Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Corso di Dottorato in Ingegneria Industriale

CAD-integrated Design for Manufacturing and Assembly: a method and a tool for manufacturing-compliant and cost-effective products

Ph.D. Dissertation of:

Federico Campi

Advisor:

Prof. Michele Germani

Ph.D. Course coordinator:

Prof. G. Di Nicola

XIX edition - new series

Università Politecnica delle Marche
Dipartimento di Ingegneria Industriale e Scienze Matematiche
Via Brecce Bianche — 60131 - Ancona, Italy

Acknowledgements

This thesis is part of the research work co-financed by *Nuovo Pignone Tecnologie S.r.l.* in Florence and *Università Politecnica delle Marche*. My first thanks go to these Institutions and Company for having given me the opportunity to accomplish this experience.

From the Company side a big thanks are in particular to the engineers *Giulio Lo Presti*, *Francesco Pescatori*, *Emanuele Checcacci* and *Irene Martinelli* who gave me the possibility to work with them in research activities of a great company.

From the university side, I wish to express my most gratitude to my advisor, Prof. *Michele Germani*, who was able to initially motivate me about the importance of research, has guided me through the Ph.D. years and also involved me in several interesting research projects.

Appreciation must also be given to *Claudio Favi* and *Marco Mandolini* whose numerous suggestions have contributed to considerable improvements in this thesis. I am really grateful to all of the Professors, Researchers and Collaborators involved in the *DT&M Research Group*, with whom I spent 3 fantastic years and share a formative period of my life in which I learned a lot from them.

Gratitude, also, to *HyperLEAN S.r.l.* in particular to *Daniele Bolla*, *Giorgio Moskwa*, *Matteo Marchionne*, *Irene Cappelli* and *Andrea Finaurini* to with whom I worked in research projects, giving me the chances to learn some of their knowledge.

The greatest thanks go certainly to all my *Family*, my *parents* and my beloved *cat*. They gave me the possibility to take up this career and supported me in any decision and in any difficulty.

A special thanks go to *Sabrina*, my girlfriend, who supported and supported me. Thank you for always being with me when I need you.

Abstract

On the competitive global markets of today, companies have the objective to increase profits by reducing development costs and increasing quality. Early engineering design decides the opportunities and limitations of the later phases and is the costs disposed of by early engineering design, and often seen later when they occur, e.g. during manufacturing, that can be high and often too high.

However, in the earlier design process, few support tools for 3D engineering design are available, often due to a lack of knowledge of design requirements and constraints. In these phases Design for Manufacturing (DfM) and Design for Assembly (DfA) take an important role, but DfM and DfA are not really integrated with 3D CAD systems. DfM and DfA principles are currently applied at the end of the 3D CAD modelling, by following the well-known guidelines available from the literature and company's know-how. This know-how is disseminated among employees and technical departments and represents a critical issue.

The research goals of this thesis could be synthesized as the definition of a new methodology and a software tool that helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed. The methodology, starting from the 3D CAD model of the part or assembly, extracts necessary information with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules validation. After retrieving the information, DfM/DfA and cost analysis can be made, and the designer can then apply the changes suggested in the 3D model.

The proposed CAD-integrated DfM/DfA and cost methodology was used to perform DfM/DfA and cost analysis by using 3D CAD models of 4 components (2 forged parts and 2 machined parts) and 2 product (assembly). Case studies show how the proposed method is able to discover the design issues avoiding manufacturing/assembly technological problems and allowing costs reduction at the same time.

Contents

List of Figures

List of Tables

List of Acronyms

2D	*2 Dimensional*
3D	*3 Dimensional*
ABC	*Activity-Based Costing*
AEM	*Assemblability Evaluation Method*
AHP	*Analytic Hierarchy Process*
AM	*Additive Manufacturing*
BOM	*Bill Of Materials*
BPNN	*Back-Propagation Neural-Network*
BRep	*Boundary Representation Model*
CAD	*Computer Aided Design*
CAE	*Computer Aided Engineering*
CAM	*Computer Aided Manufacturing*
CAx	*Computer-Aided Technologies*
CE	*Concurrent Engineering*
CPs	*Cost Primitives*
CT	*Completion Time*
DB	*Database*
DfA	*Design for Assembly*
DfD	*Design for Disassembly*
DfE	*Design for Environment*
DfLC	*Design for Life Cycle.*
DfM	*Design for Manufacturing*
DfMA	*Design for Manufacture and assembly*
DfMt	*Design for Maintainability.*
DfQ	*Design for Quality.*
DfR.	*Design for Recyclability.*
DfRL	*Design for Reliability.*
DfS	*Design for Safety*
DfSC	*Design for Supply Chain*
DfSv	*Design for Service*

DfX	*Design for X*
DtC	*Design-to-Cost*
FEA	*Finite Element Analysis*
GUI	*Graphical User Interface*
IPD	*Integrated Product Development*
KB	*Knowledge Based*
LC	*Life Cycle*
LCC	*Life Cycle Cost*
NPD	*New Product Development*
PDP	*Product Development Process*
PLM	*Product Life Cycle Management*
PMI	*Product Manufacturing Information*
SE	*Simultaneous Engineering*
SeqE	*Sequential Engineering*
TTM	*Time-to-Market*
UML	*Unified Modeling Language*

1. Introduction

This chapter introduces the dissertation, starting from a brief background of Product Development Process and Concurrent Engineering methods and tools, explaining then the motivation and the objective of the thesis and its structure.

1.1. Background

Product Development Process (PDP) is a consolidated engineering activity that takes a service or a product from conception to market. Product development includes few steps: drafting the concept, creating the overall design, developing detailed design and then prototyping. While the first stages of the PDP consist on idea generations and is an iterative process able to figure out conceptual solutions, the last stages of the PDP are focused in engineering design, with more practical activities and recursive tasks.

The engineering design defines the geometry, materials, tolerances and the complete specifications of all the product's components through detailed drawings of the parts and general assembly drawings. The result of this phase is the complete and precise physical description of all the product's parts.

One of the most recurring disciplines in the engineering design contexts is CAD (Computer-Aided Design), which relates to solid modelling and drawing. Since its birth, CAD evolved from the role of electronic drawing boards to 3D solid modellers with parametric philosophy. CAD are conceived to virtually create the part, display it in 3D view environment, verify the consistency of the final assembly and quickly realize 2D engineering drawing. Nowadays, CAD tools combine these capabilities with the benefits deriving from the integration of the multidisciplinary design methodologies. During the time, CAD systems integrated different environments for specific aims, such as environmental assessment (Morbidoni et al., 2011; Tao et al., 2018), kinematic analysis (Lee et al., 2003; Komoto et al., 2012) and ergonomic assessment (Feyen et al., 2000; Marconi et al., 2018).

On the competitive global markets of today, companies have the objective to increase profits by reducing development costs and increasing quality. To guarantee the business success, must be avoided the traditional “over the wall” work, where several company departments work separated from each other. On the contrary, integrated PDP and concurrent engineering (CE) allow to create teams that work in parallel during development in multidisciplinary way. A crucial stage in the product life cycle is the design stage. Any mistake in the design stage can be very costly in terms of engineering changes and its impact on manufacturing, delays in product release to the market with potential loss of the market, and product recalls in the case of a released product with significant financial losses and goodwill. Hence, there should be special emphasis on the design of the product, to ensure that the product can reach the market flawlessly and in the fastest time possible. Early engineering design decides the opportunities and limitations of the later phases, since the developed product geometry, for instance, affects how well the manufacturing, assembly, maintenance, and so forth will be conducted. It is the costs disposed of by early engineering design, and often seen later when they occur during, e.g. manufacturing, that can be high and often too high. When a problem is found later, e.g. during detailed design or manufacturing, going back to early engineering design and make changes is extremely difficult and involve more costs. However, in the earlier design process, fewer engineering design support tools are available, often due to a lack of knowledge of design requirements and constraints. It’s important developing an engineering design that can be manufactured by the machines and the crew of the production plant and preferably at the lowest cost. This is often referred to as Design for Manufacturing (DfM) and Design for Assembly (DfA) and several methods and guidelines for designing for manufacturing have been developed. General DfM and DfA strategies can help companies develop products that are feasible to manufacture, but to go further towards increased effectiveness, there is an opportunity to reuse results and use corporate knowledge gained from earlier projects and make this available as support tools during early engineering design.

1.2. Aim and motivation

On the other hand, DfM and DfA, which are consolidated engineering activities, are not really integrated with 3D CAD systems. DfM and DfA principles are currently applied at the end of the 3D CAD modelling, by following the well-known DfM and DfA guidelines available from the literature and company's know-how (internal tacit knowledge). This know-how suffers a strong dissemination among employees and technical departments and represents a critical issue. Results and corporate knowledge tend to stay within the group instead of being documented in a way that promotes reuse. In doing so, development performance is affected by staff turnover, which occurs when projects are finished, or by the often time demanding search for the right document that contains the right information. This issue increases when considering the extensiveness of information needed during functional product development. The mentioned practice highlights a gap in the state-of-art related to the CAD-integrated DfM and DfA methods and tools and the possibility to share manufacturing and assembly knowledge in the product design (explicit knowledge). During project development iteration are generally required, cause the project revision due to manufacturing and assembly issues. In this case iterations have a tremendous impact in terms of the amount of time and rework. Integrating DfM and DfA within CAD software's can reduce redesign and control activities and finally the overall project cost.

Then this thesis is focused in solving two questions:

1. How to make explicit the mixed manufacturing and assembly knowledge to support product designers during the product development process?
2. How to integrate knowledge into the product development process and how to make it effective during the design process and the 3D solid modelling and how to estimate the cost savings of the design changes during the 3D modelling?

Concerning the first question, it is well known that DfM/DfA design rules and cost estimation models are part of the company knowledge (through the experience and the skills of their engineers) whose dissemination among employees and technical departments is a critical issue. Knowledge can be divided into tacit and explicit knowledge. Tacit knowledge is the knowledge that people carry in their minds. Hence, this knowledge is not formalized and not widely used by an organization. Explicit knowledge, instead, refers to a set of information that can be articulated, codified, and stored in certain media. As a standard practice, designers usually use DfM/DfA guidelines as a sort of checklist once finished the engineering phase, or even worse. Sometimes, these guidelines are checked by production engineers before starting the production (approval of the technical drawings). This approach increases the time to market and the number of iterations between design and manufacturing departments (design reviews).

The main idea underpinning this research study concerns the possibility to link DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies.

The method concerns three main aspects:

1. *3D CAD Model feature recognition* and organization.
2. A *Knowledge-Based (KB) System* for DfM/DfA rules classification and deposition.
3. A *Rules Validation System* to connect 3D Model feature to DfM/DfA rules contained in the database.

At the same time, production knowledge represents the groundwork for a proper implementation of cost estimation models. To make knowledge usable, a data framework for knowledge collection is needed to deposit knowledge and then make it accessible to everyone involved within an enterprise.

From a cost estimation point of view two frameworks was developed, which can be used by designers and engineers for the analytical cost estimation of mechanical products. One framework is dedicated for manufacturing a single component, while the other one is for assembly of a group of parts. The *frameworks* are composed by five main paradigms used for formalizing the knowledge required for the cost estimation of products:

1. A *manufacturing/assembly process data structure* to represent the logical sequence of manufacturing or assembly operations.

2. A *cost breakdown structure* used for breaking out the manufacturing/assembly costs.

3. A *cost routing* used for the collection of the knowledge required for a manufacturing/assembly process definition.

4. A *cost model* used for the collection of the knowledge required for calculate the cost of each manufacturing/assembly process operation.

5. A *workflow* for determining a manufacturing/assembly process using 3D virtual prototypes.

The second question is addressed developing a methodology and a software tool that helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed. The methodology is composed by 5 main steps, starting from *3D CAD Model* of the part or assembly to be analysed (Step 1). The second step (Step 2) is dedicated to the *feature recognition and extraction*, in which are read the necessary information from the 3D CAD Model with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules. After that are conduct a *cost analysis* (Step 3) and the *DfM/DfA analysis* (Step 4), in which validated and non-validated DfM/DfA rules are displayed to the designer with the aim to keep him/her informed about the feature that are not compliant with the guidelines collected in the repository. In the last step (Step 5) the designer *update 3D CAD Model*. In this step the designer modifies the 3D model following the design suggestions in the reports within the total cost obtained. In particular, through the mean of feature recognition, specific features that generate non-validated rules are highlighted within the 3D model in order to facilitate the implementation of design modification. Once design changes are implemented, a new analysis is run to verify if the updated 3D model fits with the DfM/DfA requirements. If non-validated rules are still present, and the cost are not compliant with the project target, a new design review is required; on the other hand, if there is not any non-validated rule and the cost meet the project requirements the model can be frozen for manufacturing.

Methodology has been implemented in a specific software tool with a structure composed by four main modules: (i) *GUI*, (ii) *Feature recognition*, (iii) *Analysis framework* and (iv) *Database*.

1. The first module is dedicated to the *GUI*, the *Graphical User Interface*, with which the user interacts.

2. In the second module is contained the *Feature recognition*, which allow the connection between a CAD system and the tool.

3. The third module, the *Analysis framework*, is necessary for costs calculation and rules validations, continuously interfacing between feature recognition, databases and the GUI. Through the latter it allows the user to view costs and design rules.

4. The fourth module contain the *Database*, in which are stored the information about materials, machine and the rules for a correct design and cost estimation.

To verify the real advantages of the methodology and tool in design process was used an evaluation method based in two questionnaires, which were submitted to the tool users after extensive use (more than 6 months). The first one wants to quantify the usability of the software while the second one is focused on the advantages and disadvantages of the software use in design process. The test had the scope of evaluating the impact of the methodology and the related software on the traditional design process of a company and evaluate the interoperability between the new software and the design tools.

1.3. Organization/thesis outline

After this introduction (*Chapter 1*) the thesis has been structured as follows.

In *Chapter 2* is set the background of PDP with a focus on DfM, DfA and cost estimation methods and tools.

Chapter 3 presents the developed methodology used to make explicit the mixed manufacturing and assembly knowledge.

In *Chapter 4* are presented the developed software tool that helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed.

Chapter 5 is focused on the case studies used to validate the proposed method and tool to make clearer the various steps of the approach.

Chapter 6 presents the two questionnaires submitted to the tool users and the results derived from them.

Chapter 7 summarize the research and presents the overall conclusion of the thesis. Further, it suggests potential areas for further work.

2. Research background

In this chapter, literature will be investigated and discussed with the aim to create the research background for the subsequent development of the novel design methodology focusing at the product development process and the different approaches (traditional/sequential approach and concurrent engineering approach), describing also the methods and tools used.

The chapter is divided as following:

- *Section 2.1: introduce the product development process describing in detail the phases from which it is composed.*
- *Section 2.2: describe the difference between traditional approach and concurrent engineering and their application in scientific literature.*
- *Section 2.3: introduce the importance of cost estimation in product development, describing the various methods and tools present in academic and industrial field.*
- *Section 2.4: introduce the concept of Design for X (DfX) and the various typology which compose them. In particular, will be described the Design for Manufacture and the Design for Assembly, focusing on methods and tools present in academic and industrial field.*
- *Section 2.5: summarize the limits of the academic and industrial state of the art.*

2.1. Introduction of product development process

The recent advances in product development, global alliances among enterprises and changing customer needs, characterize a rapidly emerging global market economy. Products entering this market are designed and manufactured across geographical boundaries and distributed and marketed world-wide. In addition to a world-wide competition, companies are also faced with shrinking time-to-market for new products. This is the elapsed time between product conception to its actual availability on store shelves. During this period, the product goes through several stages, that collectively define the product life cycle (LC). The design stage is a long and iterative process for the development of certain products.

Pahl et al. (Pahl 2007) describe the workflow of the design process starting from the VDI Guidelines 2221 and 2222. VDI Guideline 2222 (VDI-Richtlinie 2222) defines an approach and individual methods for the conceptual design of technical products and is therefore particularly suitable for the development of new products. The more recent VDI Guideline 2221 (VDI-Richtlinie 2221) proposes a generic approach to the design of technical systems and products, emphasising the general applicability of the approach in the fields of mechanical, precision, control, software and process engineering.

Pahl et al. (Pahl 2007) provide an extensive description of this flow of work, focused on mechanical engineering. The description is essentially based on the fundamentals of technical systems, the fundamentals of the systematic approach and the general problem-solving process. The aim is to adapt the general statements to the requirements of the mechanical engineering design process and to incorporate the specific working and decision-making steps for this domain. In principle, the planning and design process proceeds from the planning and clarification of the task, through the identification of the required functions, the elaboration of principle solutions, the construction of modular structures, to the final documentation of the complete product.

In the first phase, customer requirements are collected and analysed, then, the requirements are translated into product functions and features, and finally, concepts that can satisfy the requirements are generated and modelled (Figure 1).

It is well known (Budiono et al. 2014) (Hooshmand et al. 2016) that although the design costs take up about 10% of the total budget for a new project, in general 80% of the production costs are determined in the development design phase. Manufacturing and assembly costs are decided during the design phase and their definition tends to influence the selection of materials, machines and human resources which are used in the manufacturing process. In traditional approaches, costs are assessed at the end of the design phase and only in this phase they are compared with the product performance.

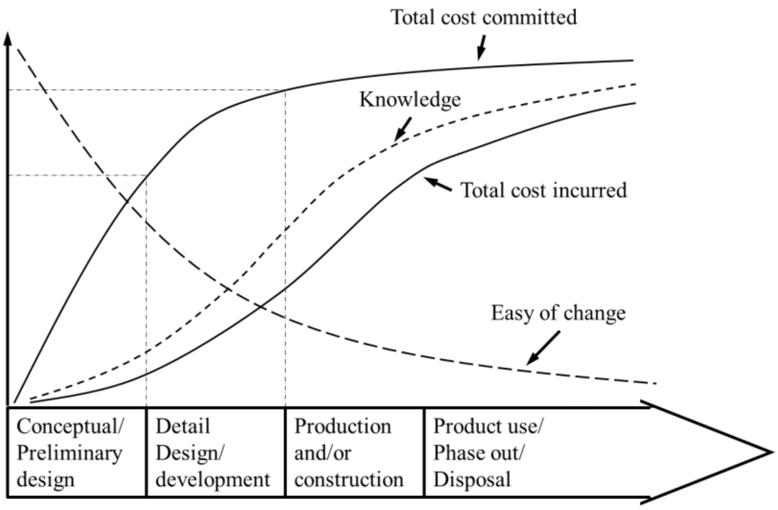


Figure 1 Time versus cost of changes

In addition to the planning of the specific tasks described above, it is useful and common to divide the planning and design process into four main phases: (i) *Planning and task clarification*, (ii) *Conceptual design*, (iii) *Embodiment design* and (iv) *Detail design*.

(i) Planning and task clarification: Generally, a product development task is given to the engineering department by the marketing department, or by a special department responsible for product planning. Irrespective of whether the task is based on a product proposal stemming from a product planning

process or on a specific customer order, it is necessary to clarify the given task in more detail before starting product development. The purpose of this task clarification is to collect information about the requirements that have to be fulfilled by the product and also about the existing constraints and their importance. This activity results in the specification of information in the form of a requirements list that focuses on, and is tuned to, the interests of the design process and subsequent working steps. The conceptual design phase and subsequent phases should be based on this document, which must be updated continuously.

(ii) Conceptual design: After completing the task clarification phase, the conceptual design phase determines the principle solution. This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Often, however, a working structure cannot be assessed until it is transformed into a more concrete representation. This concretisation involves selecting preliminary materials, producing a rough dimensional layout, and considering technological possibilities. Only then, in general, is it possible to assess the essential aspects of a the several principle solution variants and to review the objectives and constraints. The representation of a principle solution can take many forms. The conceptual design phase consists of several steps and none of which should be skipped if the most promising principle solution is to be found. In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from exaggerated concentration on technical details.

This claim does not conflict with the fact that problems may emerge during the detail design phase, even in the most promising solution principles or combinations of principles. The solution variants that have been elaborated must now be evaluated. Variants that do not satisfy the demands of the requirements list have to be eliminated; the rest must be judged by the methodical application of specific criteria. During this phase, the chief criteria are of a technical nature, though rough economic criteria also begin to play a part. Based on this evaluation, the best concept can now be selected. It may be that several variants look equally promising, and that a final decision can only be reached on a more concrete level. Moreover, various form designs may satisfy one and the same concept. The design process now continues on a more concrete level referred to as embodiment design.

(iii) *Embodiment design*: During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the specification of a layout. It is often necessary to produce several preliminary layouts to scale simultaneously or successively in order to obtain more information about the advantages and disadvantages of the different variants. After sufficient elaboration of the layouts, this design phase also ends with an evaluation against technical and economic criteria. By appropriate combination and the elimination of weak spots, the best layout can then be obtained. This definitive layout provides a means to check function, strength, spatial compatibility, etc., and it is also at this stage (at the very latest) that the financial viability of the project must be assessed. Only then should work start on the detail design phase.

(iv) *Detail design*: This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated, and all the drawings and other production documents produced. The detail design phase results in the specification of information in the form of production documentation. Quite often corrections must be made during this phase and the preceding steps repeated, not so much with the overall solution in mind, as to improve assemblies and components as well as reduce costs.

It is not always possible to draw a clear borderline between these main phases. For example, aspects of the layout might have to be addressed during conceptual design, or it might be necessary to determine some production processes in detail during the embodiment phase. Neither is it possible to avoid backtracking, for example during embodiment design when new auxiliary functions may be discovered for which principle solutions have to be found. Nevertheless, the division of the planning and control of a development process into main phases is always helpful. In Figure 2 are shown the steps in the planning and design process (Pahl 2007).

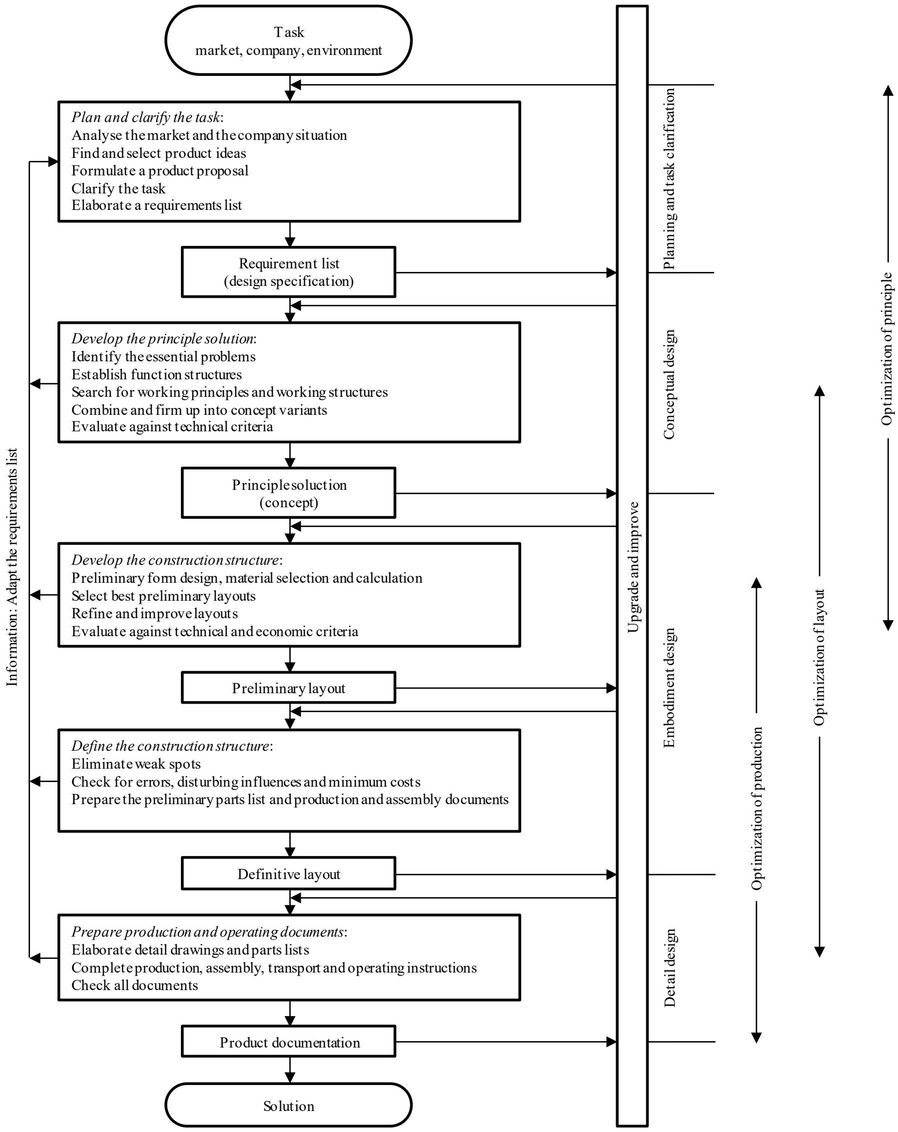


Figure 2 Steps in the planning and design process (from Pahl 2007)

2.2. Traditional approach and concurrent engineering

A crucial stage in the product life cycle is the design stage. Any mistake in the design stage can be very costly in terms of engineering changes and its impact on manufacturing, delays in product release to the market with potential loss of the market, and product recalls in the case of a released product with significant financial losses and goodwill. Hence, there should be special emphasis on the design of the product, to ensure that the product can reach the market flawlessly and in the fastest time possible. Getting it right the first time, which is all the more vital in a global market, can be implemented only with a good design. Concurrent engineering (CE), could achieve these objectives.

