°Misura	1.385	± 0.200	1.347
Gap_3	2°Misura	1.385	± 0.200	1.297
Gap_4	1°Misura	1.385	± 0.200	1.345
Gap_5	2°Misura	1.385	± 0.200	1.402
Gap_8	1°Misura	1.385	± 0.200	1.402
Gap_9	2°Misura	1.385	± 0.200	1.345
Gap_10	1°Misura	1.385	± 0.200	1.402
Gap_11	2°Misura	1.385	± 0.200	1.328
Gap_12	1°Misura	1.385	± 0.200	1.396

According to the simulation results, reported in Table 7, the Gap_3, belonging to the second state (2°Misura), is the critical one: compared to the other measurements, the capability associated with the functional measurement is the lowest. With respect to the functional requirement of $C_{pk} = 1.33$, the simulation results in a value of $C_{pk} = 1.297$, corresponding to a value of $C_{pk} = 1.31$, of σ = ± 3.94, and DPMO = 82.95 of the other capability indices, as shown in Figure 65.

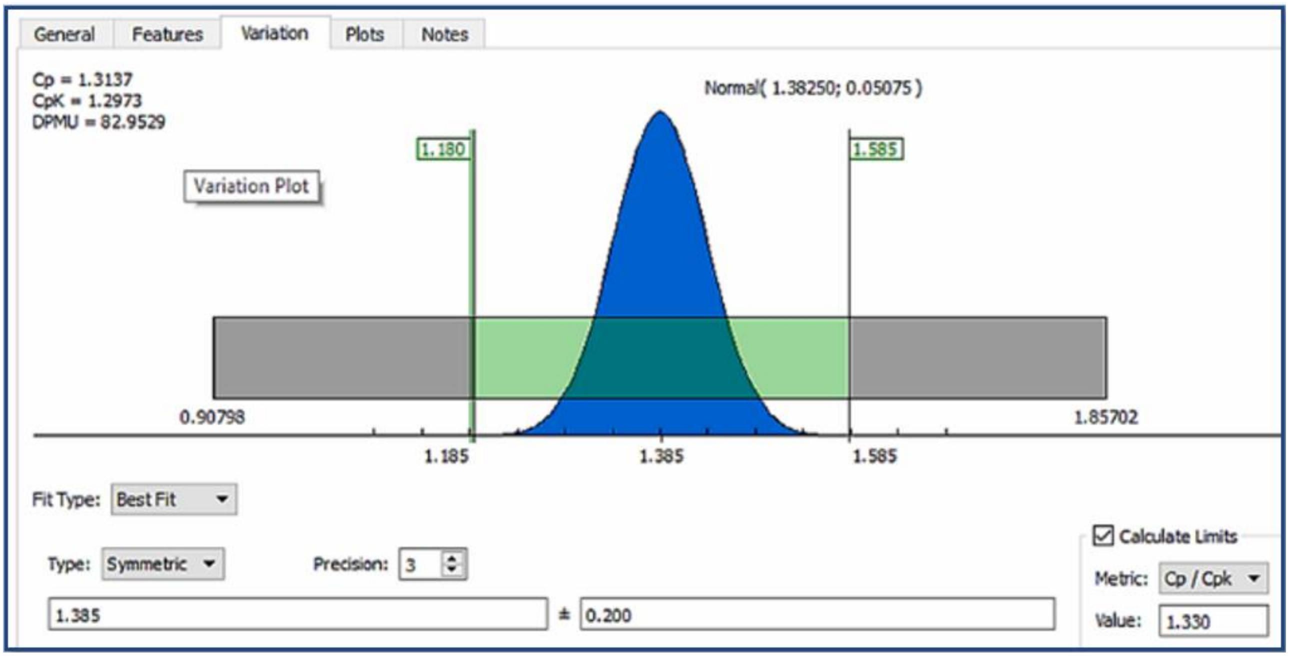


Figure 65. Critical gap simulation results: gap_3

The tolerance simulation also provides the analysis of the main contributors to variation for this measurement. As reported in Figure 66, the main contributor is the position tolerance with respect to Datum A, B, and C of the shoulder plane corresponding to the gap_3: this tolerance has the highest variance contribution of 73.19% according to the assembly sequence and, mainly, to the GD&T scheme of the part. Similar behaviour is observed for the crankshaft: the corresponding crank web shoulder is identified as the second tolerance in terms of contribution, with a value of 13.72%. These results show the correctness of the model, as the simulated behaviour is representative of the real assembly operations and comparable with the experimental data performed on prototype engines.

	Name	Context	Nominal	Tolerance	Cpk	Sensitivity	Variance Contrib
Position 5	to A|B|C	ent_791_032_ab_engine_block_simple_old;1/Shoulder 3		0.400	1.33		73.19 %
Liner 6	to Shoulder_thrust	ent_780_572_h_simple;1/Shoulder_2/3	192.525	192.525 ±0.075	1.33		13.72 %
Liner 7	to B	ent_791_032_ab_engine_block_simple_old;1/E	298.75	298.750 ±0.050	1.33		5.72 %
Liner 4	Size	ent_780_572_h_simple;1/Shoulder_2/3	29.05	29.050 ±0.050	1.33		1.52 %
Linear 4	to E	ent_791_032_ab_engine_block_simple_old;1/Shoulder ras	23.5	23.500 +0.050 -0.000	1.33		1.52 %
Liner 3	to A	ent_377_995_t2_thrust_washer_2_simple;1/Shoulder	2.635	2.635 ±0.025	1.33		1.52 %
Liner 5	to Shoulder_thrust	ent_780_572_h_simple;1/Shoulder_thrust_1	29	29.000 +0.055 -0.000	1.33		1.46 %
Perpend. 2	to D	ent_791_032_ab_engine_block_simple_old;1/E		0.035	1.33		0.93 %
Perpend. 1	to A	ent_791_032_ab_engine_block_simple_old;1/B		Ø 0.030	1.33		0.37 %
Circ runo 2	to AB	ent_780_572_h_simple;1/Shoulder_thrust_1		0.025	1.33		0.02 %

Figure 66. Tolerance main contributors to variation

As result, the important information obtained from this model is the evaluation of the critical gap. Moreover, the simulation provides the process capability resulting from the starting configuration of the tolerance values: this result is good, close to the prescribed functional requirements of $C_{pk} = 1.33$.