2.2.1. Traditional approach

Prior to describe CE and to understand it, it is useful to describe the traditional introduction and product development practice, Sequential Engineering (SeqE). This type of approach is also known by many other names, including *serial engineering*, *timephased engineering*, and the *chimney method* (Syan et al 1992). Putnik (Putnik et al. 2019) give a definition of SeqE: *"Traditional engineering, also known as sequential engineering, is the process of marketing, engineering design, manufacturing, testing and production where each stage of the development process is carried out separately, and the next stage cannot start until the previous stage is finished"*. Typically, in a manufacturing organization, marketing identifies the need for new products, price ranges and their expected performance from customers or potential consumers. As a result, the information in the different stage is not shared, and cooperation is lacking (Liu et al. 2004). Thus, the sequential operation of these functional stages results in long development times and potential quality problems due to the lack of communication and understanding of the different product design, manufacturing and above all customer requirements (Haque et al. 2000). Design and engineering receive loose specifications and commonly work alone developing the technical requirements (e.g. materials and size) and final design detail as well as the associated documentation such as drawings and bills of materials etc. As design is carried out in relative isolation, manufacturing, test, quality and service functions only see the design in an almost complete state.

The traditional approach advocates early selection of the supposedly best alternative be approved by the project management and only consider only one best solution (Maulana et al. 2016). It consists of employing more resources in the development process (De Toni et al. 2000) and develops a single solution, based on multiple disciplines or objectives. A single possibility is formulated, evaluated, and modified until a solution that meets the objective is obtained (Nahm et al. 2006).

In this sequential method of operation, a change required in a later stage will cause delay and additional costs in the upstream stages. Additionally, the subsequent stages will be delayed until the current stage has been completed. This approach encourages a large number of modifications and alterations in the later stages of the product development phase, when it is more expensive and difficult. In many cases investment in tooling and equipment is usually committed and the product launch date may already be fixed.

This traditional approach causes many weaknesses that include:

- Excessive amount of modification due to insufficient product specification.
- Little attention to manufacturability issues of the product at the design stage.
- Errors in cost estimation due to the uncontrolled late design changes.
- Expensive change in tooling or other equipment due to late changes.

2.2.2. Concurrent engineering

Concurrent Engineering (CE) was coined by Institute for Defense Analyses (IDA), USA (IDA-1986) and it was defined as: *"A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirement"*.

Concurrent Engineering, sometimes called Simultaneous Engineering (SE) or Integrated Product Development (IPD), means a way of work where the various engineering activities in the product and production development process are integrated and performed as much as possible in parallel rather than in sequence.

This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements. This results in the product development team clearly understanding what the product requires in terms of mission performance, environmental conditions during operation, budget, and scheduling. The aim is to alleviate these problems at an early stage of development by making suitable development decisions. CE provides a systematic and integrated approach to introduction and design of products. The subsets of CE include design for manufacture, design for assembly, design for maintainability, design for disposal and so on. Effective CE practice requires good communications between disparate functions associated with the product life-cycle. The information must have common ownership, be shared freely and must be easily and freely accessible. As information is seen to be power in functionally organized traditional companies, this suggests more open organizational structures such as matrix management and team work. CE is therefore the integration of all company resources needed for product development, including people, tools and resources, and information. The purpose of concurrent engineering is to ensure that the decisions taken during the design of a product result in a minimum overall cost during its life-cycle. In other words, this means that all activities must start as soon as possible, to induce working in parallel, which additionally shortens the overall product development process.

Winner (Winner et al 1988) presents the signature feature (also, basic, global, general features) of the CE, kept in virtually all definitions presented in scientific and technical papers and/or reports, in other words, about which there is a consensus in the scientific and technical community. These CE features are:

- *Simultaneity of processes* – With simultaneity there is a compression of New Product Development (NPD) Time or Completion Time (CT) or Time-to-Market (TTM), denoted T. In other words, simultaneity of processes contributes significantly to the reduction of T. Figure 3 and Figure 4 present respectively the signature structure of T, in sequentially performed operations and in case of operations performed with certain degree of simultaneity.

- *Concurrency*, through multifunctional (crossfunctional) teams (teamwork), considering "all elements of the product life cycle", that concurrently and interactively make decisions on new product development (NPD). (Simultaneity of operations (processes) does not assure concurrency per se. In the case of simple simultaneity, there is no interactive communication).

The effort of 1) and 2) from, or, in, the early stage of the NPD process, i.e. in the phase of design.

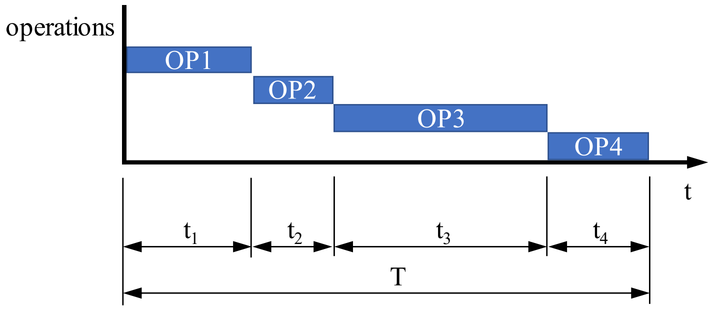


Figure 3 Sequentially performed operations

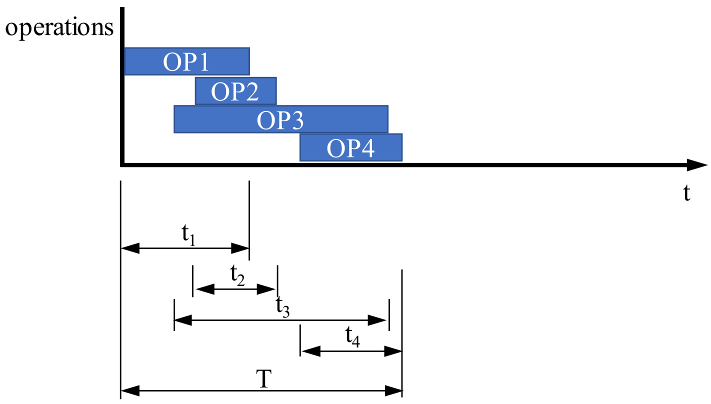


Figure 4 Simultaneously performed operations

So concurrent engineering could be:

- Decrease the product development lead-time.
- Improve the profitability.
- Improve competitiveness.
- Refine the control of design and manufacturing costs.
- Integrate the company departments.
- Enhance the reputation of the company and its products.
- Improve the product quality.
- Arise the team spirit.

The level of competition in all markets, including engineering products, is globally increasing. Reasons for this are complex, but the main contributors are use of new technology, larger number of organizations in the same markets and wider appreciation and use of continuous process improvements. Concurrent engineering is indispensable to companies that desire to remain competitive, improve their products and processes continuously and keep their development ahead of the competition.

The execution of the activities of the design in parallel leads to improvements in many areas such as communication, quality, production processes, cash flows and profitability (Kosuke 1993). The reductions of time to market, which has strategic importance, allows companies to increase their market share and reduce design changes and design iterations. They are more easily manufacturable, serviceable and are of higher quality. Once released to manufacturing, production progresses quickly to full volume because the process is well defined, documented and controlled. The remarkable performance achieved by world-class companies has been the best proof of the effectiveness of concurrent engineering. Their success has been recorded in books and articles, reporting striking improvements in terms of cycle times, cost reduction, product quality and reliability.

Can be found various application of CE in literature. One of the methodologies for achieving concurrency in the product and process engineering (Ball et al. 2000, Minis et al. 1999) is based on the formulation of an optimization problem with constraints drawn from various aspects of the product life-cycle. Tan et al. (Tan et al. 1996, Tan et al. 1997) suggest a model which brings together different phases of the product development process using an intelligent agent framework. In the first customer requirements are presented and a system iteratively generates the final designs based on cost evaluation of the initial designs. The system creates a final design taking into consideration most aspects of the product development process.

Shahrokhi et al. (Shahrokhi et al. 2011) develops a multi criteria decision making model by considering quantitative and qualitative requirements to select the best suppliers and processes in CE environment. This model is composed by three steps. First, possible processes and suitable suppliers for each component are determined by experts. Second, quality importance of each part to total product quality and safety importance of each part to total product safety are determined by fuzzy AHP (an advanced version of AHP). In third step, the best process and suppliers each part is selected by multi objective linear programming.

CE is used in various fields and applications, such as automotive industry (Gao et al. 2000, Haddad 1992, Vijaya Ramnath et al. 2018, Kaluza et al. 2017), composite materials (Sapuan et al. 2014, Kim et al. 2000), chemical industry (Paulien et al. 2000) and in other cases CE is used for risk quantification (Kayis et al. 2006, Kavis et al. 2007).

In many cases CE developed is used for finding the best product design relying in the product cost (Darken et al. 1996, Doan et al. 1993, Soundar et al. 1994, Wei et al. 2000, O'Grady et al. 1991) as the objective function.

2.3. Cost estimation and DtC methods and tools

This section describes the importance of cost estimation in product development, describing the various methods and tools present in academic and industrial field.

2.3.1. Cost estimation and DtC methods

Today, in the global economy and due to various other market pressures, the acquisition decisions of many engineering systems, particularly the expensive ones, are not made based on initial procurement costs but rather on their life cycle costs. Past experiences indicate that often engineering system ownership costs exceed acquisition costs. In fact, according to various studies (Ryan 1968), the engineering system ownership cost (i.e., logistic and operating cost) can vary from 10 to 100 times the original acquisition cost. The life cycle cost of a system may be defined simply as the sum of all costs incurred during its life span (i.e., the total of acquisition and ownership costs). The term life cycle costing was used for the first time in 1965 in a report entitled "Life Cycle Costing in Equipment Procurement" (LMI 1965). This report was prepared by the Logistics Management Institute, Washington, D.C., for the assistant secretary of defense for installations and logistics, U.S. Department of Defense, Washington, D.C.

Customers of today put less focus on initial investment price; instead they are interested in a long-term perspective where all costs that will occur during the lifetime of an asset are considered (Ahlmann, 1998). Such analyses are called Life Cycle Cost analyses (LCC). There are several approaches for making LCC analysis. According to Woodward (1997): "*The Life Cycle Cost of an item is the sum of all funds expended in support of the item from its conception and fabrication, through its operation and to the end of its useful life*" (Woodward, 1997).

LCC involves estimations and calculations of costs on the whole life basis and includes the development cost that occurs before the investment decision is made. The LCC approach shifts the focus from initial investment to a long-term perspective on the investment decision process (Durairaj et al., 2002).

Manufacturing costs form a significant proportion of the life cycle cost of engineering products, equipment, and systems (Cicconi et al. 2013).

A key target in product design is the minimization of product costs, without pre-empting its desired level of quality functionality and value (Arundacahawat et al. 2013). During the product development process (PDP), cost plays a critical role and drives most of the technical and technological solutions (Favi et al. 2018). Cost reduction can be achieved by adopting different strategies: designing cost-efficient solutions, improving manufacturing performance, increasing the competition among suppliers and/or, delocalising the production where labour cost is lower, and others (Xu et al. 2012). Cost estimation is a design task which allows to evaluate the production costs of products before their manufacturing (Mauchand et al 2008). Cost estimation activity includes a classification of cost items both for the materials and the manufacturing processes. In addition, cost estimation requires a definition of a mathematical model which integrates the cost items (Hoque et al. 2013). Cost estimation is generally linked with the so-called Design-to-Cost (DtC) methodologies aiming at the reduction of product cost during the product development process (Favi et al. 2016).

Among the several methods developed for cost estimation, they can be grouped in two main families: (i) *qualitative* methods and, (ii) *quantitative* methods (Niazi et al. 2005) (Figure 5).

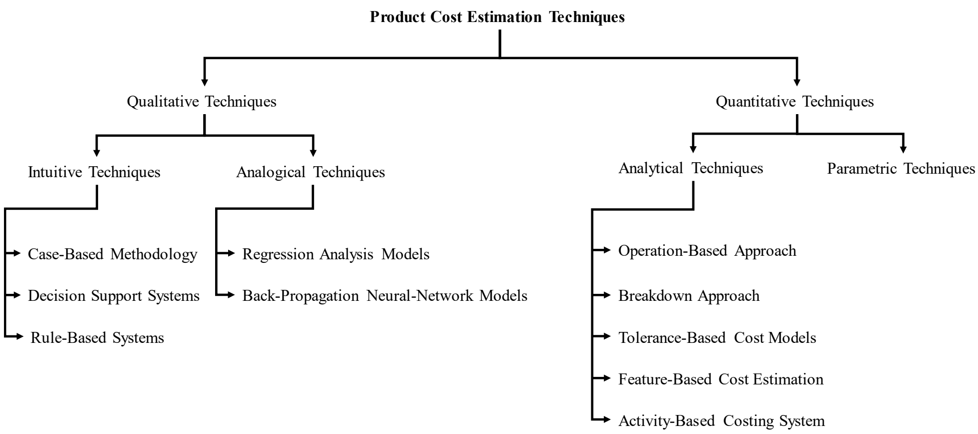


Figure 5 Product cost estimation techniques classification (from Niazi et al. 2005)

Qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. The identified similarities help to incorporate the past data into the new product so that the need to obtain the cost estimate from scratch is greatly reduced. In that sense, the past design and manufacturing data or previous experience of an estimator can provide useful help to generate reliable cost estimates for a new product that is similar to a past design case. Sometimes, this can be achieved by making use of the past design and manufacturing knowledge encapsulated in a system based on rules, decision trees, etc. Historical design and manufacturing data for products with known costs may also be used systematically to obtain cost estimates for new products. For example, regression analysis models and neural-network approaches could provide an efficient way to predict costs for new products by using historical cost data. In general, qualitative techniques help obtain rough estimates during the design conceptualization. These techniques can further be categorised into *intuitive* (Rush et al. 2011, García-Crespo et al. 2011, Shehab et al. 2002) and *analogical* (Duverline et al. 1999, Wang et al. 2002, Arundacahawat et al. 2013, Chang et al. 2012) techniques.

The *intuitive* cost estimation techniques are based on past experiences use. A domain expert's knowledge is systematically used to generate cost estimates for parts and assemblies. The knowledge may be stored in the form of rules, decision trees, judgments, etc., at a specific location, e.g., a database to help the end user improve the decision-making process and prepare cost estimates for new products based on certain input information. Intuitive techniques are composed by three subcategories: (i) Case-Based Methodology, (ii) Decision Support Systems and (iii) Rule-Based Systems.

Case-Based Methodology attempts to make use of the information contained in previous design cases by adapting a past design from a database that closely matches the attributes of a new design.

Decision Support Systems has the main purpose to assist estimators in making better judgments and decisions at different levels of the estimation process by making use of the stored knowledge of experts in the field.

Rule-Based Systems are based on process time and cost calculation of feasible processes from a set of available ones for the manufacture of a part based on design and/or manufacturing constraints.

Analogical cost estimation techniques employ similarity criteria based on historical cost data for products with known cost, such as regression analysis models or back propagation methods. Analogical techniques are composed by two subcategories: (i) Regression Analysis Models and (ii) Back-Propagation Neural-Network (BPNN) Models.

Regression Analysis models make use of the historical cost data to establish a linear relationship between the product costs for the past design cases and the values of certain selected variables so that the relationship can be used to forecast the cost of a new product. These models use a neural network that can be trained to store knowledge to infer the answers to questions that even may not have been seen by them before. Analogical methods can be applied for a particular process (i.e. machining, sheet metal stamping, forging, etc…) or for a product. An example of analogical method which can be applied for different process can be found in literature by Koonce (Koonce et al. 2000), which presented an architecture for a cost estimation tool capable of generating estimates at all stages of the design process. System uses a combination of generative and variant costing, with designs being evaluated using either a work breakdown structure or a parameter-based estimation from a similar part. In other case analogical methods could be used together whit others one, for example analytical (Bouaziz et al. 2006).

Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator. Costs are, therefore, either calculated using an analytical function of certain variables representing different product parameters or as the sum of elementary units representing different resources consumed during a whole production cycle of a given product. Although these techniques are known to provide more accurate results, their use is normally restricted to the final phases in the design cycle due to the requirement of a detailed product design. Quantitative techniques can be further categorized into *parametric* (Farineau et al. 2001, Chougule et al. 2006, Martinelli et al. 2019) and *analytical* (Feng et al. 1999, Favi et al. 2017, Campi et al. 2019) techniques.

Parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent variables. These techniques could be effective in those situations where the parameters, sometimes known as cost drivers, could be easily identified. Parametric models are generally used to quantify the unit cost of a given product. For example, Zhao et al. (Zhao et al. 2015) presents a method to estimate aircraft component production costs using a suite of parametrical cost estimation blocks. Blocks is treated as Cost Primitives (CPs), which contain attributes such as cost types, cost driving parameters, and cost estimation relationships

Analytical cost estimation approach requires decomposing a product into elementary units, operations, and activities that represent different resources consumed during the production cycle and expressing the cost as a summation of all these components. These techniques can be further classified into different categories: (i) Operation-Based Approach, (ii) Breakdown Approach, (iii) Tolerance-Based Cost Models, (iv) Feature-Based Cost Estimation and (v) Activity-Based Costing (ABC) System.

Operation-Based approach is generally used in the final design stages because of the type of information required and is one of the earliest attempts to estimate manufacturing costs. The approach allows the estimation of manufacturing cost as a summation of the costs associated with the time of performing manufacturing operations, non-productive time, and setup times.

Breakdown approach estimates the total product cost by summing all the costs incurred during the production cycle of a product, including material costs and overheads as well. The method requires detailed information about the resources consumed to manufacture a product including purchasing, processing, and maintenance details.

In Tolerance-Based cost models the objective is to estimate product cost considering design tolerances of a product as a function of the product cost.

Feature-Based cost estimation deals with the identification of a product's cost-related features and the determination of the associated costs. These features can be design related (such as the type of material used for a specific product, geometric details, etc.) or process oriented (i.e., a particular process required for manufacturing the product, e.g., machining, casting, injection moulding etc.). The methodology allows the selection of a particular design or manufacturing form feature for design-for-cost system users. However, the approach can have limitations for complex or very small geometric features, especially if machining processes are used to produce these features.

Activity-Based Costing system focuses on calculating the costs incurred on performing the activities to manufacture a product.

Table 1 summarizes the main advantages and disadvantages of each group in terms of result: (i) *Accuracy* - how much the method is accurate and consistent with the actual cost, (ii) *Robustness* - how much the method can easily adapt to the product with different features, dimensions, etc, (iii) *Scalability* - how much the method is suitable for different production sets, (iv) *Uncertainty* - how much the method is providing a small range of cost uncertainty and, (v) *Subjectivity* - how much the method is independent by the end-user. Three levels of assessment (low, medium or high) are reported within the Table 1 based on the literature analysis (Niazi et al. 2005, Arundacahawat et al. 2013, Chougule et al 2006, Shehab et al 2002, García-Crespo et al. 2011, Rush et al. 2001, Duverlie et al. 1999, Favi et al. 2017, Campi et al. 2019, Martinelli et al. 2019).

Table 1 Comparison of different cost estimation methods

Method family	Method type	Accuracy	Robustness	Scalability	Uncertainty	Subjectivity
Qualitative	Intuitive methods	Low	Low	Low	High	High
	Analogical methods	Low	Low	Medium	High	Medium
Quantitative	Analytical methods	High	High	High	Low	Low
	Parametric methods	Medium	High	High	Medium	Low

Among the existing methods suitable for cost estimation, those ones based on knowledge management and definition of relationships among features, operations, materials, physical relationships, and similarity laws are considered the best in terms of the performances reported in Table 1. In particular, analytical methods are the most suitable choice for the assessment of product costs during the design phase (Niazi et al. 2005, Favi et al. 2017, Campi et al. 2019).

Concerning the analytical approach, in literature could be found several research works focused on cost estimation of a particular operation or domain. In relation to the technology, specific models for cost estimation were developed based on the manufacturing process such as: (i) chip metal forming (Boothroyd et al. 1989, Siadat et al. 2007, Bouaziz et al. 2006, Ou-Yang et al. 1997, Jung 2002, Ben-Arieh et al. 2001, Ozbayraka et al. 2004), (ii) hole making (Luong et al. 1995), (iii) sheet metal (Verlinden et al. 2008, Naranje et al. 2014), (iv) injection molding (Fagade et al. 2000, Nagahanumaiah et al. 2008), (v) forging (Berlioz et al. 1999, Choi et al. 1984, Campi et al. 2019, Martinelli et al 2019, Knight 1992), (vi) casting (Nagahanumaiah et al. 2005, Sajid et al. 2018), (vii) electric discharge machining (D'Urso et al. 2017) and (viii) and, especially in the last years, in additive manufacturing (Urbanic et al. 2019, Mahadik et al. 2018)

Other authors, instead, exploit hybrid systems that combine several approaches, such as analogical and analytical approaches (Bouaziz, 2006) or even analytical and parametric approaches, as described by Chougule (Chougule et al, 2006). This hybrid approach was used to estimate the cost of a casting process according to the 3D solid model of the part and its attributes (i.e., material, geometry, quality, and production requirements). The authors used analytical equations to estimate material and process (energy and work) costs, while a parametric model driven by the part complexity was developed for tooling cost estimation. This cost estimation model was used to "educate" designers and engineers with scarce knowledge about manufacturing processes. By adopting the same approach, several researchers proposed hybrid techniques to estimate the production cost of specific products and components (Li 2014) (Barg et al., 2018) (Favi, 2017) (Knight, 1992). The state-of-the-art techniques related to the "design" side reveal that reaching the desired level of granularity in cost breakdown is still an open question for design purposes. A gap in the definition of manufacturing cost items and their relationships (mathematical models) with product design features is noticed. In addition, the cost estimation of a product requires the availability of many related manufacturing processes that commonly are not available at the design stage. Cooperation between designers and production technologists is mandatory for achieving this goal but will be negatively affected by the iterations that may arise in this phase. The time-to-market will be significantly improved if designers can be supported by methods and tools that automatically construct the manufacturing process and calculate the related cost of a product. This aim can be pursued only by collecting, classifying and leveraging the manufacturing knowledge required for cost estimation.

From the "manufacturing" perspective, production knowledge represents the groundwork for a proper implementation of analytical cost estimation methods (Hoque et al, 2013). Knowledge can be divided into tacit and explicit knowledge (Darai et al., 2010). Tacit knowledge is the knowledge that people carry in their minds. Hence, this knowledge is not formalized and not widely used by an organization. Explicit knowledge, instead, refers to a set of information that can be articulated, codified, and stored in certain media. To make knowledge usable, a data framework for knowledge collection is needed to deposit knowledge and then make it accessible to everyone involved within an enterprise (Grabowik et al, 2003) (Gröger et al., 2003) (Chen et al., 2014) (Jiang et al., 2010) (Bateman et al., 2006).

2.3.2. Cost estimation and DtC tools

Market globalization drastically increased competitiveness. Customers ever more have the possibility to choose products by evaluating a large number of market proposals. In this context, if a company is able to offer high quality customized products in a reasonable delivery time can gain relevant market shares. Anyway, personalised products imply new efficient and agile approaches along the whole product development process, from ideation to manufacturing. In this scenario, companies have to apply methods and tools in order to respond to the customer needs while maintain a constant control on product cost. Manufacturing cost is one of the main important aspects. It should be evaluated in the early design phases in order to rapidly compare different customized technical solutions. Manufacturing cost estimation is complex due to the huge amount of information that influences the result. In fact, it is necessary to decide which manufacturing process should be adopted, which manufacturing parameters should be chosen, which materials, which equipment have to be realized, the size of production batch, etc. On the other hand, the product designer in the early design phase has at disposal only a preliminary 3D CAD model that has been mainly conceived in order to satisfy the functional requirements. This dichotomy generates errors and numerous iterations between design and manufacturing departments. A consistent improvement can be achieved if product designer can evaluate different design alternatives by using criteria related not only to function but also to manufacturability and cost.

The ever-increasing costs of material, energy, and, especially, manpower require that manufacturing processes be designed and developed with minimum amount of trial and error with shortest possible lead times. Therefore, to remain competitive, the cost-effective application of computer-aided techniques, i.e., CAD, CAM, CAE, and, especially, finite element analysis (FEA)-based computer simulation is an absolute necessity. The practical use of these techniques requires a thorough knowledge of the principal variables of the process and their interactions.

In literature can be found various example of manufacturing cost estimation tool, developed from late 1970s till now and the most widespread are focused in machining process. Numerous commercial cost estimation tools exist and many organizations have developed proprietary cost estimation systems. The sophistication of these tools ranges from spreadsheets to multi-user mainframe database systems. The capability of these systems ranges from the ability to estimate costs for highly specific parts to generic systems which can be used to estimate costs for virtually any manufactured part.

One of the first application can be found by Orady et al. (Orady et al. 1978), which developed a computer aided estimation tool for calculation of production times for turned components. The system calculates the total processing time of making a component, considering set-up time, floor to floor time, machining time and load/unload time. In this application the user must insert input data, like machine size, accessories, part handling data, process name and geometrical data.

Machining cost estimation tools are the most widespread and various example could be found in literature. These types of tools could be classified in function of cost estimating approach.

Many of them are focused on features-based approach. These systems tend to estimate the manufacturing cost of a design according to the shapes and precision of its features. One of these system was developed by Ou-Yang (Ou-Yang et al. 1997), who provide a tool to assist a designer, who has little knowledge about the manufacturing process, to estimate the fabrication cost of a design during its conceptual stage, in order to reduce unnecessary costs in the downstream process. Also Jung (Jung 2002) presents a feature-based cost estimating system for machined parts. Machining cost is calculated from machining time, which includes operational time and non-operational time. Operation time includes rough cutting time and finish cutting time, while non-operation times are taken from past experience and approximated for modification into mathematical forms. Another example is provided by Siadat (Siadat et al. 2007), which use ontologies for an estimation system based on the cost entity.

Concerning the others cost estimation approaches, Bouaziz (Bouaziz et al. 2006) presents a cost estimation system of manufacturing dies based on the analogic approach and analytic approach. This principle has recourse to the analogic approach to search for analogies between the shapes to be machined before grouping them into complex machining features. For each feature parameter the system generates a process to be used as a sample and consequently a model of machining time. In a second stage and by using the analytic approach, the cutting time is determined either by removal rates of metal units for rough operation and/or from the finishing operation surface. Ben-Arieh (Ben-Arieh et al. 2001) instead presented a system able to estimates the cost of the design activity as well as the manufacturing of machined parts using process planning analysis for allocation of the direct costs and Activity Based Costing for allocation of overhead cost. The system provides communication between the design and the manufacturing parties using internet. The system performs cost estimation by using process planning function on the central server, while analysing the individual cost components of the manufacturing organizations at their sites.

Other tools are developed for other manufacturing process, as welding (Sajadfar et al. 2015), sheet metal forming (Naranje et al. 2014), forging (Berlioz et al. 1999, Choi et al. 1984), injection molding (Nagahanumaiah et al. 2008), casting (Sajid et al. 2018) and additive manufacturing (Urbanic et al. 2019, Mahadik et al. 2018).

In other cases, tools are not focused only in a single manufacturing process, but they are generical. Koonce (Koonce et al. 2000, Koonce et al. 2003) presented an architecture for a cost estimation tool capable of generating estimates at all stages of the design process. System uses a combination of generative and variant costing, with designs being evaluated using either a work breakdown structure or a parameter-based estimation from a similar part. This dual estimation approach will require that the tool maintain a repository of existing parts, with costs and match parameters, as well as traditional cost estimation equations and associated data files. Cicconi (Cicconi et al. 2013) presents a methodology and a software tool for the evaluation of the LCC during the early design phases of electric motors, in particular in manufacturing and use costs. The tool is also integrated in a larger platform, to consider also the environmental impacts and motor performances. Kingsman (Kingsman et al. 1997) presents a knowledge based-support system based a large number of heuristic rules to aid designer in their judgements and decisions at the various stages of the overall process. Dimache (Dimache et al. 2007) develops a life cycle cost estimation tool which is enabled to produce different design configurations (different materials, different components, different processes) to be compared not only from an environmental compliance view but also from a cost perspective. The tool offers support in the decision-making process at the early phases of the design process. The inclusion of cost permits more informed business decisions and considerations to be undertaken by the designer.

In Table 2 are summarized the reference and/or the tool discussed above, with a brief description of their limits.

Table 2 Cost estimation and DtC tools description and limits

Reference/tool name	Brief description	Limits
Ben-Arieh et al. 2001	System able to estimates the cost of the design activity as well as the manufacturing of machined parts.	Only for machined components.
Berlioz et al. 1999	Cost estimation tool for closed-die hot forged parts.	Only for closed-die forging.
Bouaziz et al. 2006	Cost estimation system of manufacturing dies based on the analogic approach and analytic approach.	Only for a particular component type and process: machining of stamping dies.
Choi et al. 1984	Cost estimation tool for closed-die hot forged parts.	Only for closed-die forging.
Cicconi et al. 2013	Software tool for the evaluation of the Life Cycle Cost during the early design phases of electric motors.	Only for a specific part type: electric motor.

Dimache et al. 2007	Software tool for the evaluation of the Life Cycle Cost of a generic component.	The tool is in the conceptual phase and is not well explained which processes it is able to analyse.
Jung 2002	Feature-based cost estimating system for machined components.	Only for machined components.
Kingsman et al. 1997	Knowledge based-support system based a large number of heuristic rules to aid designer in their judgements and decisions at the various stages of the overall process.	The tool is in the conceptual phase and is not well explained which processes it is able to analyse
Koonce et al. 2000	Cost estimation tool capable of generating estimates at all stages of the design process.	Not use of 3D cad model. User must insert manually part attributes and geometrical data.
Koonce et al. 2003	Cost estimation tool capable of generating estimates at all stages of the design process.	Not use of 3D cad model. User must insert manually part attributes and geometrical data.
Mahadik et al. 2018	Additive manufacturing cost estimation tool (AMCET) which utilizes breakdown approach. Costs are calculated using AMCET by taking limited information from the user to support quick cost estimation of a design when manufactured using one of seven different AM processes.	Only for Additive manufacturing.
Nagahanumaiah et al. 2008	Computer aided rapid tooling process selection and manufacturability evaluation methodology for injection molding.	Only for injection molding.
Naranje et al. 2014	Knowledge based system for cost-estimation of deep drawn sheet metal parts (both manufacturing and dies).	Only for sheet metal forming.
Orady et al., 1978	Computer-aided cost estimation tool for turned components.	Only for turned components. User must insert manually machine information and geometrical part data.
Ou-Yang et al. 1997	Feature-based tool for designer assistance in conceptual design phase for fabrication cost of machined components.	Only for machined components.
Sajadfar et al. 2015	Informatics framework to apply feature-based engineering concept for cost estimation of welding features supported with data mining algorithms.	Only for welding.
Sajid et al. 2018	Cost estimation system for the casting process based on the design features, which incorporates the casting information at the design stage of castings.	Only for casting.
Siadat et al. 2007	Estimation system based on the cost entity.	Only for machined components.
Urbanic et al. 2019	Development of a costing framework to provide insight on whether to use machining or AM.	Only for evaluate the type of process to use: additive manufacturing or machining.

2.3.2.1. Cost estimation and DtC commercial software tool

A good number of cost-estimating software tools are currently available in the commercial sector. There are CAD-based costing software that either incorporate

CAD as a product data module, such as product life cycle management (PLM) systems, or costing modules that are seamlessly integrated into their respective CAD software. General-purpose costing software supports product cost estimating for a broad range of cost categories. Most such software is stand-alone but some interface with CAD (Kuang-Hua Chang, 2016). Then commercial software could be divided in 4 main sectors: (i) *CAD-based costing software*, (ii) *General-purpose costing software*, (iii) *Special-purpose costing software* and (iv) *Web-based costing software*.

The *CAD-based costing software* that is of more interest is one that incorporates cost estimating as a module and seamlessly integrates it with CAD: *SolidWorks Costing* (https://www.solidworks.com/it), a module fully integrated in SolidWorks.
The tool helps designers make decisions based on the cost to manufacture and helps manufacturers create quotes for customers. The software creates automatic manufacturing cost estimates for various manufacturing process using built-in templates and customized data.
Manufacturing and material information in templates drives the costing tool to determine the manufacturing cost. In the templates are specified the material used to create the part, the manufacturing processes (such as laser cutting, bending, or milling), the manufacturing method (machining, casting, plastic molded, 3D printed) and the associated costs of these materials and manufacturing operations and methods. With the templates, custom operations such as packaging, enterprise resource planning entry, painting, or cleaning are created.
SolidWorks Costing serves different audiences. From a designer point of view, it provides estimates of how much parts should cost to manufacture. Costing can compare models to make decisions based on cost earlier in the design process. From a manufacturers point of view creates accurate quotes based on the materials, processes, and other associated costs that are required to manufacture parts. Costing creates a faster quote process than manual methods such as using spreadsheets, counting features, or estimating material removed. Costing helps eliminate errors and provides an accurate, repeatable quoting system that you can update whenever material or labor costs need revision.
SolidWorks costing could be used to estimate the cost of sheet metal, machined, plastic molded, cast, 3D printed, multibody parts, weldments, and assemblies.

Several *general-purpose costing software* products have been widely adopted: *SEER for Manufacturing*, *MicroEstimating*, *Costimator of MTI System* and *aPriori Product Cost Management*.

SEER for Manufacturing (https://galorath.com/seer-for-manufacturing/) is designed to enable its users to evaluate manufacturing process options and trade-offs along the entire length of the project process. It focuses on manufacturing project and process options and can be used to model virtually any manufacturing operation. SEER for Manufacturing was designed to enable both intermittent and advanced users in management, finance, engineering, industrial design, and manufacturing to evaluate process options and trade-offs impacting various factors (e.g., ease of fabrication and assembly, number and availability of parts, materials selection, and failure and repair rates). Users can also optimize their process strategy by performing extensive trade-off analyses by varying assumptions and options to determine which manufacturing strategy is likely to produce the best outcome. SEER-DfM offers a connection to CAD systems but users must have adequate knowledge and experience in manufacturing because they have to choose adequate processes for manufacturing individual parts.

MicroEstimating (https://www.microest.com/index.html) offers computer-aided process planning and computer-aided estimating for the machining and fabrication industries. MicroEstimating employs proprietary machine tool emulation, knowledge-based machining, and automatic feature recognition to establish production times and costs. Equipped with libraries containing detailed machine tool specifics and material specifications, the software calculates net production times and costs with speed and precision. MicroEstimating incorporates a powerful interface to utilize SolidWorks Feature Recognition, providing extremely accurate manufacturing costs estimates. MicroEstimating directly imports SolidWorks Bill of Materials (BOM), providing a powerful yet simple tool for the cost estimating of assemblies, regardless of complexity or number of items.

Costimator of MTI System is an American-based series of cost estimating software developed by Thomas Charkiewicz in 1982 and is designed to model manufacturing costs (https://www.mtisystems.com/index.html). The system comes fully loaded with hundreds of process and feature-based cost models; it covers a large array of manufacturing processes and features that are implemented for a large variety of prebuilt, ready-to-use manufacturing process cost models. Costimator employs three

key methods for the product cost estimate: parametric, feature-based and cost models. Parametric cost models are developed from historical cost data and times and costs are generated through regression analysis. Feature-based estimating gives users with little to no manufacturing experience the ability to estimate based on the identification and selection of part features (e.g., holes, slots, bends, cut-outs) rather than manufacturing processes. In this case the program automatically reads, extracts and imports part data from 3D CAD models into Costimator.
aPriori Product Cost Management (https://www.apriori.com/) offers capabilities that instantly determine the cost of a part or product from a CAD model, the materials to be used, and the country where it will be produced. aPriori calculate cost in real time using information related on material type, production volume, manufacturing process, and location of manufacture. aPriori support for major 3D CAD systems, enabling rapid and automatic evaluation of geometric cost drivers, the aspects of the product's design that drive costs (e.g., size, shape, complexity, number of holes, number of bends, thickness, profile, tolerances, and roughness of surfaces) from the solid model. aPriori can run concurrently with the CAD application or as a stand-alone application where users simply open the CAD model from within aPriori when they are ready to perform a cost assessment. aPriori determines the lowest cost manufacturing method for the part or assembly and provides that feedback to the designer in real time.

Special-purpose costing software offers cost estimates for dedicated manufacturing processes. In this category, the most common processes supported are machining, injection molding and sheet metal.
From a machining point of view various tool could be found. *uFab* (https://www.ufab.io/) can provide a complete analysis of 3D part models, enabling the automated generation of a machining plan for most parts.
Other example of machining cost estimating software are *G-Wizard CNC* (https://www.cnccookbook.com/g-wizard-cnc-speeds-and-feeds-calculator/) and *quotecam* machine shop estimating (https://quotecam.com/).
There are several codes that support injection molding cost estimating. *Injection Molding Cycle Time Estimator* (https://sourceforge.net/projects/imcycletimeest/) is a very simple software that can be used for a rough cost estimation, including different data based on resin type; it allows machine settings to override for

temperature. *CostMate* is a molding part cost estimator that has been integrated into an online plastics search engine (https://www.ulprospector.com/costmate). CostMate considers costs of shipping and packaging as well. *CalcMaster Injection Molding Software* (https://schouenc.home.xs4all.nl/) is a powerful program that can be used not only as a cost estimator but also as a good design assistant. The software allows users to quickly determine mold cost, injection molding parameters, optimal number of cavities, and complete molded product cost.
Costing software for sheet metal process are also widespread. One is *eRapid* (https://rapidmanufacturing.com/erapid/), a free instant sheet metal part quoting embedded in SOLIDWORKS. Others example are *Metalix* (https://www.metalix.net/solutions/quoting-cost-estimation/), *almaQuote* (https://www.almacam.com/products/almaquote/) and *jetcam* (https://www.jetcam.com/quickcost.php).

Concerning the *Web-based costing software*, one of the most popular and useful website that supports cost estimates is *CustomPartNet* (https://www.custompartnet.com/), which is an online resource for manufacturing cost estimation. It allows users to perform quick calculations that facilitate the product design and costing process. With CustomPartNet, users can quickly create a new cost estimate, or find a similar part from the public parts database, to use as a baseline. Estimates can be saved and shared with colleagues to collaborate on the estimation process. CustomPartNet also has educational content to help both students and practicing engineers who are new to the manufacturing industry. Process overviews and design guidelines allow users to explore how a process works and learn how to design parts more cost effectively. The site contains 4 manufacturing process: Injection Molding, Die casting, Sand Casting and machining. For each process there is a material selector, and manufacturing widgets that perform quick calculations for common design and manufacturing problems.

In Table 3 are summarized the commercial cost estimation software tool discussed above, with a brief description of their limits.

Table 3 Cost estimation and DtC commercial software tool description and limits

Reference/tool name	Brief description	Limits
almaQuote	Sheet metal parts cost estimation software.	Only for sheet metal parts.
aPriori Product Cost Management	The tool determines the cost of a part or product from a CAD model, the materials to be used, and the country where it will be produced. aPriori calculate cost in real time using information related on material type, production volume, manufacturing process, and location of manufacture.	Some manufacturing process are not evaluated.
CalcMaster Injection Molding Software	The software allows users to quickly determine mold cost, injection molding parameters, optimal number of cavities, and complete molded product cost.	Only for injection molded parts.
Costimator of MTI System	The tool covers a large array of manufacturing processes and features that are implemented for a large variety of prebuilt, ready-to-use manufacturing process cost models. Costimator employs three key methods for the product cost estimate: parametric, feature-based and cost models.	Needs of historical cost data of the parts for a correct cost estimation.
CostMate	Injection molding cost estimation software.	Only for injection molded parts.
CustomPartNet	Online resource for manufacturing cost estimation. The tool through overviews and design guidelines allow users to explore how a process works and learn how to design parts more cost effectively.	Only for Injection Molding, Die casting, Sand Casting and machining.
eRapid	Sheet metal parts cost estimation software.	Embedded in SolidWorks. Only for sheet metal parts.
G-Wizard CNC	Machining cost estimating software.	Only for machining processes.
jetcam	Sheet metal parts cost estimation software.	Only for sheet metal parts.
Metalix	Sheet metal parts cost estimation software.	Only for sheet metal parts.
MicroEstimating	The tool offers a computer-aided process planning and computer-aided estimating for the machining and fabrication industries.	Possibility to be used only in SolidWorks cause the use of SolidWorks Feature Recognition. Limited in machining and fabrication processes.
Molding Cycle Time Estimator	Injection molding cost estimation software.	Only rough cost estimation of injection molded parts.
quotecam	Machining cost estimating software.	Only for machining processes.
SEER for Manufacturing	The tool enables its users to evaluate manufacturing process options and trade-offs along the entire length of the project process. SEER for Manufacturing offers a connection to CAD systems.	Users must have adequate knowledge and experience in manufacturing because they must choose adequate processes for manufacturing individual parts.
SolidWorks Costing	A module fully integrated in SolidWorks, which helps designers make decisions based on the cost to manufacture and helps manufacturers create quotes for customers. SolidWorks costing could be used to estimate the cost of sheet metal, machined,	Possibility to be used only in SolidWorks.

	plastic molded, cast, 3D printed, multibody parts, weldments, and assemblies.	
uFab	The system provides a complete analysis of 3D part models produced by chip forming	Only for machining processes.

2.4. DfX methods and tools

In this section will be described the concept of Design for X (DfX) and the various typology which compose them. In particular will be described the Design for Manufacture and the Design for Assembly, focusing on methods and tools present in academic and industrial field.

2.4.1. DfX methods

As early as the 1960s, several companies developed manufacturing guidelines for use during product design. One of the best-known examples is the Manufacturing. Producibility Handbook published for internal use by General Electric Corp. (MPH, 1960). In this handbook, manufacturing data were accumulated into a large reference volume with the idea that designers would be able to acquire the manufacturing knowledge for efficient and effective design. However, the emphasis was only on design of individual parts for producibility and very little attention was given to the manufacturing and assembly processes.

Design for X was first appeared in 1983, in the Handbook of parts, forms, processes, and materials in design engineering (Everhart et al., 1960), in designing for manufacturing (Pech et al., 1973), and concurrent engineering's roots in the WorldWar II era (ZiemkeMC et al., 1991). Until that time, DfX was not a known term in the industry and was implicitly considered. The original "design for" was created first to make the production aspects more efficient and to reduce time, cost, and errors. Afterward, DfX techniques expanded beyond production to the entire supply chain and enabled consideration of the impact that design has on the economy, ecology, social, and the health of the company. Hence, a multitude of different DfX technique has been developed over time with a focus on several topics such as manufacturing, supply chain, environment, and so on.

Benabdellah et al. (Benabdellah et al., 2019) initially discover over 75 different DfX techniques. Hence, in order to provide a most informative, yet concise overview of these techniques, they focus first on influential and well-cited papers that contribute to the development of particular DfX techniques (literature selection step) and they found 37 DfX techniques, afterwards reduced to 6 using: design for manufacture and assembly (DFMA), design for quality (DfQ), design for service (DfSv), design for safety (DfS); design for supply chain (DfSC) and design for environment (DfE). The six DfX selected is called design for relevance (Benabdellah et al.,2019):

- To decrease the cost of ownership: DfSv.
- To reduce variation and defects: DfQ and DfS.
- To reduce environmental impact: DfE.
- To reduce supply chain costs: DfSC.
- To reduce production costs: DfMA (include DfM and DfA).

Kuo et al (Kuo et al., 2001) divided design for X in:

- DfA: design for assembly.
- DfM: design for manufacturing.
- DfD and DfR: design for disassembly and design for recyclability.
- DfE: design for environment.
- DfLC: design for life cycle.
- DfQ: design for quality.
- DfMt: design for maintainability.
- DfRL: design for reliability.

These are the methods developed and are named in function of the specific need to be improved and by the authors who developed it.

2.4.1.1. *DfMA*

Design for manufacturing and assembly (DfMA) is an analytical process that considers all aspects of the design, development, total parts, manufacturability, cost, assembly time, and modularity. DfMA has been in use by industry for several years. It focuses on product enhancements to allow improvements in manufacturing, cost, quality, reliability, time to market, and many other areas. Product design is the first step in manufacturing and is where the critical decisions are made that will affect the final form and cost of the product. Product design has an impact on more than 70% of a product’s total cost. Manufacturing and assembly concepts can greatly improve production and development costs while also improving reliability and quality. DfMA concentrates on simplifying designs while also evaluating assembly improvements to further enhance the overall design for manufacturability and quality. DfMA is a product development process and improvement methodology that provides a systematic process to achieve improved product design, robustness, and cost reductions through simplifications of the overall design.

DfMA is a systematic design evaluation process that is used to improve part design and part manufacture early in the design process. Figure 6 shows the scope of the DfMA process. Design for manufacture (DfM) methodology analyzes individual part geometry and process choices for impact on material, manufacturing process, and tooling costs, whereas design for assembly (DfA) is a structured methodology for analyzing product concepts or existing products for simplification of design and assembly processes. Even though DfA can be thought of as a separate philosophy, it is commonly thought of as a central element of DfM (Kamrani et al., 2010).

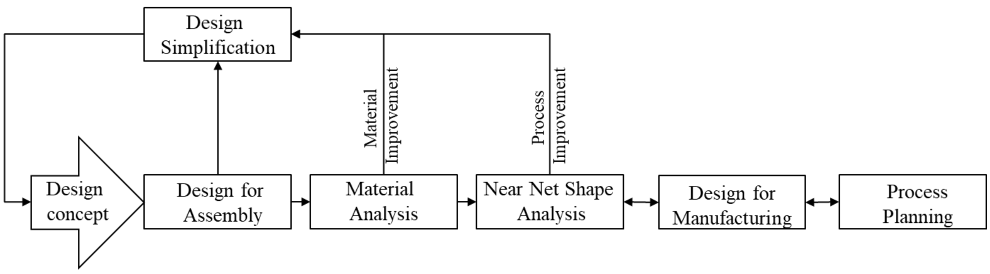


Figure 6 Scope of DFMA (from Boothroyd et al., 2011)

2.4.1.2. DfA

Design for assembly (DfA) aims to simplify the product for reducing the cost of assembly. Consequently, applications of DfA principles to product design usually result in improved quality and reliability and a reduction in production equipment and part inventory. It has been repeatedly observed that these secondary benefits often outweigh the cost reductions in assembly. DfA, in principle, recognizes the need to analyze the design of both the part and the whole product for any assembly problems early in the process to cut costs during the entire product cycle. DfA may be defined as a process for improving product design for easy and low-cost assembly, which is achieved by means of concurrent focus on the dual aspects of functionality and ease of assembly. The objective of DfA is to identify product concepts which are inherently easy to assemble and to favour product and component designs that are easy to grip, feed, join and assemble by manual or automatic means. This objective is related to the overall design for manufacture (DfM) approach to economic production. DfA can be carried out throughout the product introduction process from conceptual design to component detailing. The main aims of DfA are to:

1. Reduce the number of parts in an assembly.

2. Optimize the assemblability of the parts.

3. Optimize the handlability of parts and assemblies.

4. Improve quality, increase efficiency and reduce assembly costs.

DfA may be carried out manually or with the support of computers. The different methods of assembly are as follows (Figure 7) (Mital et al., 2015):

- *MANUAL ASSEMBLY*: Manual assembly is a process characterized by operations performed manually, with or without the aid of simple, general-purpose tools, such as screwdrivers and pliers. The cost per unit is constant, and the process requires little initial investment. Manual assembly involves parts that are transferred to workbenches, where the assembly of individual components into the final product takes place. Hand tools generally are used to aid the worker for easy assembly. Although this is the most versatile and adaptable assembly method, there usually is an upper limit to the production volume, and labor costs (including benefits, workers compensation due to fatigue and injury, and overhead for maintaining a clean and healthy environment) are higher.

- *AUTOMATIC ASSEMBLY*: Often referred to as fixed automation, this method uses either synchronous indexing machines and part feeders or nonsynchronous machines, where parts are handled by a free transfer device. The system generally is built for a single product, and the cost per unit decreases with increasing volume of production.

- *FIXED OR HARD AUTOMATION*: Fixed or hard automation characteristically involves a custom-built machine that assembles only one specific product and entails a large capital investment. As production volume increases, the fraction of the capital investment compared to the total manufacturing cost decreases. Indexing tables, parts feeders, and automatic controls typify this inherently rigid assembly method. In some instances, automatic assembly is also referred to as Detroit-type assembly

- *ROBOTIC ASSEMBLY*: This form of assembly is best suited for those products whose production volume lies between the volumes for manual and automatic assembly methods. This method of product assembly can achieve volumes closer to the automatic assembly methods. Soft automation or robotic assembly incorporates the use of robotic assembly systems. This can take the form of a single robot or a multistation robotic assembly cell with all activities simultaneously controlled and coordinated by a programmable logic controller or computer. Although this type of assembly method can have large capital costs, its flexibility often helps offset the expense across many different products.