Critical gap model

Thanks to the tolerance analysis performed on the "complete" model, the "critical gap" model is derived directly from it. The difference between these models is related to the elimination of non-contributing measurements: even if the tolerance schemes and values are not modified, this model includes only the critical gap_3 as functional measurement on which effectively optimize the tolerance values both in terms of functionality and cost reduction. In this way, the simulation behaviour and the corresponding critical gap results are not changed, as the GD&T scheme of the components is the same of the complete model. Moreover, since gap_3 belongs to the second state (2°Misura), the first state can be removed, reducing the size of the model: the optimization complexity can be reduced, providing only one functional objective to be evaluated and, mainly, a single state to be optimized. Otherwise, two different tolerance analysis models should be considered and thus two different optimization models developed.

4.3 Manufacturing cost estimation

After the CAT modelling and simulation phase, the manufacturing cost estimation phase is performed. As already highlighted, the modelling of the critical gap model provides a first simplification without affecting the functionality of the models and, therefore, of the simulations. However, before starting the cost estimation of the assembly following the PCM-based modelling approach (see section 3.4), a second step of model simplification is required for the engine block CAD model.

Engine block simplification

In this step of model simplification, the geometry of the engine block has been strongly simplified in its external geometry. The reason for this modification comes from two main issues, both of which are related to the complexity of the original engine block geometry.

Firstly, the geometry simplification provides an important reduction in manufacturing cost simulation times and, consequently, in the whole multi-disciplinary optimization times. In fact, due to the model-based nature of the ACE PCM tools, the cost calculation time is strongly affected by the complexity of the components: this is directly related to the automatic calculation of the machining operations necessary to manufacture each part. In the case of the engine block, both the dimensions and the geometry require high calculation times to perform the cost estimation: the first estimation executed on this component confirms that most of the complexity is related to the external geometry. However, since tolerance optimization focuses only on the engine block-crankshaft functional group, the external features of the engine block are not involved in the tolerance analysis and, therefore, they are not subject of the optimization.

Secondly, the possibility of highlighting the effects of tolerances on product manufacturing cost is hampered by the impact of the external geometry on the total cost. Indeed, these external features have an important contribution to the final cost of the product and the cost variation due to the variation of the tolerance values has a minor influence. Since the goal of the cost estimation is not the cost of the whole product, but the economic variation due to tolerances, removing these external features provides the possibility to better identify the tolerance contribution. Moreover, since the external features are not provided with tolerances within this case study, the cost associated with these features does not correspond to the real costs in any case.

For these reasons, the engine block geometry has been modified into a simple block, as shown in Figure 67. Since the new model must conform to the original in terms of tolerance analysis, providing the same results as CAT simulation, the modifications only affect the external features and all the non-functional features of the engine block. Therefore, all the functional features (highlighted in different colours in the Figure) are modelled respecting the original dimensions and geometries. Also, the tolerance scheme addressed as PMI is the same as the original model. This is confirmed by the CAT analysis performed on the new assembly, where the simplified engine block replaces the original engine block: the simulation results are equal to the previous ones, both in terms of capability values and contribution analysis.

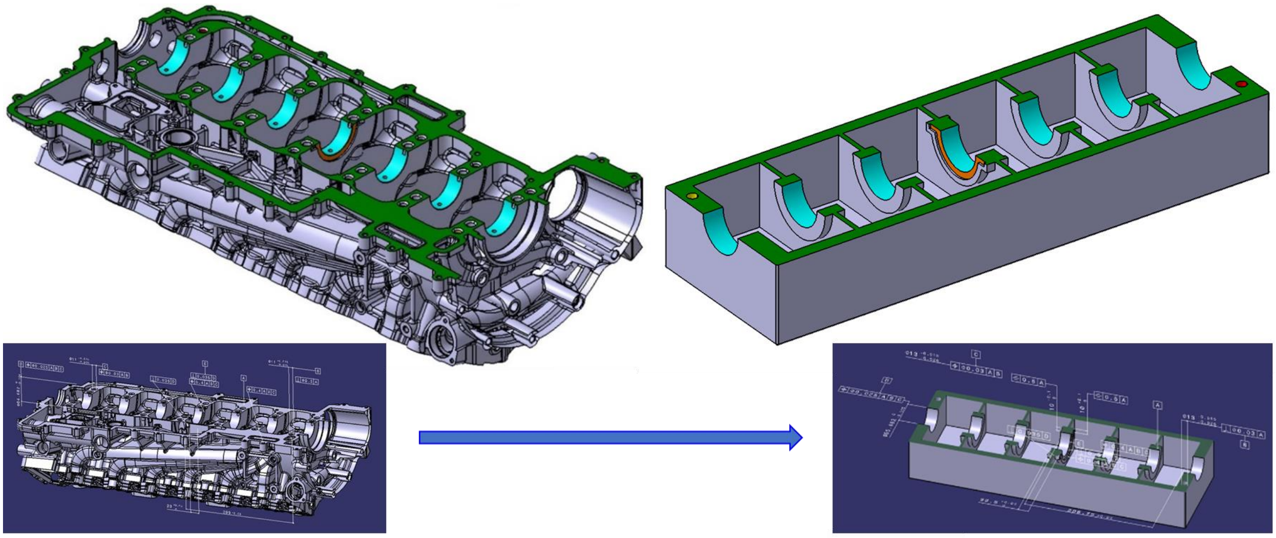


Figure 67. Engine block geometrical simplification

Manufacturing cost estimation

According to the main steps of the PCM-based modelling approach, the 3D models of the components are imported into the aPriori© software. Starting from the individual components, the primary process groups and the materials are selected and specified for each, according to the specifications provided by the company and external suppliers. For confidentiality industry requires, the materials reported here are different from the original: however, they belong to the same typology and, most importantly, to the same process group.