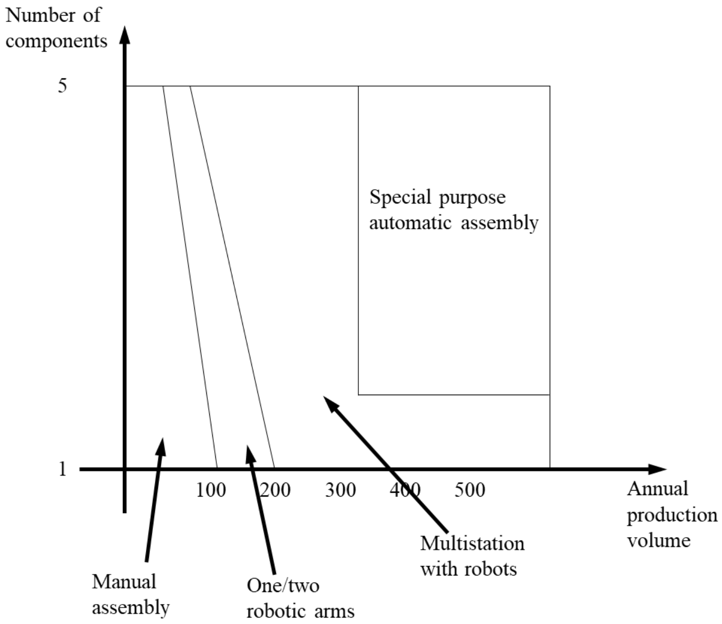


Figure 7 Distinguishing different assembly methods based on production ranges (from Mital et al., 2015)

Current DfA methodologies can be classified into 4 basic types based on their analysis method: (i) *using design principles and rules DfA approach*, (ii) *using quantitative evaluation DfA methods*, (iii) *knowledge-based approach DfA methods* and (iv) *product architecture-based DfA approach*. The 4 types are described in the following subsections.

(i) *Using design principles and rules DfA approach*: Design rules are empirical "truths" verified by extensive design practice. The basic axioms are: 1) maintain the independence of functional requirements and 2) minimize the information content. Some of the corollaries include using standardized or interchangeable parts whenever possible, conserving materials and energy or reducing the number of parts (Stone et al., 2004).
The practice of DfA is considered to be a recent development, however, many companies have been involved with DfA for a long time. General Electric (GE) (Desai et al., 2010) published an internal manufacturing producibility handbook in the 1960's. The principal objective of this was to serve as a set

of guidelines and manufacturing data for designers. These guidelines included many of the now known principles of DfA.

Andreasen, Kahler, and Lund (1982), presented a series of 'heuristic' rules or principles (Andreasen et al. 1988), which they illustrated graphically. Here, they established the importance of part reduction and simplification, and presented a range of alternative 'structural' options as the basis of building a product. Their basic argument was to first address product structure, which dominates subsequent assembly decisions, before considering the detailed design of components to ensure ease of assembly for each. They noted assembly operations of handling, composing and checking, which incorporate specific operations including orientation, transport, connection and joining *(*Moultrie et al.,2014*)*.

Suh (Suh 1998) proposes two basic axioms for design with corollaries. The basic axioms are: (1) maintain the independence of functional requirements; and (2) minimize the information content. Some of the corollaries include using standardized or interchangeable parts whenever possible, conserving materials and energy or reducing the number of parts.

(ii) Using quantitative evaluation DfA methods: Quantitative DfA analysis allows designers to rate the assemblability of their product designs quantitatively. Quantitative measures allow a more accurate and repeatable application of DfA methods. Using current quantitative approaches, the designer has to determine the assembly process operation by operation. Each assembly operation is subject to a rating that assesses the ease with which operators or assembly systems carry out the process (Stone et al., 2004).

The objective of the Hitachi – Assemblability Evaluation Method (AEM) (Leaney et al., 1992) is to facilitate design improvements by identifying weaknesses in product design at the earliest possible stage. This is achieved using two principal indicators: an assemblability evaluation score ratio (E), which assesses design quality by determining the difficulty of operations, and an assembly cost ratio (K), which projects elements of assembly cost. The Hitachi method considers both cost and quality important. This means that a low-cost design is not necessarily the best; alternatively, a good design may be too expensive. This is the only evaluation method that takes product design economics into account and hence is not purely technical in nature. The term assemblability is interpreted as meaning "assembly producibility". The interpretation of this is that the assemblability evaluation is built around the assessment of what are called "assembly operations". These assembly operations relate specifically to the insertion (and fixing) processes. In the Hitachi New AEM no direct analysis is available for parts feeding and orientation. It is for this reason that "design for automated assembling" is not an available option, the argument being that assessment of product design for automated assembling is sensitive to part configuration and is rather difficult to handle precisely at early design stages. These aspects would be dealt with at later design stages.

The Boothroyd-Dewhurst method of assembly evaluation (BDI's DfMA) (Mital et al., 2015) is based on two principles: the application of criteria to each part to determine if it should be separate from all other parts, and the estimation of the handling and assembly costs for each part using the appropriate assembly process. The Boothroyd-Dewhurst method relies on an existing design, which is iteratively evaluated and improved. The process follows the following steps: (i) Select an assembly method for each part. (ii) Analyze the parts for the given assembly methods, (iii) Refine the design in response to shortcomings identified by the analysis and (iv) Refer back to step 2 until the analysis yields a satisfactory design. The analysis generally is performed using a specific worksheet. Tables and charts are used to estimate the part handling and part insertion time. Each table is based on a two-digit code, which in turn is based on a part's size, weight, and geometric characteristics. Handling and insertion times are a function of various component parameters (size, thickness, weight, fragility, flexibility, slipperiness, stickiness, etc…). Each of these parameters directly affects the assembly process by simplifying or complicating it. Non assembly operations also are included in the worksheet. For example, extra time is allocated for each time the assembly is reoriented. Next, all parts are evaluated on the basis of whether each part is really necessary in the assembly. The list of all parts then is evaluated to obtain the minimum number of theoretically needed parts.

(iii) *Knowledge-based approach DfA methods:* Knowledge based systems are defined as those that provide new information processing capabilities such as inference, knowledge based management or search mechanisms combined with conventional computer capabilities.

The Lucas DfA evaluation method (Mital et al., 2015) was developed in the early 1980s by the Lucas Corporation in the United Kingdom. The Lucas method is based on a point scale that gives a relative measure of the difficulty associated with assembly. This method is based on three separate and sequential analyses. The procedure follows the steps below.

1. Product design specification.
2. Product analysis.
3. Functional analysis (first Lucas analysis); loop back to step 2 if the analysis yields problems.
4. Feeding analysis (second Lucas analysis).
5. Fitting analysis (third Lucas analysis).
6. Assessment.
7. Return to step 2 if the analyses identify problems.

The functional analysis forms the first part of this evaluation system. Components are divided into two groups. The first group includes components that perform a primary function, and therefore exist for fundamental reasons. These components are considered essential, or A, parts. The second group, B components, are nonessentials, such as fasteners and locators. In this first phase is calculated the design efficiency in function of essential and nonessential components. The feeding analysis forms the second part of this evaluation system. This analysis is concerned with problems associated with handling components and subassemblies before they are admitted to the assembly system. By answering a group of questions regarding the size, weight, handling difficulties, and orientation of a part, its feeding/handling index can be calculated. The fitting analysis is similar to the feeding analysis.

The last part of the Lucas method is to calculate the cost of manufacturing each component. This manufacturing cost can influence the choice of material and the process by which the part is made. Although not a true costing of the part, this method helps guide designers by giving a relative measure of manufacturing cost. Values of each of the following coefficients are derived from detailed tables developed for the purpose.

(iv) The product architecture-based DfA approach (Stone et al., 2004) moves the DfA analysis to the early stages of conceptual design requiring only a functional model for implementation. Briefly, the approach is as follows. Through a product architecture definition method, the function structure of a product is clustered into modules. Then, the focus of the conceptual design effort is to solve the overall product task module by module. If possible, the complete functionality of each module is solved by one part. During the form definition, Boothroyd and Dewhurst handling time information may be used to minimize the assembly time and cost. The end product of the design process is a detailed design for which DfA principles have continuously been applied. Thus, DfA is realized with a substantial saving in time and overall effort.

2.4.1.3. DfM

Design for manufacturability (DfM) is the process of proactively designing products to (1) optimize all the manufacturing functions: fabrication, assembly, test, procurement, shipping, service, and repair; (2) ensure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction; and (3) ensure that lack of manufacturability does not compromise functionality, styling, new product introductions, product delivery, improvement programs, or strategic initiatives and make it difficult to respond to unexpected surges in product demand or limit growth (Bralla 1998).

Before DfM, the motto was "I designed it; you build it!" Design engineers worked alone or only in the company of other design engineers in "the engineering department." Designs were thrown over the wall to manufacturing, which then had the dilemma of either objecting ("But it's too late to change the design!") or struggling to launch a product that was not designed well for manufacturability. Often this delayed both the product launch and the time to ramp up to full production, which is the only meaningful measure of time-to-market (Anderson 2014).

The following principles, applicable to virtually all manufacturing processes, will aid designers in specifying components and products that can be manufactured at minimum cost.

1. Simplicity.
2. Standard materials and components.

3. Standardized design of the product itself.
4. Liberal tolerances.
5. Use of the most processible materials.
6. Teamwork with manufacturing personnel.
7. Avoidance of secondary operations.
8. Design appropriate to the expected level of production.
9. Utilizing special process characteristics.
10. Avoiding process restrictiveness.

DfM has effects in various fields of products development, as (i) materials, (ii) economic production quantities, (iii) design recommendations and (iv) dimensional accuracy.

(i) *Effects on Materials Selection:* The choice of material is seldom affected by the degree to which the manufacturing process is made automatic. Those materials which are most machinable, most castable, most moldable, etc., are equally favorable whether the process is manual or automatic. There are two possible exceptions to this statement:

1. When production quantities are large, as is normally the case when automatic equipment is used, it may be economical to obtain special formulations and sizes of material that closely fit the requirements of the part to be produced and which would not be justifiable if only low quantities were involved.

2. When elaborate interconnected equipment is employed (e.g., transfer lines, index tables, multiple spindle tapping machines), it may be advisable to specify free machining or other highly processible materials, beyond what might be normally justifiable, to ensure that the equipment runs continuously. It may be economical to spend slightly more than normal for material if this can avoid downtime for tool sharpening or replacement in an expensive multiple-machine tool.

(ii) *Effects on Economic Production Quantities:* The use of special-purpose equipment generally requires significant investment. This, in turn, makes it necessary for production levels to be high enough so that the investment can be amortized. Special-purpose equipment is suited by and large only for mass-production applications. In return, however, it can yield considerable savings in unit costs. Savings in labor cost are the major advantage of special-purpose and automatic equipment, but there are other advantages as well: reduced work-in-process inventory, reduced tendency of damage to parts during handling, reduced throughput time for production, reduced floor space, and fewer rejects. The advantage of such equipment is that it permits automatic operation without being limited to any particular part or narrow family of parts and with little or no specialized tooling. Automation at low and medium levels of production is economically justifiable with numerical control and computer control. As long as the equipment is utilized, it is not necessary in achieving unit-cost savings to produce a substantial quantity of any particular part.

(iii) *Effects on Design Recommendations:* There are few or no differences in design recommendations for products made automatically as compared with those made with the same processes under manual control. In the preponderance of cases, however, the design recommendations included apply to both automatic and non-automatic methods. In some cases, however, the cost effect of disregarding a design recommendation can be minimized if an automatic process is used. With automatic equipment, an added operation, not normally justifiable, may be feasible, with the added cost consisting mainly of that required to add some element to the equipment or tooling.

(iv) *Effects on Dimensional Accuracy:* Generally, special machines and tools produce with higher accuracy than general-purpose equipment. This is simply a result of the higher level of precision and consistency inherent in purely machine-controlled operations compared with those which are manually controlled. Compound and progressive dies and four-slide tooling for sheet-metal parts, for example, provide greater accuracy than individual punch-press operations because the work is contained by the tooling for all operations, and manual positioning variations are avoided. Form-ground lathe or screw-machine cutting tools, if properly made, provide a higher level of accuracy for diameters, axial dimensions, and contours than can be expected when such dimensions are produced by separate manually controlled cuts. Form-ground milling cutters, shaper and planer tools, and grinding wheels all have the same advantage. Multiple-spindle and multiple-head machines can be built with high accuracy for spindle location, parallelism, squareness, etc. They have a definite accuracy advantage over single-operation machines, in that the workpiece is positioned only once for all operations. The location of one hole or surface in relation to another depends solely on the machine and not on the care exercised in positioning the workpiece in a number of separate fixtures. Somewhat tighter tolerances therefore can be expected than would be the case with a process employing single-operation equipment. Automatic parts-feeding devices generally have little effect on the precision of components produced. They are normally more consistent than manual feeding except when parts have burrs, flashing, or some other minor defect that interferes with the automatic feeding action. No special dimensional allowances or changed tolerances should be applied if production equipment is fed automatically.

Designers need some method for knowing if the new or redesigned product will meet its manufacturability and other objectives. The designer's general judgment may be very sound in weighing the design's conformance to planned design attributes, but an objective measurement almost always will be better. Designers must evaluate the (i) manufacturability, (ii) assembly and (iii) individual parts.

(i) Evaluating Manufacturability: Manufacturing cost is the most complete measure of manufacturability. It can be expressed as a total cost for the product or component or can be approximated with some major cost element such as direct labor time. Most progress of all has taken place with design for assembly (DfA). Assembly evaluation systems can provide a rapid and easy comparison between several alternatives.

Direct labor time is a straightforward indicator of manufacturing cost and is usable by itself in a large number of cases. (Exceptions are those in which materials costs, labor rates, and overhead costs also vary significantly with different design variations.) Therefore, in many cases, manufacturability of a series of design choices can be evaluated by estimating and comparing the direct labor time required for production of each design. Eventually, however, a full cost estimate is the ultimate guide to the designer in knowing how well the product design has been engineered for manufacturability.

(ii) Assembly Evaluation Systems: Sometimes there are tradeoffs between materials and labor costs of design alternatives. For example, a complex part

made by combining several simpler parts will reduce assembly costs, but the cost of the complex part could conceivably be higher than the cost of several simple parts. Fortunately, however, materials costs are easy and straightforward to estimate from per-pound or per square-foot data. Materials cost differences can be combined with the labor cost differences of alternative designs to arrive at a more nearly total cost comparison. The programs may give a design efficiency rating, a ratio comparing the calculated assembly time with a theoretical ideal for the number of parts involved. There is one other quite useful method to evaluate the manufacturability of assemblies. This is simply to count the number of parts that the design entails. Assemblies with fewer parts normally can be assembled in less time and have higher design efficiency ratings.

(iii) Manufacturability Evaluations of Individual Parts: One simple way to compare the manufacturability of alternative designs of a part is to count the number of process operations that each requires. Other factors being equal, the part with the fewest number of operations will be the simplest to manufacture and the lowest in cost. Of course, tooling complexity and materials cost often must be considered also. Nonetheless, this metric is often a useful one for comparing parts from a DfM standpoint.

2.4.2. DfMA tool

In scientific literature and also in industry, various tool and application of DfA and DfM could be found.

Design for manufacture and assembly (DfMA) has been used by many companies around the world to obtain optimal manufacturing and assembly processes. The development of DfMA started in the 1990s with research into automatic assembly (DfA). McDonnell Douglas Corporation applying DfMA reduced part count by 37% and fastener count by 46% on average (Weber, 1994). Boothroyd et al. (Boothroyd et al.,1993) developed a spreadsheet approach to rating design based on their ease of automatic assembly. The use of a software program not only predicts a board's cost but also provides indices of its manufacturability, called PCB Design for Assembly (PCB/DfA). The software is intended to reduce design cycle time and manufacturing cost. Well before placement and routing, it quickly generates alternative board designs that would be economical to manufacture.

Several researchers have extensively design product and part for a specific operation: (1) modularity (Suh, 1990), (2) while others provide methods to obtain cost estimation for specific parts of manufacturing processes for machined parts (Boothroyd et al., 1989), (3) injection-molded parts (Dewhurst et al., 1988), (4) die-cast parts (Dewhurst et al., 1989), (5) sheetmetal stampings (Zenger et al., 1988), and (6) powder-metal parts (Yamaguchi et al., 1993). The main goal from all these papers is to minimize part count and reorientation of parts, standardize parts, encourage modular design, emphasize top-down assemblies, design for component symmetry, design parts with self-aligning and fastening features, and design parts for retrieval, handling, and insertion. In other research, authors present frameworks for creating, analysing, improving, and representing manufacturing systems during the design process (Thompson et al., 2018, Benkamoun at al., 2014, Salonitis et al., 2014). Benkamoun et al. (Benkamoun at al., 2014) develop an architecture framework which establishes a common practice for creating, analysing, and representing manufacturing systems during design and re-design processes. The proposed framework is comprehensive and specifies the system representation from various levels and dimensions, considering not only abstract and general representation, but also illustration examples to represent manufacturing systems designs.

Salonitis et al. (Salonitis et al., 2014) develop a framework for the simultaneous modular product design and the design of an automated manufacturing system using design structure matrix and modular function deployment. Product designs are optimized for automation using Design Structure Matrix and Modular Function Deployment. Alternative production systems are designed and accessed based on the analysis of assembly steps hierarchically. The implementation of the framework on the design of a production system for furniture assembly, able to handle multiple variants with a large number of components, is demonstrated.

In further research, authors develop methods to decrease the complexity of the assembly process using assembly sequence analysis (De Fazio et al., 1999), using semi-autonomous teams with well-defined responsibilities (Bukchin et al., 2003), or even investigating how DfA affects the material and manufacturing costs (Favi et al., 2016). Boothoroyd et al. (Boothoroyd et al., 2011) make a significant contribution to the broader subject of product design for ease of manufacture (DfM). During this process, the best materials and processes to be used for the various parts are considered. Some authors provide guidelines and surveys to ensure the good design practices (Favi et al, 2020, Favi et al., 2021). Barbosa et al. (Barbosa et al.,

2014) presents a guideline which uses the concepts of design for manufacturing and assembly methodology for specific application on design and manufacturing of aircrafts. The main goal of this guideline was to orient the engineers during the aircraft development phases, such that a better aircraft design is achieved. The guideline comprises a set of tables to drive the engineers for a better evaluation of manufacturing processes, assembly, maintenance and human factors (ergonomics). It aims to improve the manufacturing and assembly for easy manufacturing of parts that build the aircraft with low costs, high quality and the best optimized condition.

While others combined guidelines with techniques such as axiomatic design (Gonçalves et al, 2007), decision analysis (Xiao et al., 2008; Holt et al., 2010; Lehmhus et al., 2015; Unglert et al., 2016; Matt et al., 2017), and even with optimization consideration (Mao et al., 2015). The general idea of DfMA is to design products for the ease of assembly and to design their component parts for the ease of manufacture. It provides also to designers the capability to minimize the number of components; to simplify and reduce the number of manufacturing operations; to use standard parts and materials; to design for efficient joining, for ease of part fabrication, for ease of packaging, and for ease of assembly; to use common parts across product lines, flexible components, and modular design; and to eliminate or reduce adjustment required. As a summary, to remain competitive in the future, almost every manufacturing organization has to adopt the DfMA philosophy and apply cost quantification tools at the early stages of product design. However, to be effective in product design, to increase product complexity, and to address globalization and rapid technological development, manufacturing companies need to innovate their offers to consumers by creating more complete solutions that combine maximizing the use of component (DfA) and maximizing the use of manufacturing processes (DfM).

The use of the DfA and DfM has a tremendous impact when properly applied in a concurrent engineering environment.

Khan et al. (Khan et al. 2007) present knowledge-based design methodology for automated assembly lines. The method can be applied to single, multi, and mixed product assembly lines with either deterministic operation times or stochastic operation times. The proposed method could be used to provide an overall quality assessment of object-oriented software system in early stage of development life cycle, which may be helpful to the developer to fix problems, remove irregularities and non-conformance to standards and eliminate unwanted complexities in the early development cycle.

Holzner et al. (Holzner et al., 2015) develop a systematically design approach for such systems focusing on small and medium enterprise requirements which were carried out by a questionnaire survey. Based on the survey results, customer attributes are identified and then translated in functional requirements. Subsequently functional requirements will be deduced into generally applicable design parameters for supporting the design of flexible and changeable manufacturing and assembly systems for small and medium enterprise and to apply finally these design guidelines in a case study.

Holt et al. (Holt et al., 2010) use a numerical model of the dye-sensitized solar cell to explore factors influencing device performance. A "top down" development of DfX is used, starting from the needs of design decision-making, to balance the current "bottom-up" approach. Existing DfX techniques are compared to see how they can be used together.

Huang et al. (Huang et al., 1998) present a Design for X shell, a generic framework which can be easily extended or tailored to develop a variety of DfX tools quickly with consistent quality. Several formal but pragmatic constructs are provided. Bills of materials are used to describe and analyse the overall product structure and product characteristics and a matrix approach to represent various types of modules (component swapping, component sharing, and bus modularity, etc.).

Fan et al. (Fan et al., 2003) develop a rule-based expert system, which concurrently considers product design and process planning by including six functions in the system: knowledge, conceptual design, computer-aided design, design for manufacture design for assembly, assembly system design, and assembly planning.

In Table 4 are summarized the DFMA tool discussed above with a brief description of their limits.

Table 4 DFMA tool description and limits

Reference/tool name	Brief description	Limits
Barbosa et al., 2014	Guidelines which use the concepts of design for manufacturing and assembly methodology for specific application on design and manufacturing of aircrafts.	Only a methodological study. Only for aircraft.
Benkamoun at al., 2014	Architecture framework for creating, analysing, and representing manufacturing	The tool doesn't indicate the design issues.

	systems during design and re-design processes.	
Boothroyd et al., 1989	DfM tool for machined parts.	Only for machined manufactured parts. The tool doesn't indicate the design issues.
Boothroyd et al.,1993	A software program for predicting board's cost and also provides indices of its manufacturability.	Only for manufacturing and assembly of a particular component type (electronic board). The tool doesn't indicate the design issues.
Bukchin et al., 2003	Design methodology for assembly systems based on teams.	Only for assembly processes. Only a methodological study.
De Fazio et al., 1999	Describes criterion-based searches for best subassembly partitioning and assembly sequences.	Only for assembly processes.
Dewhurst et al., 1988	DfM tool for injection-molded parts.	Only for injection molding. The tool doesn't indicate the design issues.
Dewhurst et al., 1989	DfM tool for die-cast parts.	Only for die-casting. The tool doesn't indicate the design issues.
Fan et al., 2003	Rule-based expert system which concurrently considers product design and process planning.	Only a methodological study.
Favi et al, 2020	Design for casted products.	Only for casting.
Favi et al., 2016	Investigate how the application of the conceptual DfA affects the material and manufacturing costs (Design-to-Cost).	Only a methodological study.
Favi et al., 2021	Design for welded products.	Only for welding.
Gonçalves et al, 2007	Axiomatic design (AD) is an engineering design theory that provides a framework to decision-making in the designing process.	Only a methodological study.
Holt et al., 2010	"Top down" development of DFX, starting from the needs of design decision-making, to balance the current "bottom-up" approach. Existing DFX techniques are compared to see how they can be used together.	Only a methodological study.
Holt et al., 2010	Numerical model of the dye-sensitized solar cell to explore factors influencing device performance.	Focused only in a specified part type (solar cell).
Holzner et al., 2015	Systematically design approach for such systems focusing on small and medium enterprise requirements which were carried out by a questionnaire survey.	Only a methodological study.
Huang et al., 1998	Design for X shell, a generic framework which can be easily extended or tailored to develop a variety of DfX tools.	The tool doesn't indicate the design issues.
Khan et al. 2007	Knowledge-based design methodology for automated assembly lines.	Only a methodological study.
Lehmhus et al., 2015	Exploration of the state of the art in gathering and evaluating product usage and life cycle data, additive manufacturing and sensor integration, automated design and cloud-based services in manufacturing.	Only a methodological study.

Mao et al., 2015	Design methodologies for HES green cellular networks.	Only a methodological study.
Matt et al., 2017	Design handbook for assembly lines for mass customization production systems.	N.A.
Salonitis et al., 2014	Framework for modularization of product families in order to introduce automation in the production.	Focused only in design modularization.
Suh, 1990	Design handbook	N.A.
Thompson et al., 2018	Proposes a framework with sets of key performance indicators (KPIs) to measure and improve producibility and product quality throughout the product development process.	The tool doesn't indicate the design issues in detail. It estimates only the materials and tolerances are complaint with the process selected.
Unglert et al., 2016	Computational Design Synthesis used as a method to support design tasks by automating the generation and applied in form of a software tool.	Only for automobile industry.
Xiao et al., 2008	Coordination of a supply chain with one manufacturer and two competing retailers after the production cost of the manufacturer was disrupted.	Only a methodological study.
Yamaguchi et al., 1991	DfM applied to powder-metal parts.	Only a methodology study.
Zenger et al., 1988	DfM applied to sheetmetal stampings.	Only a methodology study.

2.4.2.1. DfMA commercial software tool

The *DFM Concurrent Costing and DFA Product Simplification software of Boothroyd Dewhurst* (https://www.dfma.com/) allows users to generate accurate part, tooling and assembly cost estimates at the design concept stage. DFM Concurrent Costing software provides users with an understanding of the primary cost drivers associated with manufacturing the product and establishes a benchmark for what the product "should cost". Central to the should-cost approach is accumulating real information about manufacturing costs and noting where specific costs are in the product design. The cost models in the DFM Concurrent Costing software guide users through an assessment of alternative processes and materials, which provides cost information for the bill of materials. Costs update automatically as users determine tolerances, surface finishes, and other part details. Gradually, as users choose effective shape-forming processes and consider how to modify part features to lower cost, the product becomes optimized.

Users must have adequate knowledge and experience in manufacturing because they have to choose adequate processes for manufacturing individual parts and also this tool has only a simplified 3D CAD recognition and user must insert manually part

dimensions and characteristic.
The DFA Product Simplification allows engineers to scrutinize parts and assemblies for structural efficiency, guiding them toward the creation of single, multifunctional components with significantly improved performance-to-cost ratios. DFA Product Simplification software utilizes an intuitive question-and-answer interface that identifies opportunities for substantial cost reduction in a product. By applying industry-tested minimum part count criteria, the software finds parts that can be consolidated/eliminated while maintaining 100% functionality. As happened in DFM, also in this case the user must have a remarkable knowledge to choose the adequate assembly operations.

DFMPro by HCL (https://dfmpro.com/) is a CAD-integrated design for manufacturing software which helps to identify and correct downstream issues early in the design stage, leading to reduction of cycle time and, in turn, resulting in high-quality products with lower product development costs. DFMPro is integrated within CAD platforms like Creo Parametric, SOLIDWORKS and NX which ensures that users are able to identify and rectify DFM checks within their own CAD platform. DFMPro allow a rapid and automatic evaluation of geometric feature of the part or assembly (size, shape, complexity, number of holes, number of bends, thickness, profile, tolerances, and roughness of surfaces) from the solid model. DFMPro helps the designer providing guidelines for the correct design whit the representation of errors that affected the part or assembly.

AviX DFX (https://www.avix.eu/process-mapping-tools/avix-dfx) is the generic name for a module of AviX focused on the product and its design. AviX DFX simplifies and standardizes how to work with issues of manufacturability – Design For Assembly. In AviX DFX it is easy to build up the product structure which provides an integrated approach for products and modules as well as the analysis. It is possible to import a BOM or parts from external sources, such as Excel. During the analysis the user is questioned about different design aspects for the modules and objects chosen to analyse.

In Table 5 are summarized the DFMA commercial software tool discussed above with a brief description of their limits.

Table 5 DFMA commercial software tools description and limits

Reference/tool name	Brief description	Limits
AviX DFX	Module of AviX focused on the product and its design.	3D CAD model feature recognition not present.
DFM Concurrent Costing and DFA Product Simplification software of Boothroyd Dewhurst	DFM Concurrent Costing software provides users with an understanding of the primary cost drivers associated with manufacturing the product and establishes a benchmark for what the product "should cost". The DFA Product Simplification allows engineers to scrutinize parts and assemblies for structural efficiency, guiding them toward the creation of single, multifunctional components with significantly improved performance-to-cost ratios.	User must be expert in manufacturing to perform a correct analysis. 3D CAD model feature recognition is not present. The tool doesn't indicate the design issues, but only the expensive process phases.
DFMPro by HCL	CAD-integrated design for manufacturing software which helps to identify and correct downstream issues early in the design stage.	No cost estimation, only design issues indications.

2.5. State of the art conclusion/limits and objective motivation

The state-of-the-art related to the manufacturing cost side show how dedicated cost models were developed to address the specificity of each manufacturing process. Generalized methods for the elicitation of the manufacturing knowledge of different technologies has not yet been developed. Knowledge could be tacit, the knowledge that people carry in their minds and that's not formalized and not widely used by an organization, or could be explicit, which refers to a set of information that can be articulated, codified, and stored in certain media. Furthermore, when multiple technologies are adopted for the manufacturing of complex products, several processes need to be included by different cost models, and the cost estimation framework requires the inclusion of additional cost items (setup, equipment, consumable, etc.), which is not formalized by adopting dedicated methods.

On the other hand, DfM and DfA, which are consolidated engineering activities, are not really integrated with 3D CAD systems. DfM and DfA principles are currently applied at the end of the 3D CAD modelling, by following the well-known

DfM and DfA guidelines available from the literature and company's know-how (internal tacit knowledge). This know-how suffers a strong dissemination among employees and technical departments and represents a critical issue. As a standard practice, designers usually use DfM/DfA guidelines as a sort of checklist once finished the engineering phase, or even worse. Sometimes, these guidelines are checked by production engineers before starting the production (approval of the technical drawings). This approach increases the time to market and the number of iterations between design and manufacturing departments (design reviews).

Results and corporate knowledge tend to stay within the group instead of being documented in a way that promotes reuse. In doing so, development performance is affected by staff turnover, which occurs when projects are finished, or by the often time demanding search for the right document that contains the right information. This issue increases when considering the extensiveness of information needed during functional product development.

In literature can be found various example of manufacturing cost estimation tool, developed from late 1970s till now and the most widespread are focused in machining process. Numerous commercial cost estimation tools exist and many organizations have developed proprietary cost estimation systems. The sophistication of these tools ranges from spreadsheets to multi-user mainframe database systems. The capability of these systems ranges from the ability to estimate costs for highly specific parts to generic systems which can be used to estimate costs for virtually any manufactured part.

It worth noting how most of manufacturing cost estimation tool are focused on a single manufacturing process (the most widespread are machining cost estimation tools) while in other cases they are too general and require a lot of information from the user and do not allow the use of 3D CAD models.

A good number of cost-estimating software tools are currently available in the commercial sector. There are CAD-based costing software that either incorporate CAD as a product data module, such as product life cycle management (PLM) systems, or costing modules that are seamlessly integrated into their respective CAD software. General-purpose costing software supports product cost estimating for a broad range of cost categories.

Also for cost estimation tools belonging to the commercial sector, there is a strong presence of tools focused on a single manufacturing process, in particular machining, sheet metal and injection molding. In others cases they are embedded in a single CAD system (e.g. SolidWorks) or they require by the user an adequate knowledge and experience in manufacturing for choice of adequate processes for manufacturing individual parts.

In scientific literature and also in industry, various tool and application of DfA and DfM could be found. Design for manufacture and assembly (DfMA) has been used by many companies around the world to obtain optimal manufacturing and assembly processes. The development of DfMA started in the 1990s with research into automatic assembly (DfA).

Many of these studies are still "methodological" and not provide a specific tool, while in other cases the tools exist but are focused on a single manufacturing process (assembly, machining, injection molding), or the tool is designed for a particular industry or component. From a commercial point of view there are few examples in this field, in most cases incomplete (no indication of cost or design errors) or difficult to use.

Summarizing and analysing the scientific literature from the academic perspectives could be show a gap in the design methodologies and tools able to implement design for manufacturing and assembly rules during the product modelling or, in case of cost estimating systems, they are focused in only one or few manufacturing process. At the same time the analysis of commercial solutions on this aim provides few exciting systems (SEER for Manufacturing, aPriori Product Cost Management, DFM Concurrent Costing and DFA Product Simplification, DFMPro, etc.).

Then the mentioned practice highlights two main issues in literature. *The first is the absence of a standardized methodology to make explicit the mixed manufacturing and assembly knowledge to support product designers during the product development process.*

This point defines the first research question of the thesis: *How to make explicit the mixed manufacturing and assembly knowledge to support product designers during the product development process*?

The first issue highlights a gap in the state-of-art related to the CAD-integrated DfM and DfA methods and tools and the possibility to share manufacturing and assembly knowledge in the product design (explicit knowledge). During project development iteration are generally required cause the project revision due to manufacturing and assembly issues. In this case iterations have a tremendous impact in terms of the amount of time and rework. At the same time, production knowledge represents the groundwork for a proper implementation of cost estimation models. To make knowledge usable, a data framework for knowledge collection is needed to deposit knowledge and then make it accessible to everyone involved within an enterprise.

The main idea underpinning this thesis to respond at the first research question is focused in the link DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies. In particular, this research work aims to reduce the gap between the design departments and manufacturing through the creation of a KB system able to translate tacit knowledge about DfM/DfA in explicit and reusable knowledge. This is completed through a methodology focused in three aspects: (i) *3D CAD Model feature recognition* and organization, (ii) A *Knowledge-Based (KB) System* for DfM/DfA rules classification and deposition, and (iii) A *Rules Validation System* to connect 3D Model feature to DfM/DfA rules contained in the database.

The *3D CAD Model feature recognition* allows to read the necessary information from the 3D CAD Model with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules.

A *Knowledge-Based (KB) System* is used to classify the DfM/DfA rules, based on three main fundamentals:

(i) *Knowledge acquisition*: refers to the literature analysis and industry best practices investigation for the collection of DfM/DfA design rules.

(ii) *Knowledge processing*: refers to the connection between the DfM/DfA design rules collected in knowledge acquisition phase and the geometrical features of a virtual 3D model (CAD file).

(iii) *Knowledge representation*: refers to the definition of a structured database repository for the collection and the formalization of DfM/DfA knowledge.

The *Rules Validation System* is the core of the entire system with three main purposes: interaction with the 3D CAD Model, extrapolate rules from the DB repository and then evaluate which design rules in 3D CAD Model are respected and which are not.

From a cost estimation point of view two frameworks was developed, which can be used by designers and engineers for the analytical cost estimation of mechanical products. One framework is dedicated for manufacturing a single component, while the other one is for assembly of a group of parts. The *frameworks* are composed by five main paradigms used for formalizing the knowledge required for the cost estimation of products: (i) a *manufacturing/assembly process data structure*, (ii) a *cost breakdown structure*, (iii) a *cost routing*, (iv) a *cost model*, and (v) a *workflow*.

A *manufacturing process data structure* can be defined as sequence of operations needed to transform raw materials into final components, while an *assembly process data structure* is the sequence of operations needed to join the single components together and obtain final products.

A *cost breakdown structure* is necessary to collect information of each phase and operation and is used for breaking out the manufacturing/assembly costs

A *cost routing* is defined as a hierarchical data model of five classes. Each class contains groups of attributes and rules for generating manufacturing or assembly processes from 3D virtual models of components. It is used for the collection of the knowledge required for a manufacturing/assembly process definition

A *cost model* is a structured information object which contain the knowledge necessary for production time and cost estimation for each operation.

The *workflow* allows the determination of a manufacturing/assembly process using 3D virtual prototypes.

The second issue highlighted in literature is the need of method and a tool to integrate knowledge into the product development process and how to make it effective during the design process and the 3D solid modelling and how to estimate the cost savings of the design changes during the 3D modelling.

This point defines the second research question of the thesis: *How to integrate knowledge into the product development process and how to make it effective during the design process and the 3D solid modelling and how to estimate the cost savings of the design changes during the 3D modelling?*

The second issue found in literature is solved by this research through the developing a methodology and a software tool that helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed. The integration between DfM and DfA within computer-aided design software's can reduce redesign and control activities and finally the overall project cost. The system and the tool will be used to verify part and assembly 3D model in the early design process (embodiment design) by analysing the 3D product features, give feedback about the design choices implemented in each model, and estimate manufacturing and assembly costs. The analysis of a 3D CAD model allows to anticipate manufacturing issues and to control manufacturing cost during product design.

The methodology is composed by 5 main steps, starting from *3D CAD Model* of the part or assembly to be analysed (Step 1). The second step (Step 2) is dedicated to the *feature recognition and extraction*, in which are read the necessary information from the 3D CAD Model with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules. After that are conduct a *cost analysis* (Step 3) and the *DfM/DfA analysis* (Step 4), in which validated and non-validated DfM/DfA rules are displayed to the designer with the aim to keep him/her informed about the feature that are not compliant with the guidelines collected in the repository. In the last step (Step 5) the designer *update 3D CAD Model*. In this step the designer modifies the 3D model following the design suggestions in the reports within the total cost obtained. In particular, through the mean of feature recognition, specific features that generate non-validated rules are highlighted within the 3D model in order to facilitate the implementation of design modification. Once design changes are implemented, a new analysis is run to verify if the updated 3D model fits with the DfM/DfA requirements. If non-validated rules are still present, and the cost are not compliant with the project target, a new design review is required; on the other hand, if there is not any non-validated rule and the cost meet the project requirements the model can be frozen for manufacturing.

Methodology has been implemented in a specific software tool with a structure composed by four main modules: (i) *GUI*, (ii) *Feature recognition*, (iii) *Analysis framework* and (iv) *Database*.

The *GUI*, the *Graphical User Interface*, is the module which the user interacts. The tool interface is positioned next to the CAD software for viewing features and design errors directly in it.

The second module, the *Feature recognition*, allows the connection between a CAD system and the tool. Material and physical features can be extracted from a 3D geometry (B-rep model – boundary representation) because attributes included in this class are readily available. Manufacturing features can be extracted from a 3D model by using a specific kernel for manufacturing features recognition. Kernel can compute manufacturing features for a comprehensive set of components shapes (e.g. prismatic, axisymmetric, sheet metal) and assemblies (e.g., welded structures mounted assemblies). For each feature, it is possible to watch the most relevant attributes expected for the further DfM rules processing.

The third module, the *Analysis framework*, is necessary for costs calculation and rules validations, continuously interfacing between feature recognition, databases and the GUI. Through the latter it allows the user to view costs and design rules. This module is the main module of the Cost and DfM/DfA tool. Inside it is contained algorithms for organizing a manufacturing process, for cost calculation (cost analysis framework) and for design guidelines validation (DfM/DfA analysis framework).

The fourth module contain the *Database*, in which are stored the information about materials, machine and the rules for a correct design and cost estimation.

To verify the real advantages of the methodology and tool in design process was used an evaluation method based in two questionnaires, which were submitted to the tool users after extensive use (more than 6 months). The first one wants to quantify the usability of the software while the second one is focused on the advantages and disadvantages of the software use in design process. The test had the scope of evaluating the impact of the methodology and the related software on the traditional design process of a company and evaluate the interoperability between the new software and the design tools.

3. Materials and method

This chapter describes the developed DfM/DfA and cost estimation methodology used to make explicit the mixed manufacturing and assembly knowledge. The chapter is divided in 3 main sections:

- *Section 3.1 describes the overall workflow of the methodology, the concept and type of features involved.*
- *Section 3.2 is focused in analytical cost estimation method and framework.*
- *Section 3.3 describes the DfM/DfA methodology.*

3.1. Material and method introduction

As already mentioned in the previous chapter, one of the goals of the thesis is to have a method and a tool able to calculate the cost of a component and/or assembly and in the same way help the designer in the development phase by identifying design errors occurred in this phase.

Manufacturing and assembly costs are decided during the design phase and their definition tends to influence the selection of materials, machines and human resources which are used in the manufacturing process.

In addition, DfM/DfA design rules are part of the company knowledge and are generally disseminated (through the experience and the skills of their engineers) among employees and technical departments. As a standard practice, DfM/DfA guidelines are usually recalled as a checklist at the end of the engineering design process, or even worse, a final check of the manufacturing and assembly department is necessary before the approval of the technical drawing, increasing the time to market and iterations between design and manufacturing departments (design reviews).

The main idea is the possibility to link analytical manufacturing cost and DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies.

Figure 8 show the developed methodology workflow. The workflow is divided in 5 main steps:

1. *3D CAD Model*: The start point is the initial 3D CAD Model of the part or assembly to be analysed.

2. *Feature recognition and extraction*: This step allows to read the necessary information from the 3D CAD Model with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules. In particular, within this step, all the 3D model is analysed and its features are divided in three main categories in function of information contained: (i) material features, (ii) physical features and (iii) manufacturing features. Section 3.1.1 goes into a more detailed description of feature concept.

3. *Analytical cost estimation analysis*: This step contains the manufacturing and assembly cost estimation procedure, based on (Mandolini et al., 2020) and (Boothroyd et al., 2011). A framework is defined and can be used by designers and engineers for the analytical cost estimation of mechanical components starting from features of 3D CAD model. A detailed description of cost analysis methodology is shown in section 3.2. At the end of cost analysis a report containing a detailed cost breakdown is generated.

4. *DfM/DfA analysis*: This step allows to check design rules against the analysis of the features contained in the 3D model. A framework is defined and it is composed by a database rules depository, mathematical equations and 3D CAD model feature recognition. Mathematical equations are used to verify the compliance of design guidelines with the information retrieved by the 3D model data reading. A dedicated repository (DfM/DfA rules DB) is necessary to collect all the information in a structured way based on the KB system. Validated and non-validated DfM/DfA rules are displayed to the designer with the aim to keep him/her informed about the feature that are not compliant with the guidelines collected in the repository. Section 3.3 provide

a more detailed description of DfM/DfA methodology. At the end of DfM/DfA analysis a report containing validated and non-validated DfM/DfA rules is generated. Is important to notice that step 3 and step 4 could be carried in a different order than this one proposed (step 4 before step 3) or concurrently.

5. *Update 3D CAD Model*: In this step the designer modifies the 3D model following the design suggestions in the reports within the total cost obtained. Each design guideline describes the type of design action to implement, the reason why the design guideline improves the part manufacturability and also an image showing in which way a rule can be implemented. In particular, through the mean of feature recognition, specific features that generate non-validated rules are highlighted within the 3D model in order to facilitate the implementation of design modification. Once design changes are implemented, a new analysis is run to verify if the updated 3D model fits with the DfM/DfA requirements. If non-validated rules are still present, and the cost are not compliant with the project target, a new design review is required; on the other hand, if there is not any non-validated rule and the cost meet the project requirements the model can be frozen for manufacturing.

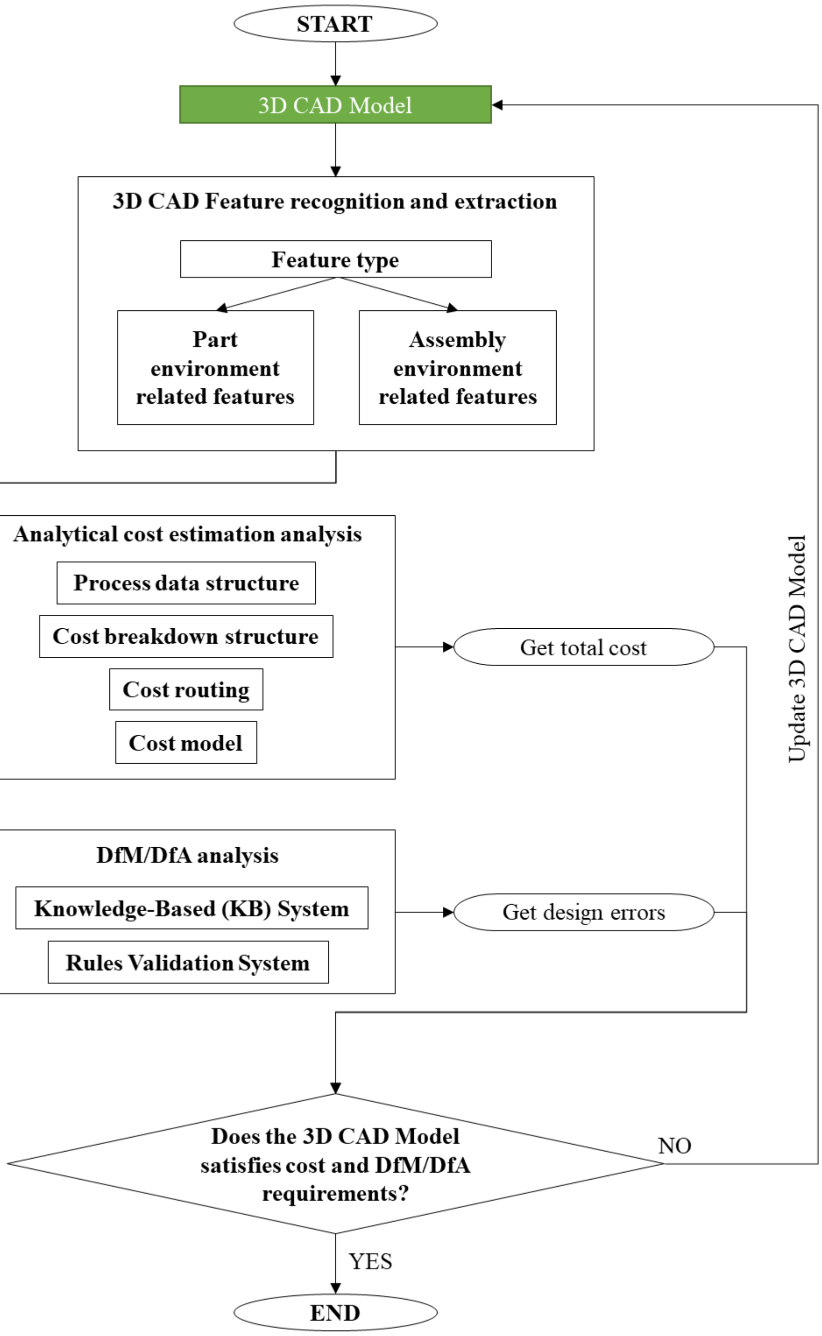


Figure 8 Workflow of manufacturing cost and DfM/DfA methodology

3.1.1. Feature recognition and extraction

Prior to go into more detail on the methodology, an introduction regarding the concept of feature is necessary. In fact, both the methodology used for the estimation of costs and that for the identification of errors in the design are based on the recognition of the features of the component or assembly analysed.

Features were introduced in the late ’70s as modelling elements in CAx systems to represent and reason over both quantitative and qualitative data relevant for product development purposes (Sanfilippo et al., 2016). The term feature has different meanings in different environments depending on the specific domain. For example, in design it refers to a web or a notch section, while in manufacturing it refers to slots, holes, and pockets. Generally, classification of features is totally in function of application. It is very difficult to produce a classification of feature independent of application (Nasr et al., 2006).

In the background of product engineering, features were firstly intended to model the geometry of a product. Other than geometric representation, feature concepts were further developed to model non geometric product properties which are essential in different stages of the whole product lifecycle (Li et al., 2020).

There are different ideas for the feature definition trough the authors. According to Sreevalsan et al. (Sreevalsan et al., 1992) “*A feature is any entity used in reasoning about the design, engineering*”, while Pratt et al. (Pratt et al., 1985) define feature as “*A geometric form or entity whose presence or dimensions are required to perform at least one CIM function and whose availability as a primitive permits the design process to occur*” and “*A region of interest on the surface of a part*”. Dixon et al. (Dixon et al., 1988) consider feature as “*A geometric form or entity that is used in reasoning in one or more designs or manufacturing activities*”, while according to Mantyla et al. (Mantyla et al., 1996) feature is “*A parametric shape associated with such attributes as its intrinsic geometric parameters – length, width, and depth – as well as position, orientation, geometric tolerances, material properties, and references to other features*”. Wilson et al. (Wilson et al., 1988) define feature as “*A region of interest in a part model*”, Deneux (Deneux, 1999) considers feature as “*An information unit describing an aggregation of properties of a product model that are relevant in the scope of a specific view on the product*”. Others author consider feature as “*The characteristics of a product that result from design*” (Groover, 2007) or “*The engineering meaning of the geometry of a part or assembly*” (Wingård, 1991) or also “*a physical entity that makes up some physical part*” (Shah et al, 1995).

These definitions of feature shown that the meaning of feature is not unique, it is based on the application and context and, unfortunately, without a systematic treatment of its semantics. The double understanding of feature, a modelling element and a physical entity, emerges clearly from the definitions (Sanfilippo et al., 2016).

After this introduction of feature concept is carried a description of the features present both in the methodology used for the estimation of costs and that for the identification of errors in the design.

3.1.1.1. Features type

The first type of feature to describe is *manufacturing feature*. It is consisting of a series of faces and related properties, such as slot depth, slot shape, maximum and minimum tolerance, maximum and minimum roughness. Some examples of product manufacturing features are slots, holes, threaded holes, cut-outs, fillets, chamfers, milling features, turning features.

Another important feature is *material feature*, which contains the information about the material of the part and then the information correlated to it (density, melting temperature, forging temperature, etc…).

Physical features are instead associated with the part or assembly dimensions (volume, area, shape, etc.).

In Table 6 are summarized the previous features.