- *Engine block* – ANSI 357 Aluminium Alloy is selected for the engine block, with Casting – Die identified as the primary process group. Then, the software automatically identifies high pressure die casting as the cheapest process.
- *Thrust washers* – The material for the thrust washers is chosen from the software database as the 220 Bronze Cast. The primary process group is Casting – Die, as for the engine block. Similarly, the software selects high pressure die casting as the cheapest process.

- *Crankshaft* – AISI 4140H Alloy Steel is selected for the crankshaft, with stock machining operations selected as the primary process group. In this case, as provided by the product specifications, the machining operations selected on the software are the 2 axes Lathe and 5 axis mill machining.

Then, 5500 annual units for 5 years are selected as production rate for all components, and the production location is set in western Europe. Once the cost model settings are completed, the first configuration of tolerances is imported, already inserted in the 3D CAD models as PMI: the software automatically reads these values and associates them with the corresponding geometric features. In this way, it recognizes the additional operations to achieve the tolerance values, identifying each associated cost driver. This results in the final manufacturing process for each component, as reported in Figure 68.

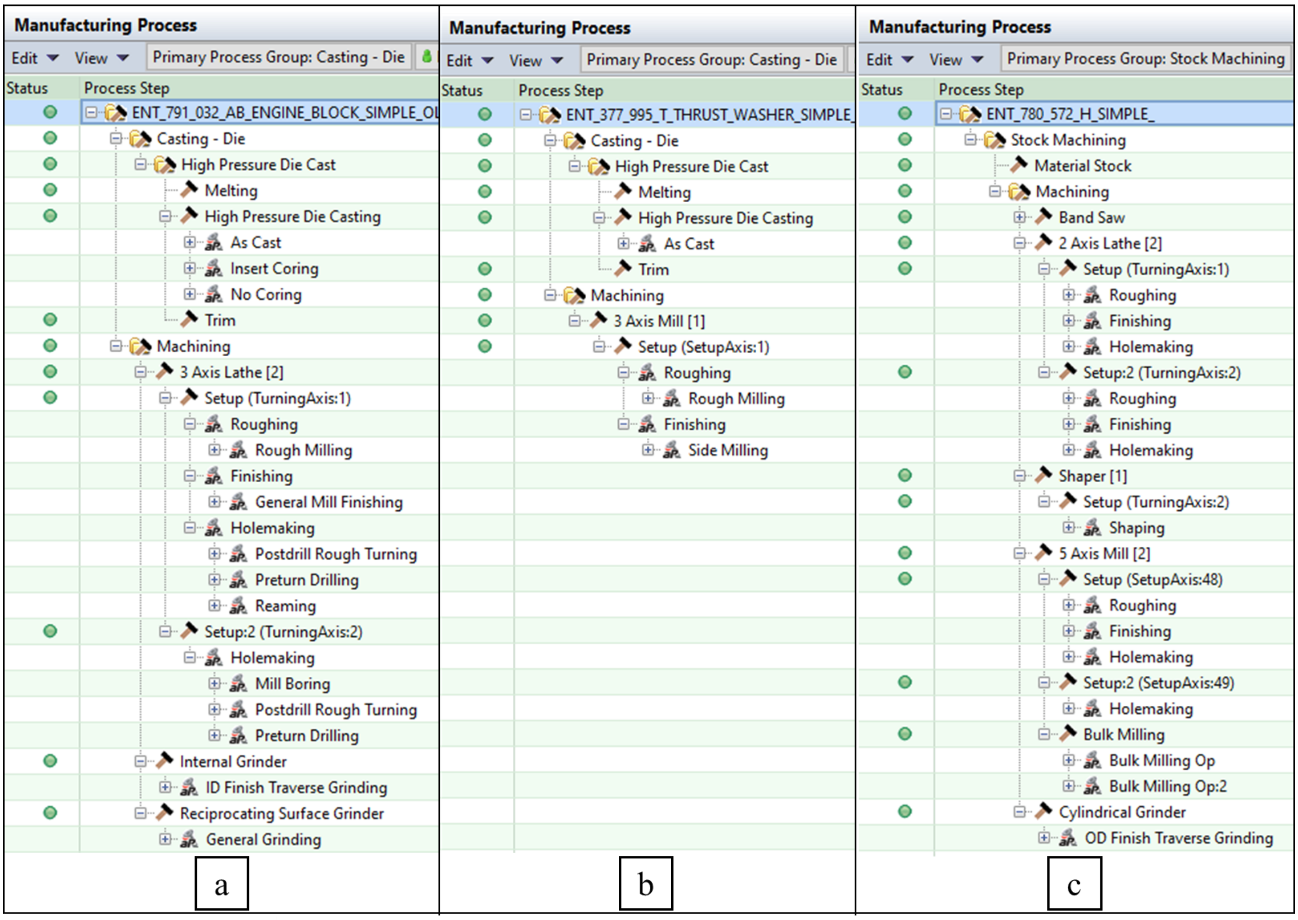


Figure 68. Manufacturing process: a. Engine block; b. Thrust washer; c. Crankshaft

Finally, the same manufacturing options are assigned to the assembly model, whose assembly process consists of simple pick and place operations.

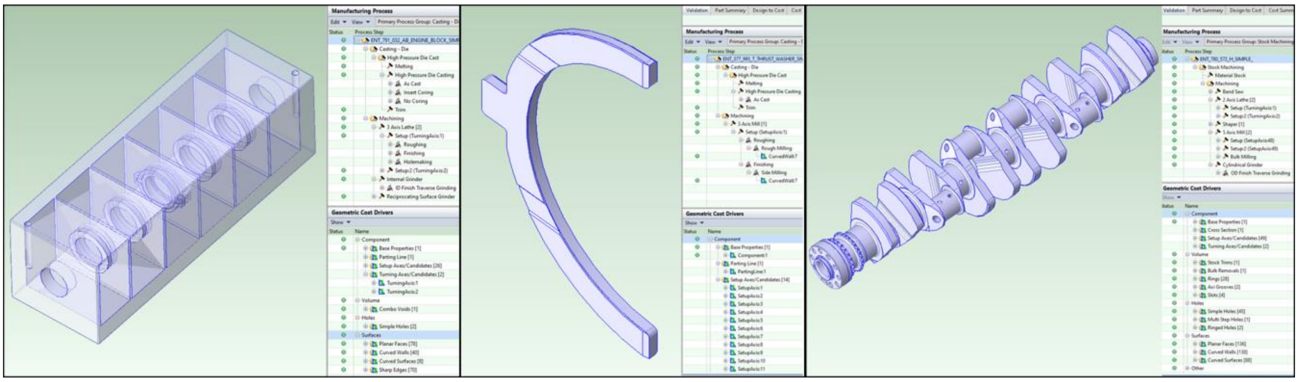


Figure 69. Engine components manufacturing models

After setting up the manufacturing models (reported in Figure 69), the cost estimation for the starting tolerance configuration is executed, providing the values of manufacturing cost for each component:

- *Engine block* – $ 197.00
- *Thrust washer* – $ 1.67 (for each thrust washer)
- *Crankshaft* – $ 1133.22
- *Assembly operation* – $ 2.25

This results in a total cost (considering the two thrust washers) of $ 1335.81. This is the initial cost of the model and, in conjunction with the results of the initial CAT analysis, it provides the starting configuration of tolerance values for the tolerance-cost optimization model.

Therefore, together with the 3D CAD models of the components, these models are imported as input into the multi-disciplinary optimization environment to implement and set up the optimization problem, as described in the next subsection.

4.4 Tolerance-Cost Optimization

MDO implementation

Once the starting configuration for both tolerance and cost simulation models is completed, the MDO structure for the tolerance-cost optimization of the engine is implemented. The structure follows the workflow introduced in the previous chapter and developed in-depth in section 3.5: the structure provided with the last case study has been applied, thanks to the good results obtained. Indeed, the assessment provided by the introduction of PMI has improved both interoperability, through the enhancement of data sharing between simulation models, and automation of the optimization process, since the iteration of the input variables, i.e., the update of tolerance values, is improved acting directly on the PMI within the CAD models.

For this reason, the MDO environment is developed following this workflow, as shown in Figure 70. As for the other case study, the CAD models are inserted as starting elements of the optimization structure. In this case, the four components are inserted (highlighted in light green in the Figure): the engine block, the two thrust washers, and the crankshaft, all as CAD files (.CATpart). Also in this case the assembly file (.CATproduct) is directly linked to the part models and included in the CAT and PCM models, so it is not necessary to add an assembly node to the structure. The tolerances entered in the CAD models as PMI are selected from the models and identified as optimization variables (highlighted in green in the Figure). For each of them, the required variation limits are included: in particular, the admissible range of variation for the tolerances of the functional areas (i.e., the dimensional tolerances on both main journal bearings and main journal supports) is set to guarantee the correct coupling conditions.

Then, the CAT analysis model is implemented as usual (highlighted in red in the Figure), with all the nodes required to let the simulation run automatically: in order, import the CAT file (.cxm) with the assembly model; link the optimization variables (the PMI tolerances) with the tolerances scripted in the CAT file; run the analysis in batch mode; extract the capability value (as for the previous case, the C_{pk} index is selected) from the simulation output file (.cxm). For each iteration, the output value of each configuration is evaluated with respect to the functional target, set as the first optimization objective (highlighted in orange in the Figure): in this case, the objective is to maximize C_{pk}, with the constraint of $C_{pk} \geq 1.33$.