Table 6 Feature type used in analytical cost and DfM/DfA methodologies

Feature type	Attributes/information contained in the feature
Material feature	→ Material of the part (Aluminium alloy 1060, Nickel alloy 718, etc.) [string]
Physical feature	→ Shape of the part (axisymmetric, prismatic, etc.) [string] → Volume of the part [mm^3] → Area of the part [mm^2] → Dimensions (length, width and height) [mm]
Manufacturing feature	→ Type of feature (hole, slot, fillets, etc.) [string] → Coordinate of the feature in reference with origin [xx;yy;zz] → Properties of the feature (size, diameter, length, etc.) [mm] → Volume of the feature [mm^3] → Area of the feature [mm^2] → Faces of the feature [string] → PMI of the feature (roughness, tolerances, coatings, etc.) [string]

Part environment related features

As said in previous chapters, both analytical cost methodology and DfM/DfA methodology are based on models feature recognition. A feature recognition procedure begins by defining the types of feature to be identified. Nowadays, a shared methodology for feature classification is still missing because it depends on the application scenario (Sanfilippo et al., 2016).

Concerning the features recognition related to a single part, this is composed by three main blocks. Each block contains the feature necessary in function of the DfM/DfA rules to verify or the cost estimation model to calculate. The blocks could be divided in this way:

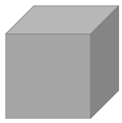
- Block 1: Physical and material features of the model.
- Block 2: Manufacturing and material features of the model (isolated).
- Block 3: Manufacturing and material features of the model in relation with other feature/s (interrelated for part).

The blocks have the scope to classify and organize the features of a part (or assembly) in order to be read and analysed by the framework which calculate the cost and verify the DfM/DfA rules. The division into several blocks has been implemented cause each block collects different types of features to be associated with specific DfM/DfA rules and specific elements of the manufacturing/assembly cost routing structure (a more detailed explanation of the cost routing structure is in section 3.2.3).

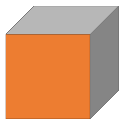
In (Table 7) are summarized the blocks of features related to the part environment.

Table 7 Block 1, 2 and 3 of the methodology

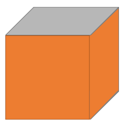
Block 1: Physical and material features of the model	

	→ Material feature:
	  → Material: [string]
	→ Physical feature:
	  → Shape: [string]
	  → Volume: [mm^3]
	  → Area: [mm^2]
	  → Dimensions (lenght*widht*height) [mm]

Block 2: Manufacturing and material features of the model (isolated)	

	→ Material feature:
	  → Material: [string]
	→ Manufacturing feature vs. Manufacturing feature/s:
	  → Type of feature: [string]
	  → Coordinates of the feature in reference with origin: [XX;YY;ZZ]
	  → Properties of the feature: [mm]
	  → Volume of the feature: [mm^3]
	  → Area of the feature: [mm^2]
	  → Faces of the feature: [string]
	  → PMI:
	    → Specific roughness: [string]
	    → Specific tolerance: [string]
	    → Coating: [string]

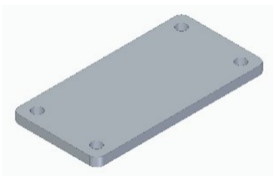
Block 3: Manufacturing and material features of the model in relation with other feature/s (interrelated for part)	

	→ Material feature:
	  → Material: [string]
	→ Manufacturing feature vs. Manufacturing feature/s:
	  → Type of feature vs type of feature/s: [string] vs. [string]
	  → Coordinates of the feature vs. coordinate of the feature/s: [XX;YY;ZZ] vs. [XX;YY;ZZ]
	  → Properties of the feature vs. properties of the feature/s: [mm] vs. [mm]
	  → Volume of the feature vs. volume of the feature/s: [mm^3] vs. [mm^3]
	  → Area of the feature vs. area of the feature/s: [mm^2] vs. [mm^2]
	  → Faces of the feature vs. faces of the feature/s: [string] vs. [string]
	  → PMI:
	    → Specific roughness vs. specific roughness: [string] vs. [string]
	    → Specific tolerance vs. specific tolerance: [string] vs. [string]
	    → Coating vs. coating: [string] vs. [string]

1° block: Physical and material features of the model

This first block includes the feature needed for generic characteristics of the part, in particular material and physical features. The information and attributes contained in these features are volume, area, shape of the part (physical features) and material (material feature). These types of features are used generally for the DfM rules concerning the overall dimensions of the part for transportation limits and its manoeuvrability or for the selection of the type of raw material. In Table 8 are reported an example (3D model of a plate) of the features recognized by this analysis.

Table 8 Example of 1° block

	→ Material feature: → Material: Aluminium alloy – 1060 → Physical feature: → Shape: Prismatic → Volume: 24366,20 [mm^3] → Area: 11589,00 [mm^2] → Dimensions (lenght*widht*height): 100*50*5 [mm]

2° block: Manufacturing and material features of the model (isolated)

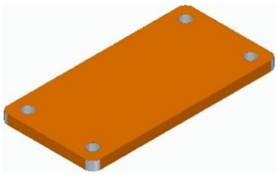
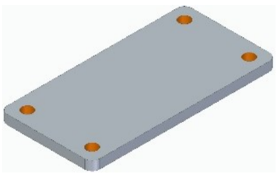
This second block take into consideration material and manufacturing features of the part. A manufacturing feature consist in a series of faces and related attributes, such as slot depth, max and min roughness. Information contained in a manufacturing feature are the type of feature, the coordinate of the feature in reference with origin, its properties such size, diameter or length, and also the volume, the area and the faces of the feature. In addition, manufacturing feature has information regarding the PMI of the feature (roughness, tolerances, coatings, etc.).

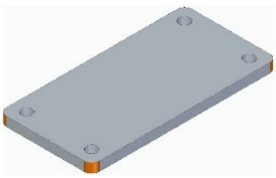
The DfM rules which refer to this second block are related to a single feature isolated (e.g. avoid sharp internal corners in machining process). At the same time this block, in connection whit the 3° block, is used to define the manufacturing strategy and operation bundle of the cost routing structure (section 3.2.3). Manufacturing strategy defines the specific manufacturing process to be used for converting a stock into a finished component (e.g., machining vs additive) and is composed by a series of operations bundles. An operations bundle is composed by the group of operations needed for a specific product manufacturing feature. Manufacturing features affect the operation bundle, cause in function of the type of feature there will be different operations (drilling for holes, milling for slots, etc.) that can be produced with different tools and machinery and then different costs.

Also material features are important, cause they allow to evaluate a feature feasibility whit some material (e.g. avoid treated hole in plastic components) and the influence on costs.

In Table 9 are reported an example of manufacturing and material features of the model (isolated) (3D model of a plate).

Table 9 Example of 2° block

	→ Material feature: → Material: Aluminium alloy – 1060 → Manufacturing feature: → Type of feature: **Feature_1 - PAD** → Coordinates of the feature in reference with origin: [50;-25;00] [50;25;00] [-50;25;00] [-50;-25;00] → Properties of the feature: → Height: 5 [mm] → Volume of the feature: 25000,00 [mm^3] → Area of the feature: 11500,00 [mm^2] → Faces of the feature: → Rectangular_face_01.01 → Rectangular_face_01.02 → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Rectangular_face_01.02 → Specific tolerance: NO → Coating: NO
	→ Material feature: → Material: Aluminium alloy – 1060 → Manufacturing feature: → Type of feature: **Feature_2 - HOLE RECTANGULAR PATTERN** → Coordinates of the feature in reference with origin: → For rectangular pattern [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05] → Properties of the feature: → For holes: → Diameter: 6 [mm] → Length: 5 [mm] → Volume of the feature: 1570,80 [mm^3] → Area of the feature: 1256,64 [mm^2] → Faces of the feature:

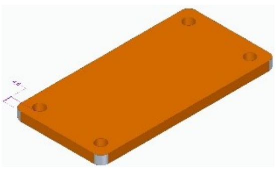
	→ Circular_face_02.01 → Circular_face_02.02 → Circular_face_02.03 → Circular_face_02.04 → Circular_face_02.05 → Circular_face_02.06 → Circular_face_02.07 → Circular_face_02.08 → Cilindrical_face_02.01 → Cilindrical_face_02.02 → Cilindrical_face_02.03 → Cilindrical_face_02.04 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Cilindrical_face_02.01 → Cilindrical_face_02.02 → Cilindrical_face_02.03 → Cilindrical_face_02.04 → Specific tolerance: NO → Coating: NO
	→ Material feature: → Material: Aluminium alloy – 1060 → Manufacturing feature: → Type of feature: **Feature_3 - PAD CORNER FILLETS** → Coordinates of the feature in reference with origin: [50;-25;00] [50;25;00] [-50;25;00] [-50;-25;00] → Properties of the feature: → Radius: 4 [mm] → Height: 5 [mm] → Volume of the feature: 17,17*4 [mm^3] → Area of the feature: 31,42*4 [mm^2] → Faces of the feature: → Semicircular_face_03.01 → Semicircular_face_0.02 → Semicircular_face_03.03 → Semicircular_face_03.04 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

3° block: Manufacturing and material features of the model (interrelated for part)

The third block take into consideration material and manufacturing features of the part evaluating the relationships between them (e.g. distance between two holes, space for tools, etc.), which could affect the accessibility or the feasibility of a particular feature (e.g. a small space to manufacture a hole implies the use of a special tool with increases in production cost). As said previously, the third block is used (in connection with the second) to define the manufacturing strategy and operation bundle of the cost routing structure (section 3.2.3).

In Table 10 are reported an example of manufacturing and material features of the model (interrelated for part).

Table 10 Example of 3° block

	→ Material feature:
	  → Material: Aluminium alloy – 1060
	→ Manufacturing feature vs. manufacturing feature/s:
	  → Type of feature vs. type/s of feature/s: **Feature_1 – PAD vs. Feature_2 - HOLE RECTANGULAR PATTERN**
	  → Coordinates of the feature vs. coordinates of the feature/s: [50;-25;00] vs. [42,5;-17,5;05]
	  → Properties of the feature vs. properties of the feature:
	    → Minimum distance: 4,5 [mm]
	  → Volume of the feature vs. volume of the feature/s: 25000,00 [mm^3] vs. 196,35*4 [mm^3]
	  → Area of the feature vs. area of the feature/s: 11500,00 [mm^2] vs. 94,22*4 [mm^2]
	  → Faces of the feature vs. faces of the feature/s:
	    → Rectangular_face_01.01 vs. Circular_face_02.01
	    → Rectangular_face_01.01 vs. Circular_face_02.02
	    → Rectangular_face_01.01 vs. Circular_face_02.03
	    → Rectangular_face_01.01 vs. Circular_face_02.04
	    → Rectangular_face_01.02 vs. Circular_face_02.05
	    → Rectangular_face_01.02 vs. Circular_face_02.06
	    → Rectangular_face_01.02 vs. Circular_face_02.07
	    → Rectangular_face_01.02 vs. Circular_face_02.08
	    → Rectangular_face_01.03 vs. Cilindrical_face_02.01
	    → Rectangular_face_01.04 vs. Cilindrical_face_02.01
	    → Rectangular_face_01.04 vs. Cilindrical_face_02.02
	    → Rectangular_face_01.05 vs. Cilindrical_face_02.02
	    → Rectangular_face_01.05 vs. Cilindrical_face_02.03
	    → Rectangular_face_01.06 vs. Cilindrical_face_02.03
	    → Rectangular_face_01.06 vs. Cilindrical_face_02.04
	    → Rectangular_face_01.03 vs. Cilindrical_face_02.04
	  → PMI vs. PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

Assembly environment related features

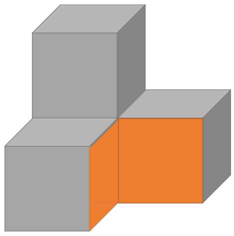
Other features to mentioned are connected to the assembly. An *assembly feature* is a stereotypical assembly “situation”. An assembly feature is here defined as an information carrier for assembly-specific information. Assembly information can be divided into two types: The first type represents assembly information used to handle a component, i.e. handling-specific assembly information on generic level. The second type represents information about the connections between components. So the assembly features are divided into handling features, representing handling information, and connection features, representing connections between components. A *handling feature* provides information about feeding, fixturing and grasping, for a generic component. The feeding and fixturing information consist of predefined position and orientation information, together with involved contact areas. The gripper information consists of, among other things, the number of fingers, the maximum finger width, the finger length, minimal and maximal grasp forces, and available motions. Handling features could be obtained from the 1° and 2° blocks introduced before.

From the 1° block could be obtained information regarding for example the slipperiness or the fragility of the part (from material features) and could be calculated the number of people or the needed of grasping tool for the part movements (physical features). From the 2° block could be evaluated the presence of sharp points in the part of fragile section (thin or sharp manufacturing features).

The idea of *connection features* is that characteristics of connection types can be incorporated in these features. A connection feature provides assembly information for a specific connection between several components. Some example of connecting feature are: involved form feature types, final position, insertion position, insertion path, tolerances, contact areas, internal freedom of motion, geometric refinements (Kimura, 2001).

For the connection features is necessary the introduction of a 4° block: Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly). (Table 11)

Table 11 Block 4 of the methodology

Block 4: Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly)	
	→ Material feature vs. material feature/s: → Material vs. material/s: [string] vs. [string] → Manufacturing feature vs. manufacturing feature/s: → Type of feature vs type of feature/s: [string] vs. [string] → Coordinates of the feature vs. coordinate of the feature/s: [XX;YY;ZZ] vs. [XX;YY;ZZ] → Properties of the feature vs. properties of the feature/s: [mm] vs. [mm] → Volume of the feature vs. volume of the feature/s: [mm^3] vs. [mm^3] → Area of the feature vs. area of the feature/s: [mm^2] vs. [mm^2] → Faces of the feature vs. faces of the feature/s: [string] vs. [string] → PMI: → Specific roughness vs. specific roughness: [string] vs. [string] → Specific tolerance vs. specific tolerance: [string] vs. [string] → Coating vs. coating: [string] vs. [string]

Features used in analytical and DfM/DfA methodologies for assembly are summarized in Table 12, describing also their information/attributes.

Table 12 Features classification for assembly environment

Assembly feature	Handling feature	1° Block	Material feature [strings] Physical feature [strings]
		2° Block	Material feature [strings] Manufacturing feature [strings]
	Connection feature	4° Block	Material feature vs material feature [strings vs. strings] Manufacturing feature vs. manufacturing feature/s [strings vs. strings]

4° block: Manufacturing and material features of the model (interrelated for assembly)

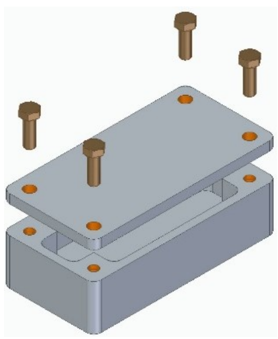
The 4° block is similar to the previous one (3° block) but in this case the features are related to different components. The fourth block take into consideration the relation between material and manufacturing features of two or more components in an assembly. In this block, a given material or manufacturing feature of a model (component) needs to be investigated against features of other models (components) that are composing the same assembly (features relation).

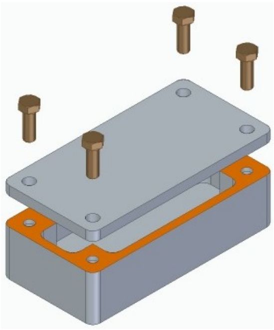
The fourth block is used (in connection with the second) to define the assembly strategy and operation bundle of the cost routing structure (section 3.2.3).

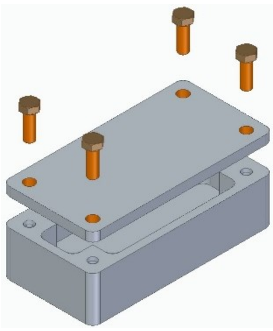
Assembly strategy defines the specific assembly process to be used for converting a series of components in final assembled product (e.g., welding vs gluing vs bolding) and is composed by a series of operations bundles. The choice for a specific assembly strategy is also based on material of assembly components (e.g. for plastic parts welding operation are not feasible).

In Table 13 are reported an example of manufacturing and material features of the model (interrelated for assembly).

Table 13 Example of 4° block

	→ Material feature vs. material feature/s: → Material vs material/s: Aluminium alloy – 1060 vs. Aluminium alloy – 1060 → Manufacturing feature vs. manufacturing feature/s: → Type of feature vs. type/s of feature/s: **Feature_2 - HOLE RECTANGULAR PATTERN (upper part) vs. Feature_2 – THREADED HOLE RECTANGULAR PATTERN (base part)** → Coordinates of the feature vs. coordinates of the feature/s: [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05] vs. [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05] → Properties of the feature vs. properties of the feature/s: → Axis gap: 0 [mm] → Diameter gap: 1 [mm] → Volume of the feature vs. volume of the feature/s: 392,70*4 [mm^3] vs. 196,35*4 [mm^3] → Area of the feature vs. area of the feature/s: 179,91*4 [mm^2] vs. 94,22*4 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cilindrical_face_02.01 (upper part) vs. Cilindrical_face_02.01 (base part) → Cilindrical_face_02.02 (upper part) vs. Cilindrical_face_02.02 (base part) → Cilindrical_face_02.03 (upper part) vs. Cilindrical_face_02.03 (base part) → Cilindrical_face_02.04 (upper part) vs. Cilindrical_face_02.04 (base part)

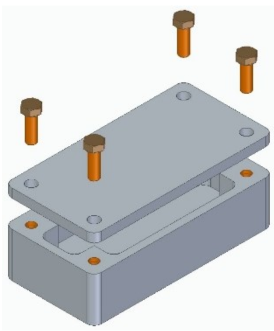




→ PMI vs. PMI:
  → Specific roughness: NO
  → Specific tolerance: NO
  → Coating: NO

→ Material feature vs. material feature/s:
  → Material vs material/s: Aluminium alloy – 1060 vs. Aluminium alloy – 1060
→ Manufacturing feature vs. manufacturing feature/s:
  → Type of feature vs. type/s of feature/s: **Feature_1 - PAD (upper part) vs. Feature_1 - PAD (base part)**
  → Coordinates of the feature vs. coordinates of the feature/s: [50;-25;00] [50;25;00] [-50;25;00] [-50;-25;00] vs. [50;-25;00] [50;25;00] [-50;25;00] [-50;-25;00]
  → Properties of the feature vs. properties of the feature/s:
    → Minimum distance: 0 [mm]
  → Volume of the feature vs. volume of the feature/s: 25000,00 [mm3] vs. 125000,00 [mm3]
  → Area of the feature vs. area of the feature/s: 11500,00 [mm^2] vs. 11500,00 [mm^2]
  → Faces of the feature vs. faces of the feature/s:
    → Rectangular_face_01.02 (upper part) vs. Rectangular_face_01.02 (base part)
  → PMI vs. PMI:
    → Specific roughness:
      → Ra 1,6 [µm] on:
        → Rectangular_face_01.02 (upper part) vs. Rectangular_face_01.02 (base part)
    → Specific tolerance: NO
    → Coating: NO

→ Material feature vs. material feature/s:
  → Material vs material/s: Aluminium alloy – 1060 vs. 11SMn30 (class 4.6)
→ Manufacturing feature vs. manufacturing feature/s:
  → Type of feature vs. type/s of feature/s: **Feature_2 - HOLE RECTANGULAR PATTERN (upper part) vs. Feature_1 – CYLINDRICAL PAD (screw)**
  → Coordinates of the feature vs. coordinates of the feature/s: [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05] vs. [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05]
  → Properties of the feature vs. properties of the feature/s:
    → Axis gap: 0 [mm]
    → Diameter gap: 1 [mm]
  → Volume of the feature vs. volume of the feature/s: 196,35*4 [mm^3] vs. 284,71*4 [mm^3]
  → Area of the feature vs. area of the feature/s: 94,22*4 [mm^2] vs. 227,69*4 [mm^2]
  → Faces of the feature vs. faces of the feature/s:
    → Cilindrical_face_02.01 (upper part) vs. Cilindrical_face_01.01 (screw 1)



- → Cilindrical_face_02.02 (upper part) vs. Cilindrical_face_01.01 (screw 2)
- → Cilindrical_face_02.03 (upper part) vs. Cilindrical_face_01.01 (screw 3)
- → Cilindrical_face_02.04 (upper part) vs. Cilindrical_face_01.01 (screw 4)

→ PMI vs PMI:
- → Specific roughness: NO
- → Specific tolerance: NO
- → Coating: NO

→ Material feature vs. material feature/s:
- → Material vs material/s: Aluminium alloy – 1060 vs. 11SMn30 (class 4.6)

→ Manufacturing feature vs. manufacturing feature/s:
- → Type of feature vs. type/s of feature/s: **Feature_2 – THREADED HOLE RECTANGULAR PATTERN (base part) vs. Feature_1 – CYLINDRICAL PAD (screw)**
- → Coordinates of the feature vs. coordinates of the feature/s: [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05] vs. [42,5;-17,5;05] [42,5;17,5;05] [-42,5;17,5;05] [-42,5;-17,5;05]
- → Properties of the feature vs. properties of the feature/s:
  - → Axis gap: 0 [mm]
  - → Diameter gap: 0 [mm]
- → Volume of the feature vs. volume of the feature/s: 392,70*4 [mm^3] vs. 284,71*4 [mm^3]
- → Area of the feature vs. area of the feature/s: 179,91*4 [mm^2] vs. 227,69*4 [mm^2]
- → Faces of the feature vs. faces of the feature/s:
  - → Cilindrical_face_02.01 (base part) vs. Cilindrical_face_01.01 (screw 1)
  - → Cilindrical_face_02.02 (base part) vs. Cilindrical_face_01.01 (screw 2)
  - → Cilindrical_face_02.03 (base part) vs. Cilindrical_face_01.01 (screw 3)
  - → Cilindrical_face_02.04 (base part) vs. Cilindrical_face_01.01 (screw 4)
- → PMI vs. PMI:
  - → Specific roughness: NO
  - → Specific tolerance: NO
  - → Coating: NO

3.2. Analytical cost estimation analysis

As said in previous chapters analytical cost estimation approach consist in decomposing a product into elementary units, operations, and activities that represent different resources consumed during the production cycle and expressing the cost as a summation of all these components. This section will define two *framework* which can be used by designers and engineers for the analytical cost estimation of mechanical products. One framework is dedicated for manufacturing a single component, while the other one is for assembly of a group of parts. Is important to notice that the two frameworks are similar in some aspect. The proposed approach is based on an article written in collaboration with other university colleagues (Mandolini et al., 2020) and in case of assembly is based on Boothroyd methodology (Boothroyd et al., 2011)

The *frameworks* are composed by five main paradigms used for formalizing the knowledge required for the cost estimation of products:

(i) a *manufacturing/assembly process data structure* to represent the logical sequence of manufacturing or assembly operations;

(ii) a *cost breakdown structure* used for breaking out the manufacturing/assembly costs;

(iii) a *cost routing* used for the collection of the knowledge required for a manufacturing/assembly process definition;

(iv) a *cost model* used for the collection of the knowledge required for calculate the cost of each manufacturing/assembly process operation;

(v) a *workflow* for determining a manufacturing/assembly process using 3D virtual prototypes.

Manufacturing process could be classified into *finishing*, *forming/shaping* and *joining processes* (Ashby, 2010). Since there are great differences among such processes, the framework presented in this thesis has been conceived for forming/shaping processes. Joining and finishing are beyond the boundaries of this framework.

Mainly forming processes are:

- *casting*: sand casting, die casting, investment casting;
- *moulding*: injection moulding, compression, blow moulding;
- *deformation*: rolling, forging, drawing;
- *powder*: sintering, HIPing;
- *machining*: cutting, turning, drilling, grinding, etc.;
- *heat treatments*: quench, temper, etc.

On the contrary the assembly process can be done temporarily with fasteners or permanently by welding or gluing. If the assembled part requires service, it is better to connect temporarily. During the assembly process, the order should also be considered during the design stage

Section 3.2.1 defines *manufacturing process data structure*, the logical sequence for transforming a raw material into the final product, and *assembly process data structure*, the logical sequence for connect the single parts together into the final product. Section 3.2.2 describe the *cost breakdown* structure. Section 3.2.3 provides *cost routing* used for collecting the manufacturing and assembly-related knowledge, while section 3.2.4 provides the *cost model* used for collecting the cost-related knowledge considering each operation within a manufacturing/assembly process. Section 3.2.5 describes the *workflow* in the component's manufacturing/assembly cost estimation starting from a component's 3D virtual prototype.

3.2.1. Process data structure

A manufacturing process (Figure 9) can be defined as sequence of operations needed to transform raw materials into final components, while an assembly process (Figure 10) is the sequence of operations needed to join the single components together and obtain final products. To describe a manufacturing or an assembly process for product cost analysis are needed:

(i) the representation of the characteristics of the product to be manufactured (geometrical features, components required, etc.);

(ii) the available technology (machines, services, equipment, tool, etc.);

(iii) the tasks/operations required to achieve these features. Each task of a generic manufacturing process is defined based on the geometrical product features and other features that are affecting the process (status of the machines, characteristics of the raw material, etc.) (Garcia-Crespo, 2010).