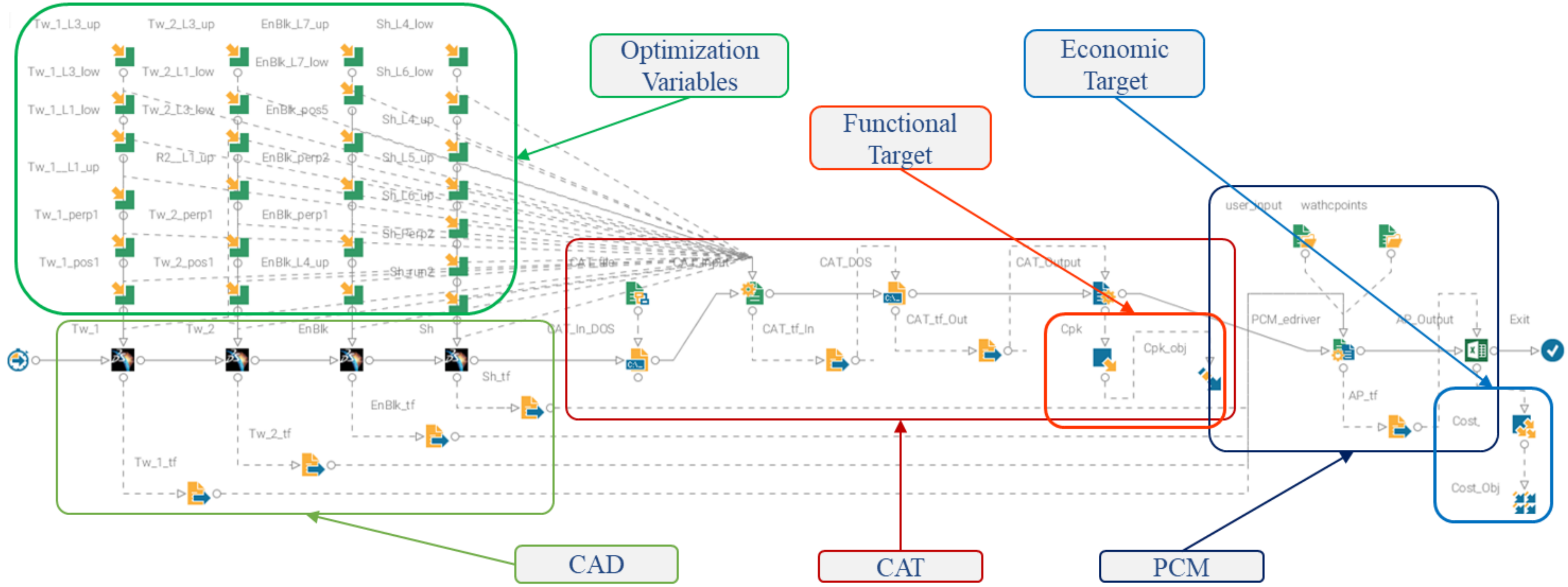


Figure 70. Tolerance-Cost Optimization model (MDO)

Finally, the manufacturing cost estimation is structured (highlighted in dark blue in the Figure) implementing the PCM model as for the previous case study: the CAD models of the part are connected to the PCM simulation node, as well as the other nodes necessary to let the simulation run in batch mode. Then, the component costs are selected and extracted from the results of the cost estimation (.xlsx) and compared with the economic targets (highlighted in light blue in the Figure): also in this case, the economic objective is the minimization of the total production cost through the minimization of the cost of each component (the cost of the assembly operation is not affected by the variation of the tolerance values).

At this point, the entire structure of the MDO model for the engine assembly is defined, so the final step is the set-up of the optimization. The high complexity of the case study requires planning the proper optimization strategy. Compared to the previous case study, the number of optimization variables is similar, as are the optimization objectives, but the geometric complexity of the components is greater. As already described in the previous subsection, the CAD model of the engine block has been simplified to avoid the issues associated with estimating the cost of the external geometry. However, the number of features to be considered is still large, particularly for the crankshaft. Moreover, the manufacturing processes provided by the PCM software have multiple steps and different machining operations. The result is that the simulation time required for the optimization to complete each tolerance configuration, including both tolerance and cost simulations, is 15 minutes.

Therefore, to comply with the need to explore a large number of configurations in the shortest possible time, the pilOPT algorithm (already applied in the previous case study) is selected as optimization technique. Since the algorithm must start from a preliminary design to generate new populations, the Sobol DOE algorithm is selected, as for the previous tolerance-cost optimizations performed. Considering the number of variables and objectives, 50 DOE configurations are programmed to be generated. Then, the optimization algorithm investigates the design space, based on the number of programmed evaluations (alternatively, different conditions can be entered as stopping criteria): in this case, 600 evaluations are planned. In this way, the optimization provides a wide exploration of the design space to define a Pareto frontier of the most suitable solutions. Since each point of the frontier represents a Pareto-optimal point, in terms of tolerances-cost design, multiple solutions can be identified and analysed.

Tolerance-cost optimization results

The optimization results are analysed by comparing all the simulated configurations with respect to the economic and functional objectives. The values of the manufacturing costs of all the components and the value of the capability index for each configuration are shown in Figure 71. Starting from 600 configurations, only 67 feasible configurations are identified (highlighted in green in the Figure), which comply with the constraint of $C_{pk} \geq 1.33$.

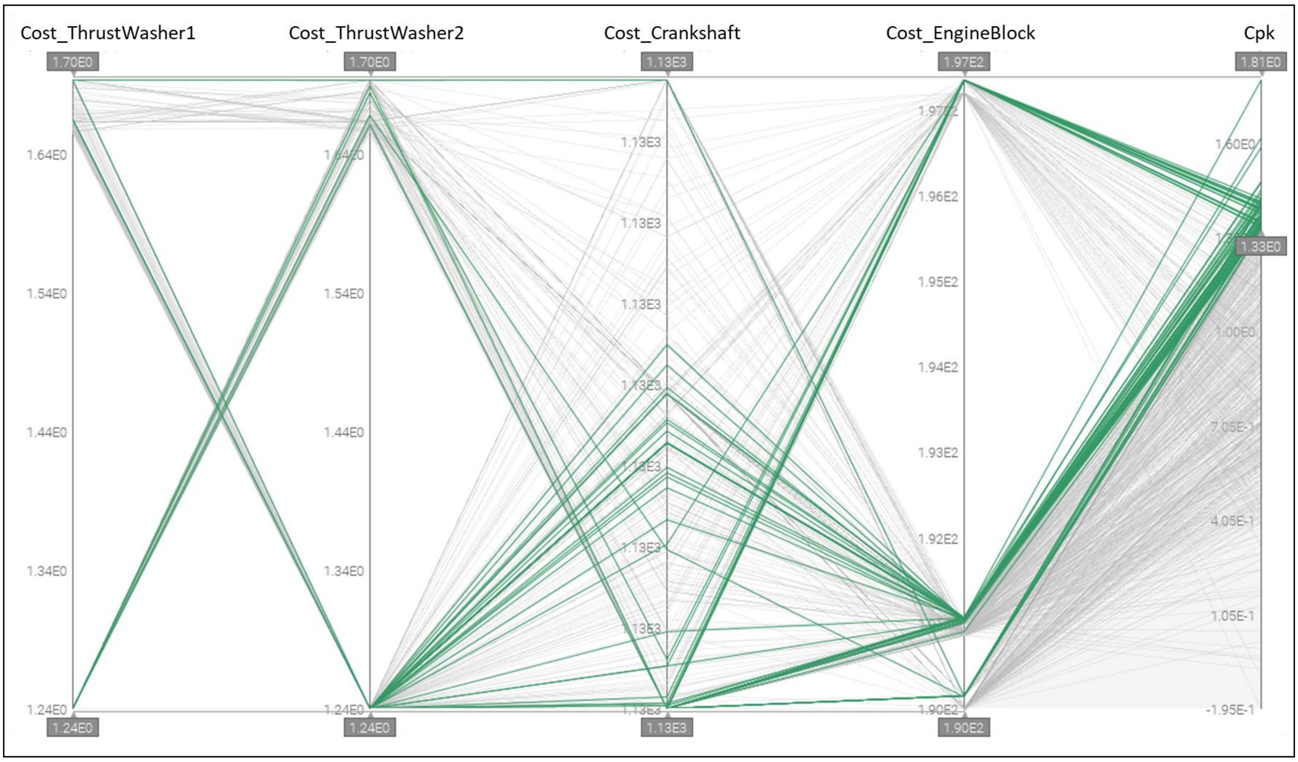


Figure 71. Optimization results

The configurations that achieve the functional constraint are then evaluated. Several factors must be considered to identify the most suitable, first of all the feasibility of tolerance values with respect to production costs. In fact, some of these configurations provide high values of C_{pk}, but require an excessive increase in cost, which is not achievable with the current manufacturing process and the production rates adopted by the manufacturer. In addition, their feasibility with respect to the other component tolerances must be considered: although reducing the number of tight tolerances is always a good strategy to avoid costly machining operations, sometimes these still have to be included in the manufacturing process, due to other product requirements. Therefore, evaluating the optimal configuration can be a complex activity for some industrial products: the best way to take full advantage of this approach is to plan a complete optimization approach, to address and optimize the tolerance design of each functional area.

For this reason, the evaluation of the optimal configurations for the present case study has followed a qualitative approach, to select the most promising: the distribution of feasible configurations in the design space is evaluated with respect to the objective values and the Pareto front as shown in Figure 72. Then, the values for all optimal configurations are compared according to the design specifications of each component, as provided by the company.

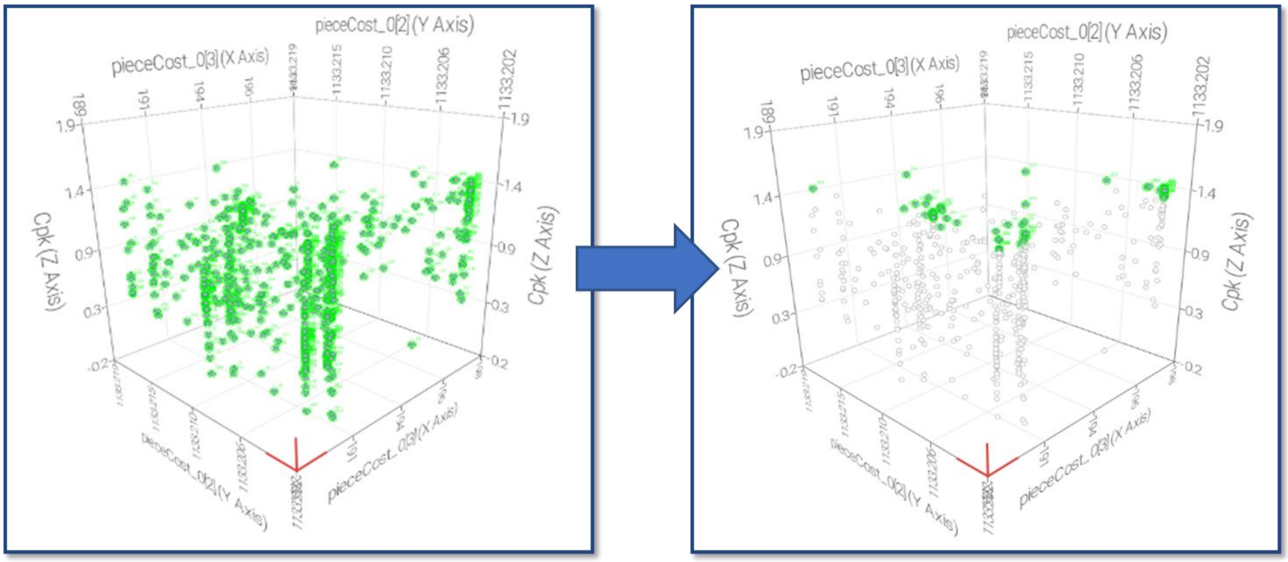


Figure 72. Optimization design space: evaluation of optimal configurations

As a result, in the set of 67 feasible configurations, 3 optimal configurations are identified: the best C_{pk} configuration n°353, the least cost configuration n°575, and the best trade-off configuration n°527, reported in Table 8 together with the values of the initial configuration.

Table 8. Simulation results: optimal configurations

ID	Cost_TW1	Cost_TW2	Cost_CS	Cost_EB	Cost_AO	Total_Cost	C_{pk}
0	$ 1.67	$ 1.67	$ 1133.22	$ 197.00	$ 2.25	$ 1335.81	1.297
353	$ 1.24	$ 1.68	$ 1133.20	$ 190.87	$ 2.25	$ 1329.24	1.592
527	$ 1.24	$ 1.24	$ 1133.20	$ 190.85	$ 2.25	$ 1328.78	1.486
575	$ 1.24	$ 1.24	$ 1133.20	$189.94	$ 2.25	$ 1327.87	1.422

- Best C_{pk} #353 – This configuration achieves the best value of C_{pk}, corresponding to 1.592. Compared to the original values of the functional requirement, the increase is 22.74 %. The corresponding total manufacturing cost of $ 1329.24 provides a 0.49 % reduction over the original cost of the product. In this case, the cost of all components has been reduced compared to the original, except for the second thrust washer, with an increase of $ 0.01. In addition, it should be noted that the crankshaft cost is reduced by only \$ 0.02. This is due to the complexity of its geometry: as several manufacturing operations still have to be addressed, the variation of tolerances on the overall cost provides a minimal effect. Different configurations allow a greater reduction in the cost of the crankshaft but have been excluded as they do not meet the other conditions. This configuration is very interesting in terms of functional capability, but the two thrust washers have a different cost due to the different tolerance values addressed: even if the values are feasible, this is unavoidable for the real application as both thrust washers must have the same specifications to guarantee the same performance for all operating conditions (i.e., the states “1°Misura” and “2°Misura”).