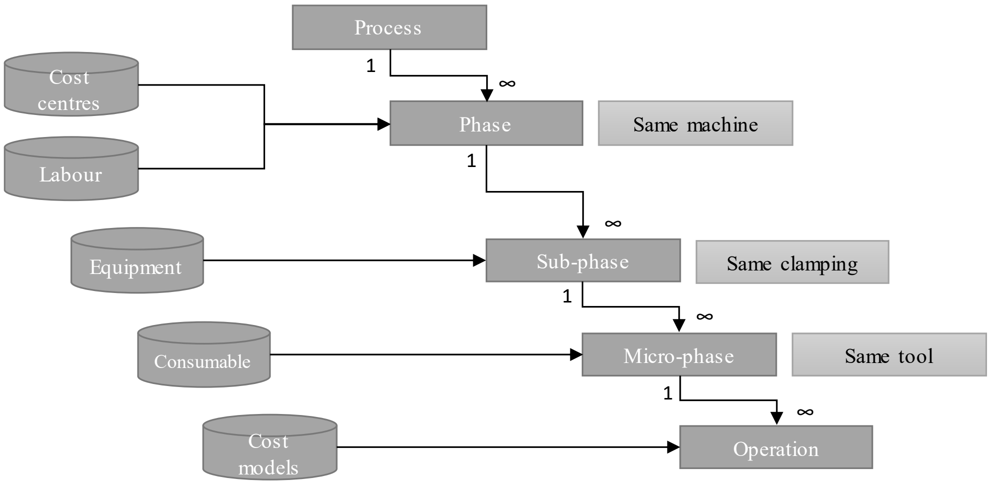


Figure 9 Schematic model of a generic manufacturing process (UML class diagram)

A working plan consists of several phases and operations performed with the same machine or in the same cost centre. In a single phase, operations are grouped into sub-phases, in which they are realized with the same work-piece clamping. A clamping contains different tools which can be used in the manufacturing of the final part. Micro-phases grouped operations realized through use of the same machine, work-piece clamping, and tools.

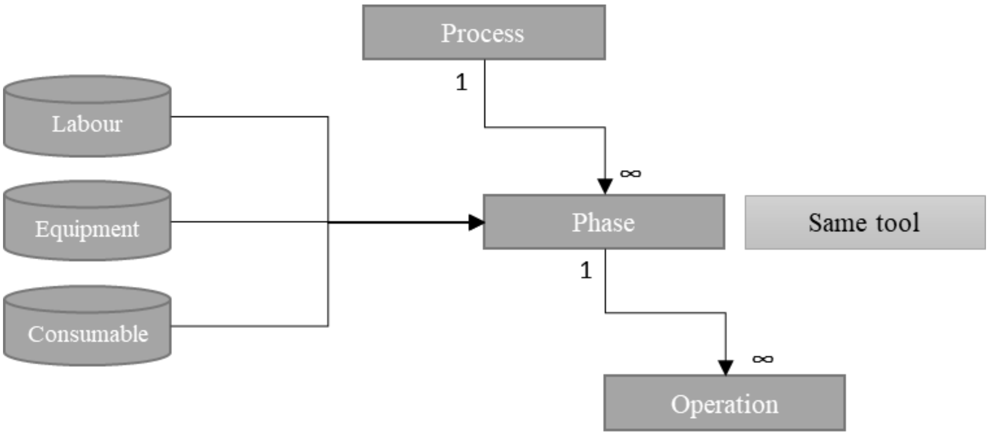


Figure 10 Schematic model of a generic assembly process (UML class diagram)

Assembly planning can be roughly divided into three phases (Nasr, 2006):

1. Selection of assembly method: identifying the one most suitable method for the product while accounting for the type of assembly system to be used.

2. Assembly sequence planning: generating a sequence of assembly phases. Each phase groups operations realized with the same tools (e.g. tighten a series of identical screw for closing a lid).

3. Assembly operations planning: emphasizing the details of individual assembly steps, such as access directions, mating movements, and application of fasteners.

3.2.2. Cost breakdown data structure

Starting from the proposed process data structure, a cost breakdown data structure is necessary to collect information of each phase and operation. The schema for collecting the costs of each item is represented by the tree in Figure 11 (manufacturing) and in Figure 12 (assembly).

The costs, in case of manufacturing, are divided into six categories:

(i) *material;*

(ii) *machine*;

(iii) *labour*;

(iv) *equipment*;

(v) *consumables;*

(vi) *energy*.

While in case of assembly the costs are divided into four categories:

(i) *labour*;

(ii) *equipment*;

(iii) *consumables;*

(iv) *energy*.

These representations derive from a literature analysis and combines the retrieved information to reflect the most common classifications for the cost estimation of different manufacturing/assembly processes and the cost items generally used in the manufacturing technologies (Chiadamrong et al, 2003)(Wang et al., 2007)(H'mida et al, 2006)(Xu et al, 2012).

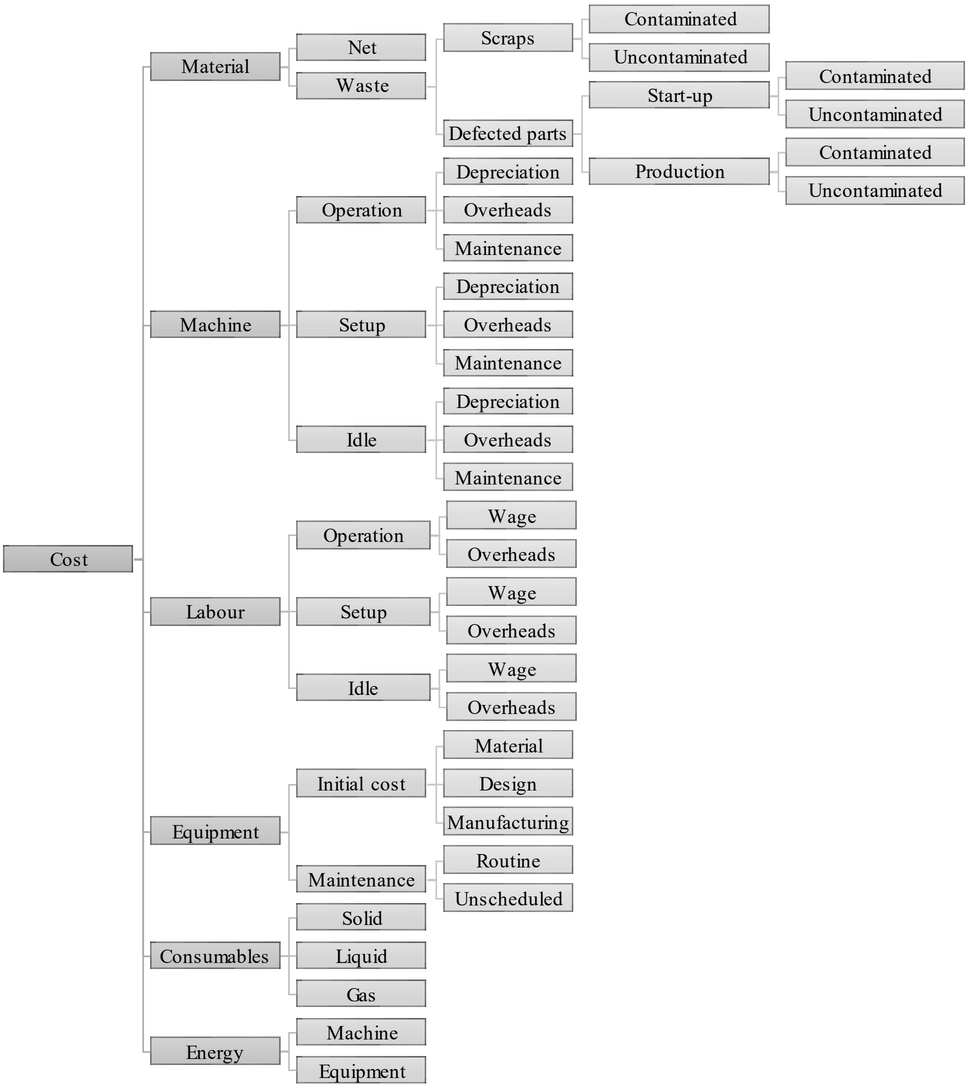


Figure 11 Cost breakdown structure (manufacturing) (UML class diagram)

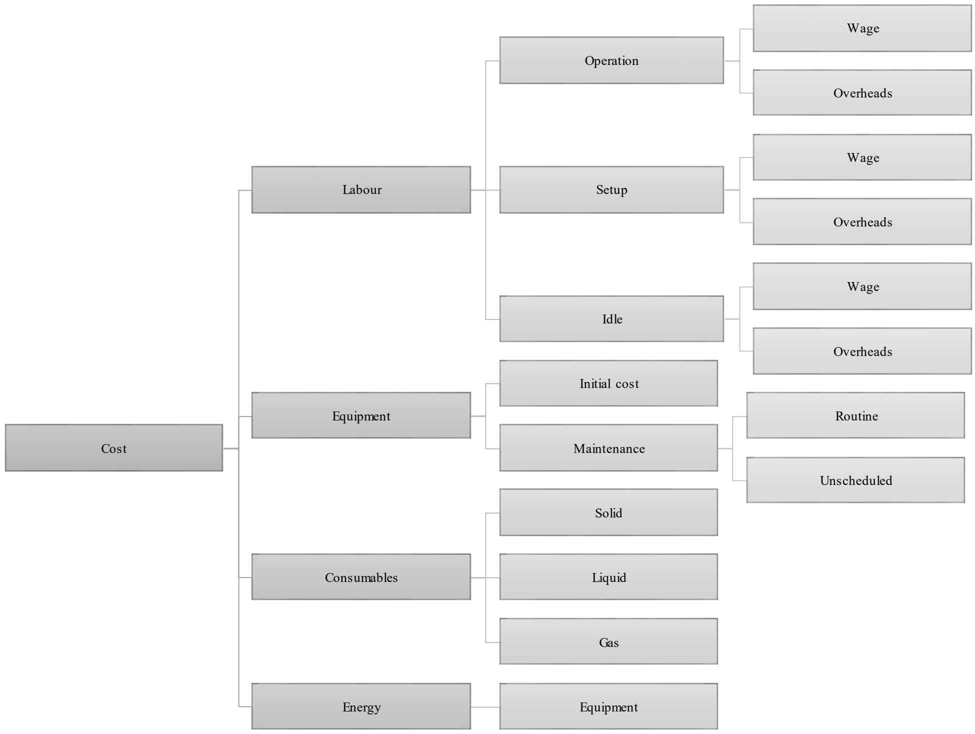


Figure 12 Cost breakdown structure (assembly) (UML class diagram)

The *material* category represents the costs of raw material needed to manufacture a specific part/component. The raw material cost, or also called gross cost, includes the sum of the parts' net cost and waste cost.

Material waste is composed by two categories:

(i) *Scraps*: the material in excess of what is necessary for processing (e.g., flash in the forging process or the runners in casting). In some cases, scraps can be contaminated with lubricant, which decreases their value cause additional cleaning and decontamination operations required for their reuse.

(ii) *Defected parts*: the non-compliant components realized during the initial process start-up or during production. A typical example of start-up waste are the initial pieces in the plastic injection process when a change

of the component colour is made; this initial parts will not be of the expected colour, but there will still be some leftover pieces from the previous colour that remained inside the moulds. Both types of defected parts (those realized during start-up and those realized during production) are classified into contaminated and uncontaminated pieces.

Machine and *labour* categories refer to the cost-centres used for performing an operation. These costs are further classified into to:

(i) *Operation*: A sub-category referred to the manufacturing or assembly operations (e.g., chip removal, plastic deformation, forging, heating, screwing, welding etc.) that directly contribute toward the realization of the final component. These items are considered a product's direct cost.

(ii) *Idle:* A sub-category referred to a passive phase when one operation has been completed and tooling or materials for the next one is not yet completed or available. In this condition, the machine or the operator (or also the equipment in case of assembly) is available in theory, but it does not perform any work. This item is also considered a product direct cost as manufacturing operations.

(iii) *Setup:* A sub-category referred to the previous idle operations, such as tool setting and machine/equipment cleaning, required before starting the production. The operations time not depend by the batch dimension, but, the related cost must be split according to the batch quantity for calculating the setup cost for each component. For this motivation, the machine set-up cost is an indirect cost.

For each process operation, according to the degree of automation, one/no machine and/or one/multiple worker(s) can be employed. The hourly cost rate of a machine comprises its maintenance, overhead and depreciation cost, whereas the rate for an operator comprises the operator's wage and overhead.

The *equipment* category refers to those tools, such as mould jigs and fixtures (in case of manufacturing) or drill and welding machines (in case of assembly), required for performing a specific process operation. The cost is the sum of the initial expenditure and the maintenance cost during its usage. The initial expenditure considers the cost for bought them or in case of internal equipment production considers the design and manufacturing plus the material cost. This cost is independent of the production volume; hence, the related cost must be split for the production volume for calculating the equipment cost for each component. Therefore, the equipment cost is considered an indirect cost.

The *consumables* category refers to those materials that enable the process itself (e.g., lubricants used for forging, gas cutting assistance for laser cutting, shielding gas or filler material used for welding, etc.). This item is a direct and accessory cost directly allocated to the cost of each component or assembly.

The *energy* category refers to the energy vectors (e.g., electricity, water, steam, etc.) that guarantee that the process works. Energy may be required by machines and/or equipment, and the related cost is function of their power and working time. This item is considered a product direct cost.

3.2.3. Cost routing

A cost routing (manufacturing in Figure 13 and assembly in Figure 14) is defined as a hierarchical data model of five classes (in blue colour). Each class contains groups of attributes and rules for generating manufacturing or assembly processes from 3D virtual models of components. This hierarchical data model is required cause each process is defined through a multi-step approach (section 3.2.5), which starts from the setting of a production scenario to the calculation of the elementary operations necessary for converting raw materials into finished parts. A cost routing does not contain direct information for computing the cost of a process, while such knowledge is contained in cost models. Rules contained in a cost routing can be classified into three groups and are required for generating a manufacturing process:

(i) *Validity rules:* necessary for establishing only the feasible manufacturing/assembly solutions in the group of all the possible ones. Validity rules are required in case of multi-scenario simulation.

(ii) *Priority rules*: needed for sorting the feasible solutions, with the purpose of selecting the best one. Priority rules are required to identify the optimized production process.

(iii) *Calculation rules:* used for computing process parameters. Calculation rules are needed for evaluating and sorting the manufacturing/assembly solutions.

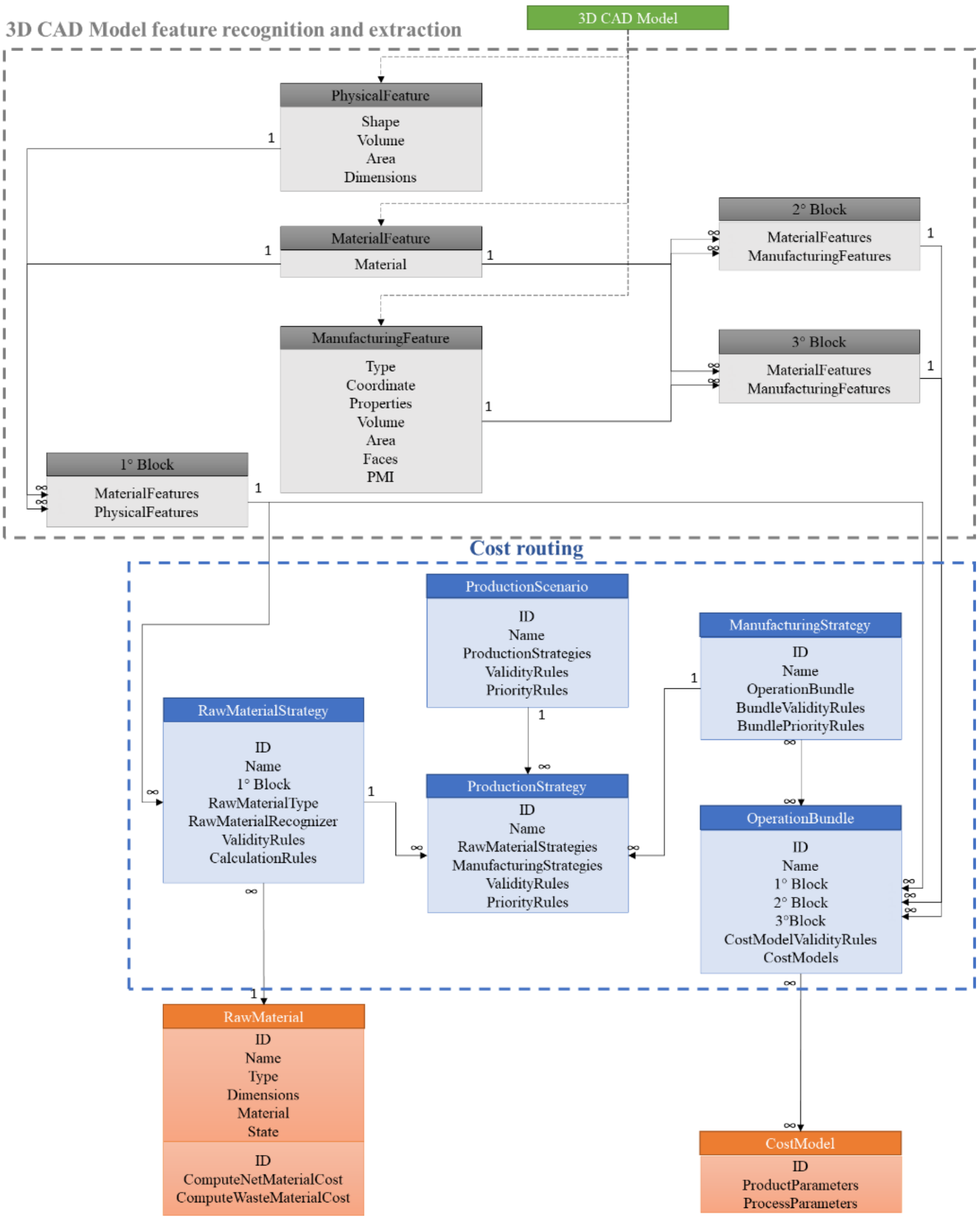


Figure 13 Manufacturing cost routing structure (UML class diagram)

In case of manufacturing the five constructs of a cost routing can be summarized as follows:

- *Production scenario*. It consists of a list of production strategies and represents the first container of knowledge required for defining a manufacturing process. A scenario could represent the facilities and production technologies available (the context) in which the manufacturing process is realized (make a product internally or buy from a supplier). At this level, validity and priority rules are required for establishing the production scenario in which a component is realized.

- *Production strategy*. This strategy roughly defines the overall manufacturing process (e.g., machining from block vs machining from semi-finished casted part) to be used for realizing a component and contains list of pairs, such as raw material and manufacturing strategies. Validity and priority rules are both required for defining a specific production strategy.

- *Raw material strategy*. This strategy defines the raw material (e.g., commercial semi-finished material, casted/forged elements) to be used for realizing the final part. Feature recognition algorithms compute in automatic way a raw material strategy, which is obtained by the characteristics of the material and the parts (1° block of the feature recognition). Algorithms calculate dimensions and typology of raw material (rawmaterial recognizer). For this strategy, only validity and calculation rules are applicable. The last ones are used for determining the size of a stock.

- *Manufacturing strategy*. This strategy defines the specific manufacturing process to be used for converting a stock into a finished component (e.g., machining vs additive) and is composed by a series of operations bundles. Each operation bundle has a series of validity and priority rules.

- *Operations bundle*. An operations bundle is composed by the group of operations needed for a specific product manufacturing feature (1°, 2° and 3° block of feature recognition). It is consisting of a series of faces and related properties, such as slot depth, slot shape, maximum and minimum tolerance, maximum and minimum roughness. Some examples of product manufacturing features are slots, holes, threaded holes, cut-outs, fillets, chamfers, milling features, turning features. A product manufacturing feature can be alternatively realized by one bundle at a time. Specific recognizers contain feature recognition algorithms which calculate these product manufacturing features. For each kind of product to be analysed, such as turned axisymmetric parts, milled prismatic parts, casted parts, or forged parts, there is one specific recognizer. Each feature has different product manufacturing feature properties which are used within the validity rules of each bundle to establish which one is valid. The bundle is also responsible for transferring the product manufacturing feature properties to the valid operations defined inside the bundle. Indeed, a bundle may contain multiple operations, whose validity is managed by validity rules defined within each operation.

Feature recognition play an important role in the definition of an operation bundle.

Manufacturing features affect the operation bundle, cause in function of the type of feature there will be different operations (drilling, facing, milling, etc.) that can be produced with different tools and machinery. Also, the relationships between two or more features (e.g. distance between two features, space for tools, etc.) could be affect the accessibility or the feasibility of a particular feature (e.g. a small space implies the needs of special tools). The machineries and tools used affect the production cost, cause each machinery has different hourly cost, a defined number of crew, or different tools.

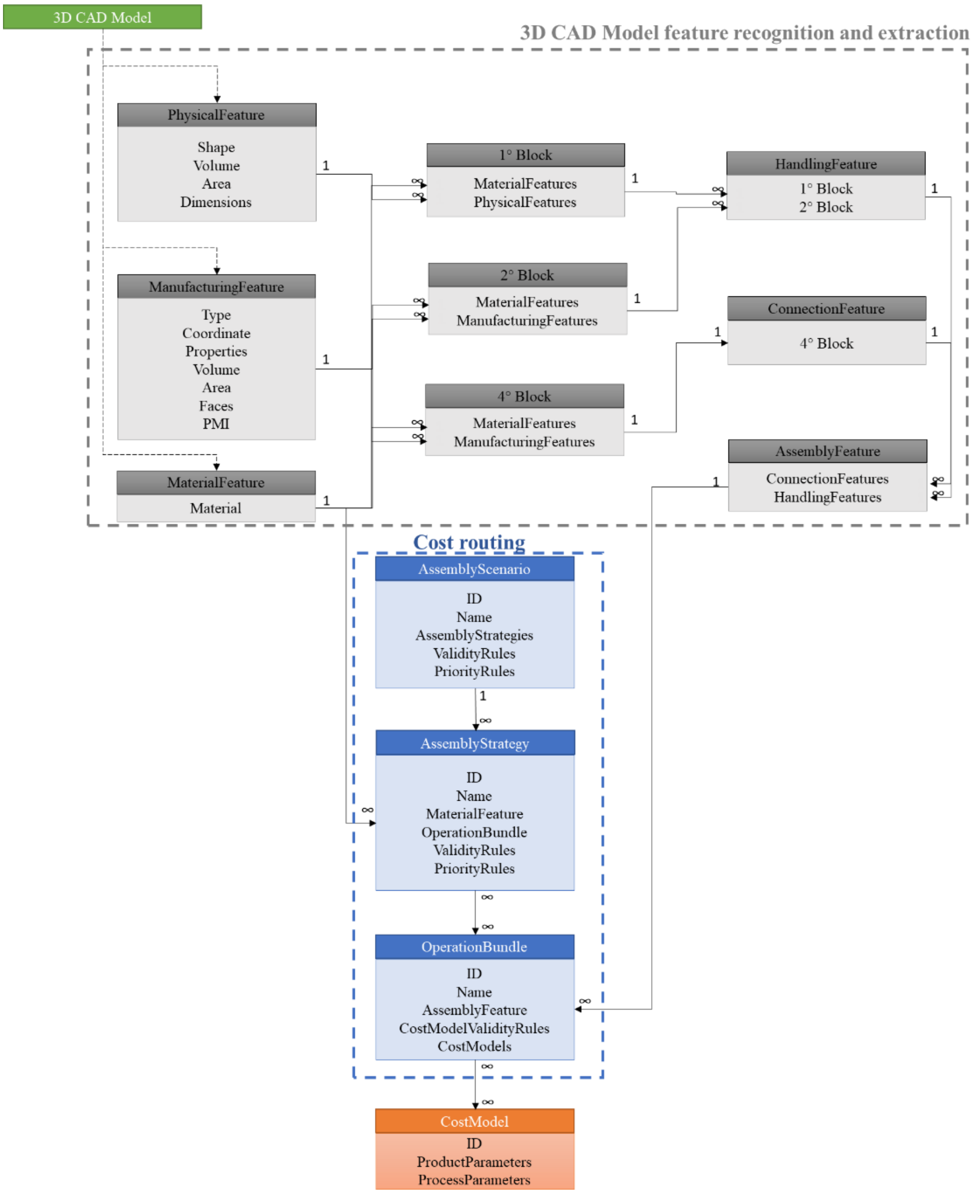


Figure 14 Assembly cost routing structure (UML class diagram)

In case of assembly the constructs are three and can be summarized as follows:

- *Assembly scenario*. It consists of a list of assembly strategies and represents the first container of knowledge required for defining an assembly process. A scenario could represent the facilities and production technologies available (the context) in which the assembly process is realized (make a product internally or buy from a supplier). At this level, validity and priority rules are required for establishing the assembly scenario in which a product is realized.