- Least cost #575 – This configuration provides the best achievement of the economic objective, the minimization of the overall cost. In this case, the total manufacturing cost is \$1327.87, corresponding to a 0.59 % reduction from the starting value. The total cost reduction is obtained with a reduction of the cost of all the components: as for the previous configuration, the cost of the crankshaft has a minimal variation compared to the original value. This time the cost of the thrust washers is the same, so the configuration is more suitable for a feasible implementation. As for the capability performance, the configuration reaches a C_{pk} of 1.422: although lower than the best C_{pk} value, it is still much higher than the original configuration, with an increase of 9.64 %. Consequently, this configuration is very attractive since it achieves all objectives through the effective optimization of tolerance values.

- Best trade-off #527 – Compared to the previous configurations, this has been identified as the best trade-off, as it provides the most balanced tolerance values. The C_{pk} value obtained is 0.486, with an increase of 14.57 % from the original product capability. Although lower than the best C_{pk} configuration, this value is achievable as it is obtained from a feasible manufacturing process for all components (the thrust washers have the same production cost). In addition, the total manufacturing cost provided by this configuration is \$ 1328.78, with a reduction of 0.53 % from the original cost. This means that, even if the total cost provided is higher than the least cost configuration, the relative difference is minimal and compensated by the increase of capability, i.e., the reduction in the number of rejects.

As a result, the best trade-off configuration seems to be the most attractive, providing the best configuration of product tolerances. As already mentioned, further investigations are necessary to verify the total feasibility of the configuration with respect to the other tolerances applied to the components.

Therefore, it is foreseen that the tolerance-cost optimization of the V12 engine assembly will be applied to a large number of sub-groups to achieve the goal of a complete tolerance design optimization and, consequently, the product design validation.

Conclusions

The design process of industrial products has always been subjected to continuous evolution, forced by the increased complexity of products, strong competitiveness and limited profit margins. This has led to a growing demand for advanced techniques to optimize product development, improving quality while reducing time-to-market and production costs. For this reason, Design for Tolerance and Design to Cost methodologies have been developed over the years: important innovations and design strategies have been proposed to increase the appeal of these methodologies for industries, especially in main industrial sectors such as automotive. As pointed out, tolerance-cost optimization is becoming the key practice to provide the effective application of DfT and DtC approaches: addressing all major stages of the tolerance design process, it leads to an integrated strategy for design optimization. However, even though other important techniques and tools for enabling DfT and DtC approaches are already known to the industry and are constantly being refined, tolerance-cost optimization is not yet fully explored. Consequently, despite its high potential, a profitable application in the industry is hampered by several factors: the high number of interdisciplinary elements, the difficult modelling of the relationship between influencing factors and the lack of detailed information on processes are the main obstacles. In addition to this, as already highlighted in section 2, the main limitation is methodological and organizational rather than technical: an important number of companies already use Computer-Aided tools and advanced techniques, but the lack of an integrated and multi-disciplinary approach limits their effective application and, therefore, their potential. With respect to the design process currently adopted by most car manufacturers, described in section 2, the fragmentation of the design process and the lack of a systematic approach for tolerance and cost optimization are the most challenging drawbacks and issues.

The PhD research activity aimed to define and develop an integrated design methodology for design optimization to better exploit the capabilities of both DfT and DtC approaches and Computer-Aided advanced simulations. A Computer-Aided Integrated Approach of Tolerance-Cost Optimization for product/process design optimization has been proposed.

More in detail, the research work aims to:

- Overcome the limitations of the design process currently adopted in industry, proposing a convenient and effective application of research strategies and techniques.
- Structure a design process based on the development of digital models with high information content (data and know-how), to increase their change and updating, minimizing errors and data scatter during design activities.

- Improve design optimization, using advanced simulation tools and integrating frameworks to optimize tolerances, to achieve product quality, functionality, and cost requirements.

- Effectively predict the performance of the final product from the early design stages, reducing development times and costs.

Therefore, the methodology has been formulated addressing two main objectives: to integrate the production process into the product design process, by centralizing the information required for tolerance design within the CAD models through a widespread use of 3D semantic annotations (PMI); to increase the accuracy of the analysis, avoiding dimensional simplifications by using integrated techniques, simulations, and optimization tools.

Chapter 3 describes the development of the methodology, consisting of several phases composed of subsequent steps to which are assigned the corresponding Computer-Aided tools to convert each step into a clear sequence of practical activities. For each phase, a systematic modelling procedure is formulated and implemented on different case studies: according to the state-of-art and the corresponding tools, the methodology has been stressed, proving its suitability for real applications.

The methodology development consists of:

- <u>An integrated method to systematically apply geometrical product specifications on 3D models.</u>

A CAD-based tolerance specification and annotation framework has been provided for the systematic selection of optimal GD&T schemes and types (section 3.2). The framework aimed to overcome the main difficulties of the tolerance specification process through the integration between the GD&T-based approach and parametric 3D CAD modelling. The use of 3D semantic annotations, provided with guidelines for the selection of DRFs and functional features on 3D CAD models, has been formalized for an easy and unambiguous definition of tolerance schemes. In addition, this method gives engineers the ability to move beyond the 2D drawing phase, reducing data scattering during the design process and enhancing MBD. The proposed workflow has been implemented for the tolerance specification of a general mechanical assembly to provide practical application and evaluate the method.

- <u>A systematic approach for Computer-Aided tolerance analysis modelling.</u>

A CAT-based modelling approach is provided to support engineers in the correct use of the tool (section 3.3). The CAT modelling procedure has been formalized to give practical guidelines, allowing easier use even without particular skills and regardless of the particular CAT software. Thanks to the presence of 3D semantic annotations within the CAD models, the integration between CAD and CAT is a key element for the automatic transfer of information and, therefore, the automation of the whole tolerance-cost optimization. A simplified model of an industrial gear motor has been considered to assess the modelling approach: a complete analysis is provided to identify the main contributors to variation, understanding which tolerances affect the functional requirements the most. Then, a V12 engine assembly from the automotive sector has been chosen as second case study to verify the suitability of the method for a real industrial application: the CAT analysis has been performed on the assembly of the engine block components to ensure a high process capacity. The tolerance design of the assembly is checked and validated providing corrective actions to fulfil the expected requirements, through the identification of the most influential tolerances and reference elements. The same engine is then used as a final case study for the tolerance-cost optimization.

- A systematic approach for the Manufacturing Cost estimation modelling.

A PCM-based modelling approach is provided to standardize the modelling and simulation procedure for PCM ACE software (section 3.4). The approach has been structured in several steps, addressed in a hierarchical order. In this way, it is possible to overcome the current limitations of these relatively new and not standardized tools. In particular, the model-based approach of ACE PCM tools is further enhanced by the use of PMI: product specifications are imported directly from 3D models, increasing interoperability and automation between software. The PCM-based modelling approach has been applied to a general mechanical assembly to enable its implementation for manufacturing cost estimations on industrial case studies.

- An integrated framework for the tolerance-cost Multi-Disciplinary Optimization.

The Computer-Aided Tolerance Cost Optimization has been formalized (section 3.5). Two main tasks have been addressed. First, the integration of the developed approaches for tolerance specification, CAT simulation, and PCM cost estimation, identifying the proper strategy for linking CAT and PCM simulation models. Second, the development of the multi-disciplinary optimization structure through the integration of PMI, to enable the automatic sharing and updating of tolerance information, and the definition of the optimization strategy. The methodology has been implemented within a Multi-Disciplinary Optimization (MDO) Platform, defining the main structure of the framework and providing the connections between software models, design variables, objectives, and constraints. An archetypal model belonging to an automotive engine assembly has been the first case study to focus on the integration between CAT and PCM models: the tolerance-cost optimization of the assembly has led to setting the main structure of the optimization model. Hence, a more systematic assessment of 3D semantic annotations within the MDO has been addressed, becoming the key element of the optimization. PMI are set as optimization variables, improving the methodology: data sharing and interoperability between Computer-Aided tools are exploited and CAD models are automatically updated. An evolution of the mechanical assembly has been selected as a case study to assess the new structure of the framework and to stress the optimization strategy: the increased complexity of the optimization problem has been addressed through a more refined optimization setting. The tolerance-cost optimization returns optimal configurations for the assembly and validates the modifications addressed to the MDO structure. These final stages of methodology development resulted in improved suitability of tolerance-cost optimization for industrial applications.

Finally, to allow the validation of the methodological aspects, the Computer-Aided Integrated Approach for Tolerance-Cost Optimization has been applied to an industrial case study in collaboration with Automobili Lamborghini S.p.A.: the high-performance V12 engine assembly. Unlike the previous case study developed on the same assembly (the CAT analysis of the engine block assembly operations), this case study has focused on optimizing engine tolerances to meet both functional and economic objectives. The optimization has involved the tolerances affecting the engine block-crankshaft subgroup, achieving the expected performance while reducing the overall production costs. Several configurations of tolerances resulted from the tolerance-cost optimization. Among these, the most interesting have been evaluated and selected to identify the optimal configuration of tolerance values. Therefore, the expected targets in terms of tolerance design optimization have been achieved for both product performance and cost reduction.

From a scientific viewpoint, the case study confirms the industrial applicability of the methodology for tolerance-cost optimization, showing the importance of applying a systematic approach to all the modelling and simulation phases, a key point to correctly address the required specifications. Furthermore, the study has highlighted the need to balance the complexity of the models, to ensure the realism of the simulations without affecting the calculation times and the complexity of the optimization itself: indeed, the modelling of the starting configuration models is critical to optimize the whole process.

To conclude, the Computer-Aided Integrated Approach for Tolerance-Cost Optimization provides an improvement in the field of Dimensional Management and Cost Management. The integration between theoretical approaches and Computer-Aided tools has led to the achievement of the aforementioned goals, proving the suitability of the methodology to achieve product design optimization.

Future developments

Considering the attractiveness of the methodology and the good results, further investigations are planned to strengthen its implementation for industrial applications. The research work is foreseen to investigate different areas of improvement, according to two main objectives.

First, new variables related to product design will be addressed to improve the methodology:

- Tolerance-cost optimization capabilities will be further explored to compare different tolerance schemes. Not only tolerance values but also tolerance types and DRFs can be considered as optimization variables.
- In addition to GD&T, the nominal dimensions of the components will be included within the MDO framework to optimize the dimensions of the functional features related to the 3D models.

Then, several applications are foreseen to stress the methodology, addressing new case studies and, in particular, focusing on the design optimization of products with specific production processes and technologies. Two case study applications are currently being explored, focusing on:

- Welding – A fuel tank assembly from a motorbike is selected to investigate the tolerance-cost optimization of a welded assembly. The main goal of the application is the modelling of tolerance and cost simulations to address the manufacturing process, consisting of two steps: the welding operation between the fuel tank components and the fuel tank assembly operation on the motorbike. Considering the wide range of welded products currently produced in the automotive sector and the critical steps related to welding operations in terms of geometric deviation, this application will provide important refinements to the methodology.
- Directed Energy Deposition – The object of this case study is the design optimization of a high-performance automotive component produced through Directed Energy Deposition (DED) technology. A suspension wishbone has been selected to be redesigned, verifying both assembly and economic requirements. Considering the growing popularity of this technology and the wide range of parameters related to this process, the implementation of the methodology appears to be very promising for optimizing product design and achieving the best trade-off between product performance and manufacturing costs.

Furthermore, CAE simulations will be implemented within the Computer-Aided Integrated Approach. Integrating CAE simulations with CAT and PCM simulations can be a key factor to enhance product design optimization and refine the methodology, exploiting the capabilities of the MDO environment.

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