- *Assembly strategy*. This strategy defines the specific assembly process to be used for converting a series of components in final assembled product (e.g., welding vs gluing vs bolding) and is composed by a series of operations bundles. Each operation bundle has a series of validity and priority rules. The choice for a specific assembly strategy is also based on material of assembly components (e.g. for plastic parts welding operation are not feasible).

- *Operations bundle*. An operations bundle is composed by the group of operations needed for a specific product assembly feature. A complete description of assembly feature is in section 3.1.1.1.

An assembly feature can be alternatively realized by one bundle at a time, as was the case with the manufacturing feature.

3.2.4. Cost model

As said before, a manufacturing or assembly operation is a simple block of a more complex process, instantiated directly by a bundle. A *cost model* is a data model which contain the knowledge necessary for production time and cost estimation for each operation. A cost model could be considered a structured information object, as shown in Figure 15 (for manufacturing) and Figure 16 (for assembly), and is composed by a list of parameters of product and process. The product parameters are defined by the bundle and are function of the manufacturing or assembly features associated with the bundle. The process parameters characterize the operations from a technological point of view. Considering as example the injection moulding process, some of these parameters are injection temperature and pressure, mould temperature, injection tonnage, mould dimensions. These parameters are computed using specific calculation rules which are based on the product parameters. These rules are contained in a specific database and they come from industrial practice or industrial and scientific literature. A cost model also contains several validity rules and calculation rules. Validity rules are used for restricting the possible cost centres (machine and labour), energy vectors, consumables, equipment and materials applicable for a specific operation. Calculation rules evaluate the consumption of the energy vector, consumables, equipment and the generation of waste. Finally, consistent with the cost breakdown presented in Figure 11 and Figure 12, an operation contains rules for computing the manufacturing time and cost.

Assembly rules derive from Boothroyd-Dewhurst (Boothroyd et al., 2011) method of assembly. It entails the estimation of the assembly time for each component, which is the sum of five contributions: (i) acquisition, (ii) movement, (iii) orientation, (iv) insertion, and (v) fastening. The assembly time depends on multiple factors that affect the assembly steps above-mentioned. Handling and insertion times are a function of the following component parameters. Each of these parameters directly affects the assembly process by simplifying or complicating it:

- Component size.
- Component thickness.
- Component weight.
- Tendency of the component to nesting.
- Tendency of the component to tangling.
- Component fragility.
- Component flexibility.
- Component slipperiness.
- Component stickiness.
- Necessity of using two hands to effect assembly.
- Necessity of using specialized grasping tools to effect assembly.
- Necessity of optical magnification to effect assembly.
- Necessity of mechanical assistance to effect assembly.

Non assembly operations also are included in the worksheet. For example, extra time is allocated for each time the assembly is reoriented. According to empirical measurements and geometric considerations, the acquisition, movement, orientation, insertion, and fastening times can be separately or jointly related to these factors. This approach allows designers to estimate the assembly time of a component considering its actual conditions within an assembly. For this aim, Boothroyd et al. defined proper classification systems where establishing the relationships among part features and manual handling, insertion, and fastening time. In addition to these classifications systems, Boothroyd et al. also proposed equations and graphs for estimating the assembly time according to the most important part features.

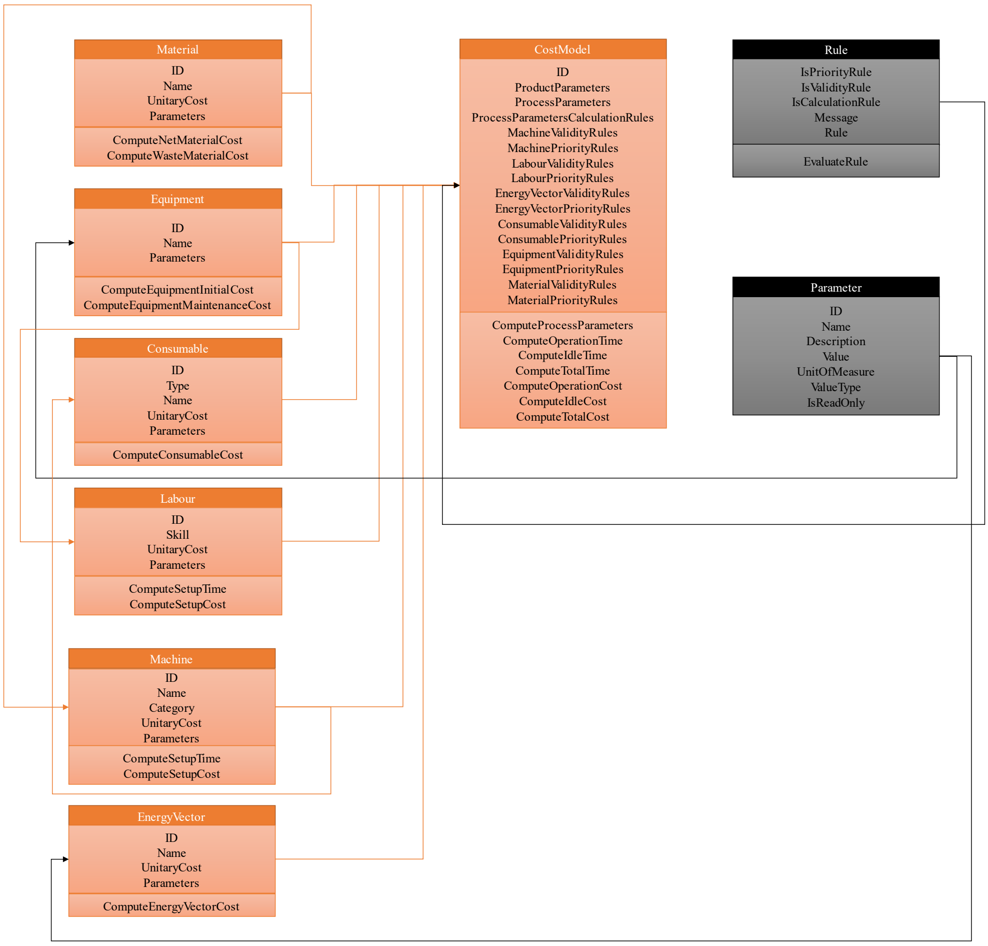


Figure 15 Manufacturing cost model structure (UML class diagram)

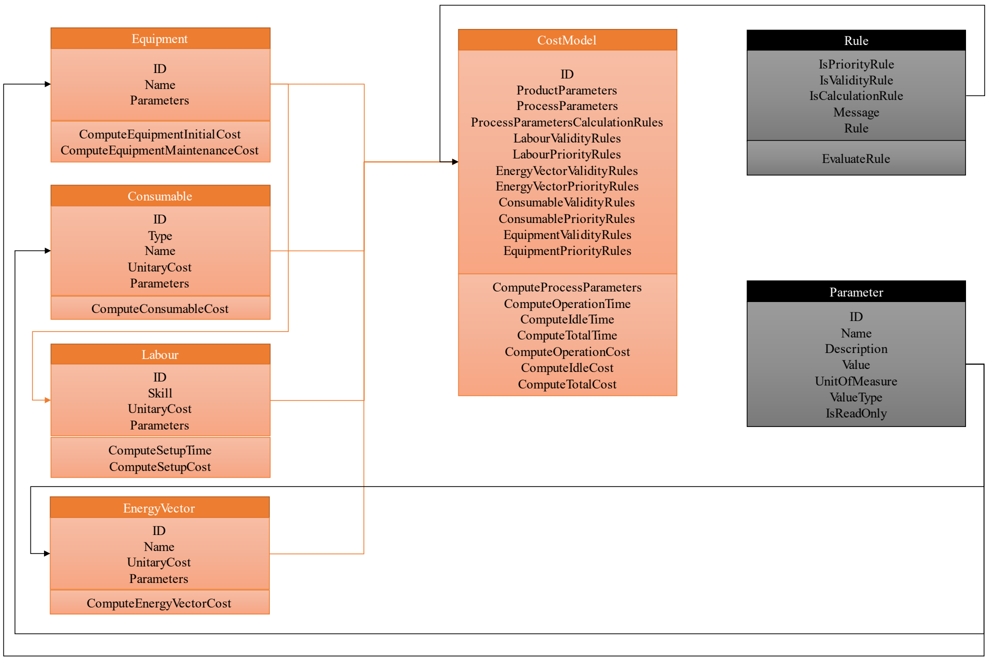


Figure 16 Assembly cost model structure (UML class diagram)

To compute the process parameters, it is necessary to establish the following information:

- *Machine (only for manufacturing)*. The machine is the cost centre used for realizing the operation. Each operation has a list of available machines restricted by a list of validity rules (e.g., press tonnage in injection moulding or in forging must guarantee a camping force greater than that one required by the process) Is important to emphasize that process parameters are influenced by the machine (e.g., in forging process the forging time depends on the press force and dimensions).

- *Labour (both for assembly and manufacturing)*. Labour is another cost centre that can be used for operation realization. It behaves in the same way as the *Machine*.

- *Energy (both for assembly and manufacturing)*. An energy vector is generally electricity. For each operation could be used one, multiple or no energy vectors. The energy consumption mainly depends on the machine, product, process parameters, the equipment or tool used (e.g., electricity consumption depends on the machine or equipment power and time of usage).

- *Consumable (both for assembly and manufacturing)*. Regarding consumables can be made the same considerations of energy. Consumable are lubricants, cutting tools, cutting assistance gas, shielding gas for welding, filler materials, glue, etc. Each operation could use one, multiple or no consumables. The consumables consumption mainly depends on the machine, product and process parameters.

- *Equipment (both for assembly and manufacturing)*. Equipment are jigs, fixture and moulds, welding machine, wrenches, screwdriver and as well as for energy and consumables each operation uses one piece of equipment, multiple pieces of equipment, or no equipment. The equipment depends by the machine and some process parameters, such as batch size or production volume. In many cases an equipment influences other process parameters (e.g., hot chambers in injection moulding process are used to reduce raw material scrap).

- *Waste (only for manufacturing)*. Each operation generates scraps or defected parts during the process start-up or normal production (runner volume in casting, or flash in forging). Waste depends on both the product and process parameters and the maturity of a process. In-fact in a well-tested process scrap are limited compared to a new process (learnability curve).

All this information contributes to the calculation of the operations cost, but not all are necessary. In-fact, while one machine or labour is required, all the other components are optional (e.g., a consumable is not applicable for injection moulding or for bolted assembly).

3.2.5. Workflow for the definition of a manufacturing process

As show in previous sections, the analytical manufacturing cost estimation process is a sequence of multiple steps, and the calculation of its cost breakdown is presented in Figure 11 and Figure 12 (UML Sequence Diagram). Starting from a 3D virtual prototype of a component, the workflow for the definition of a manufacturing process consists of six decision steps (Figure 17), while the workflow for the definition of an assembly process consists of 4 decision steps (Figure 18). Each step is supported by the proper knowledge, which is a combination of databases and knowledge-based rules.

The cost estimation process, both for manufacturing and assembly, is based on the following set of product and process related information:

- *3D CAD model*. This is the Boundary Representation model (BRep) of the part which will be analysed for extracting process specific attributes required for defining the manufacturing process. Specific attributes are stamping or machining direction, quantity of undercuts, etc.

- *Geometrical and non-geometrical attributes*. These attributes are general and represent overall dimensions, maximum/average thickness, weight, material, shape (i.e., axisymmetric, prismatic, sheet metal, etc.). These attributes are retrieved from the 3D CAD model.

- *Product Manufacturing Information (PMI)*. PMI are the roughness, tolerances, welding length and other attributes, such as surface coatings, heat treatments and surface finishing, that are related to the manufacturing process and are directly linked to the 3D CAD model.

- *Process attributes*. These attributes denote information related to manufacturing aspects, such as batch size, production volume, and delivery time.

Manufacturing

The first step of the cost estimation of a manufacturing process is composed by sub-steps 1a, 1b, 1c and 1d. In this step is established the overall production scenario. In the first one the user defines the production information (batch size, production volume and general PMI (roughness, tolerance and coating)) and select the CAD model of the part. After that, from 3D CAD model, are extracted product manufacturing information (material, shape, ect) and at the end the production scenario is instantiated. Indeed, the manufacturing process and the related costs first depend on the production environment, which is characterized by the production facility (e.g., machine tools, tools, plant layout, and overall equipment effectiveness), the raw materials warehouse and the sourcing strategy. The selection of the right production environment is usually determined by vendor ratings and supplier selection methodologies.

The second step of the cost estimation process is the definition of the production strategy and includes the selection of the raw material and manufacturing process. The selection of raw material type (e.g., commercial semi-finished product or custom stock) and the manufacturing process type (e.g., forging vs chip forming) is performed at the same time since these two aspects are dependent on each other. For example, closed die forging process is valid only for metal materials (validity rule), which are appropriate only for production volumes greater than hundreds of components (priority rule). The validity of a production strategy is also triggered by the validity of the raw material and manufacturing strategy. In the case of one of these rules are not valid, the production strategy where such manufacturing or raw material strategies are used will be invalidated.

The third step, composed by 3a, 3b and 3c sub-steps, is the definition of raw material features. Based on the information on the type of material, some features are assessed by the model such as the following:

- Type of supplied material: commercial bar, sheet metal, or billet.
- Shape: circular, rectangular, or solid/hollow.
- Dimensions: thickness, length, width, and height.
- Supply status: hot rolled, extruded, grinded, or galvanized.
- Volume.
- Weight.
- Unitary cost.

The type of supplied material is computed according to the product-related information previously presented, by using validity and calculation rules. For computing such information, feature recognition algorithms should be employed for analysing the 3D CAD model, with the aim of defining specific raw material features consisting of a set of geometrical information required for selecting the stock (Han, 2000) (Cicconi, 2010). The raw material cost is computed by multiplying the amount of requested material by the unitary cost.

The fourth step of the cost estimation process is the definition of the manufacturing strategy to be employed for making a component/product. For example, mass products should be realized by adopting high-production processes and machines. Considering the closed die forging, this process is recommended only for production volumes greater than hundreds of components.

The fifth step, composed by 5a, 5b, 5c, 5d and 5e sub-steps, is an intermediate phase before the calculation of the operations sequence. Indeed, a whole component or a group of its surfaces can be realized employing multiple and different operations. For example, although a specific manufacturing strategy may be already defined, a hole (according to its shape, diameter, depth, roughness, tolerance, and product material) can be realized by adopting different operations. Indeed, for a milling from a block strategy, a hole can be realized with a simple drilling operation or rather from combining drilling and boring operations according to the dimensional tolerance for its diameter. The operations bundle is the container of knowledge that provides the definition of the sequence of operations required for a certain product manufacturing feature.

The sixth step (6a and 6b sub steps) consists in combining all the valid operations calculated up to now (with related cost) to define the operations list that represents the manufacturing process of a product. The total manufacturing cost is computed by adding the raw material cost and the cost of each single operation.

Figure 17 summarize the workflow of a manufacturing process cost estimation.

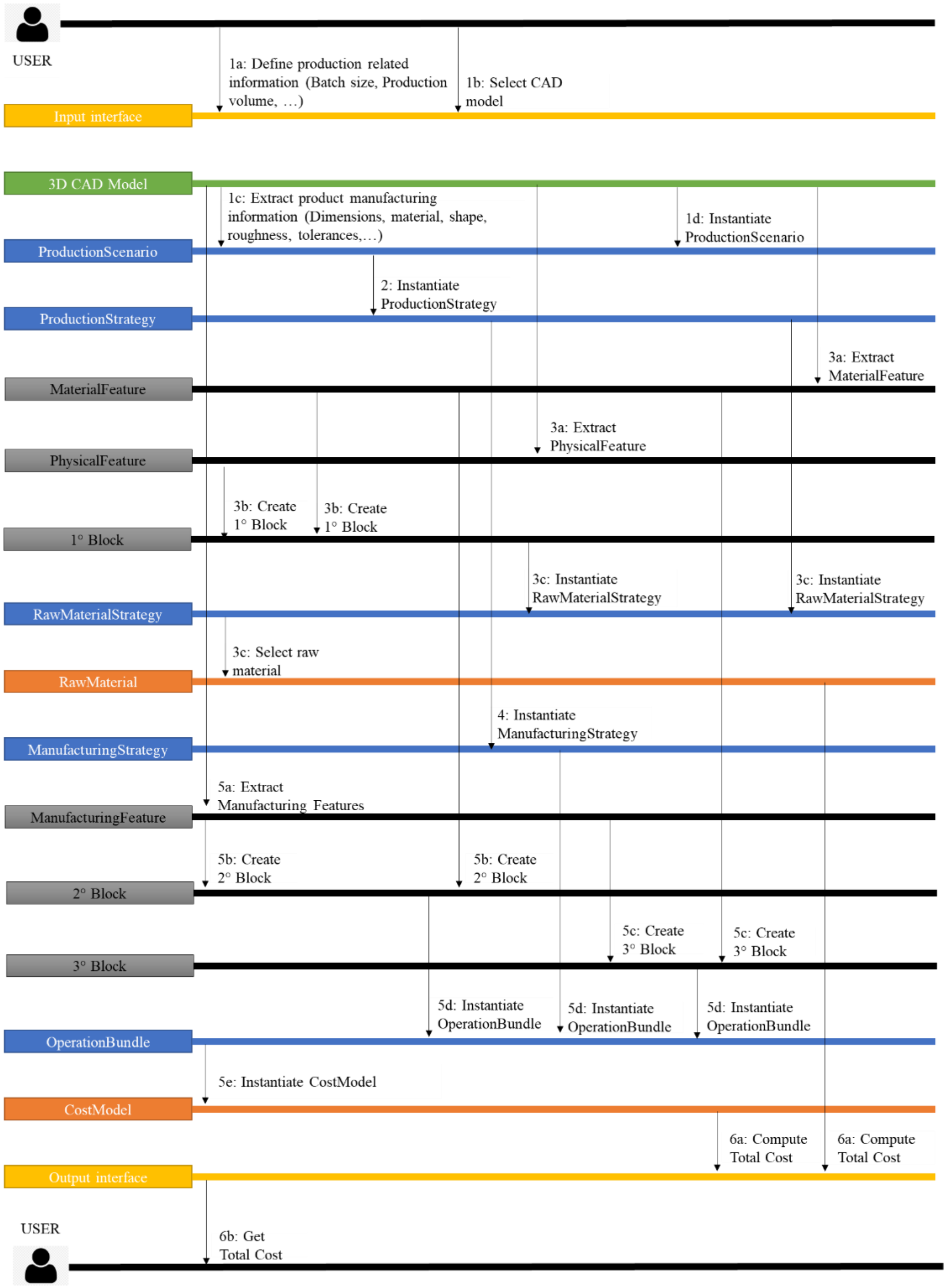


Figure 17 Workflow for defining a manufacturing process (UML sequence diagram)

Assembly

The first step of the cost estimation process of an assembly is composed by sub-steps 1a, 1b, 1c and 1d. In this step, as well as in the case of manufacturing, is established the overall production scenario. In the first (1a, 1b) the user defines the production information (batch size, production volume) and select the CAD model of the assembly and then parts which compose them. After that, from 3D CAD model, are extracted assembly and manufacturing information (material, shape, ect) and at the end the assembly scenario is instantiated (1c, 1d). Indeed, the assembly process and the related costs first depend on the production environment, which is characterized by the production facility (e.g., machine tools, tools, plant layout, and overall equipment effectiveness) and the sourcing strategy. The selection of the right production environment is usually determined by vendor ratings and supplier selection methodologies.

The second step (2a) of the assembly cost estimation process is the definition of the assembly strategy and includes the selection of the assembly process in function of material and components features. The selection of the assembly process type (e.g., welding vs bolting) is performed taking in consideration components material and shape at the same time since these two aspects are dependent on each other. For example, automated welding jointing is valid only for metal materials (validity rule), which are appropriate only for high production volumes (priority rule).

The third step, composed by 3a, 3b, 3c, 3d, 3e and 3f sub-steps, is an intermediate phase before the calculation of the operations sequence. Indeed, joining two or more components of an assembly can be realized employing multiple and different operations. For example, although a specific assembly strategy may be already defined, a screw (according to its shape, diameter, depth, roughness, tolerance, and product material) can be tightened by adopting different operations (for example using manual wrench or an electrical screwdriver). The operations bundle is the container of knowledge that provides the definition of the sequence of operations required for a certain product assembly feature.

The fourth step (4a and 4b sub steps) consists in combining all the valid operations calculated up to now (with related cost) to define the operations list that represents the assembly process of a product.

Figure 18 summarize the workflow of an assembly process cost estimation.

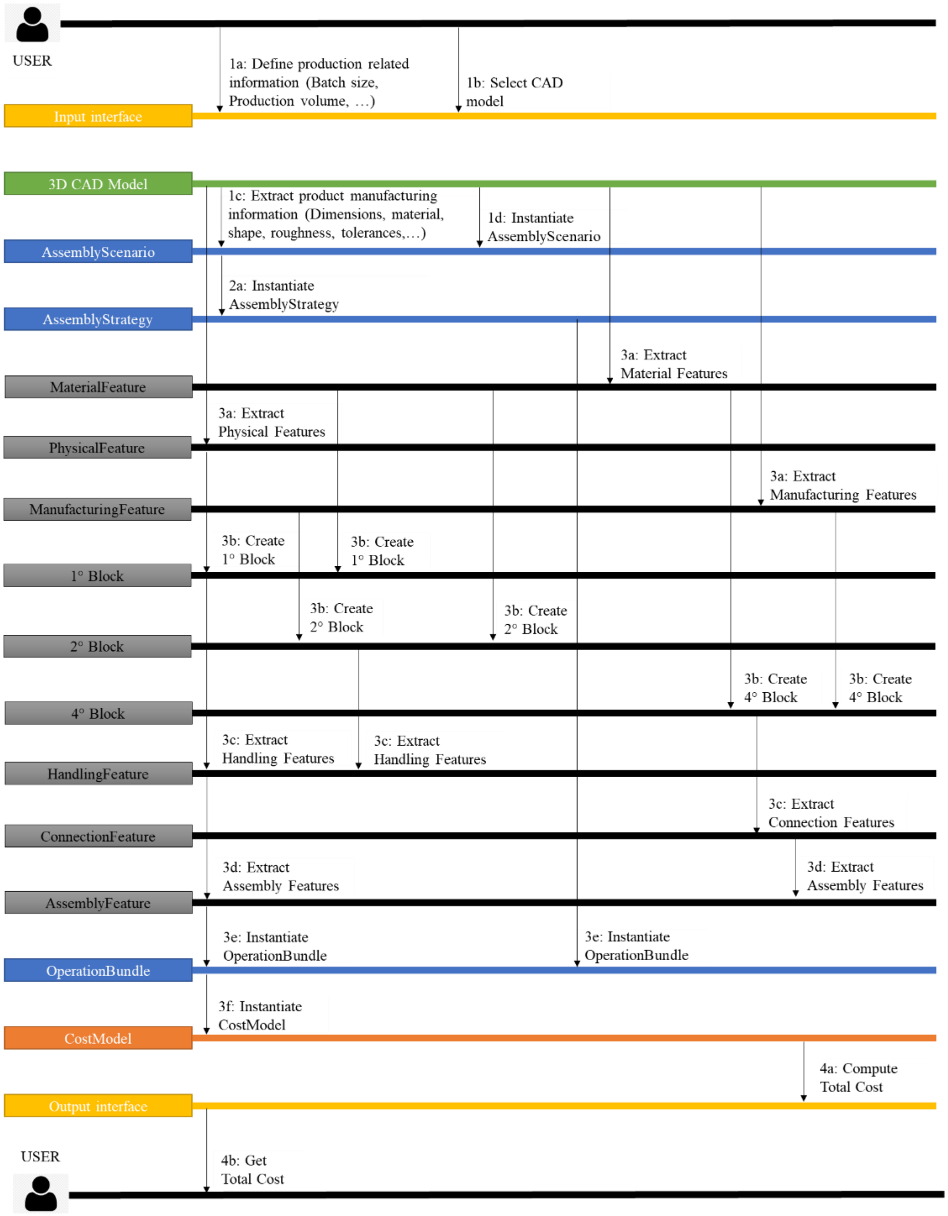


Figure 18 Workflow for defining an assembly process (UML sequence diagram)

3.3. DfM/DfA analysis

In this step DfM/DfA design rules are linked with 3D CAD features developed during the engineering design process of parts or assemblies. The methodology is based in a framework composed by a database rules repository, mathematical equations and 3D CAD model feature recognition. Mathematical equations are used to verify the compliance of design guidelines with the information retrieved by the 3D model data reading. A dedicated repository (DfM/DfA rules DB) is necessary to collect all the information in a structured way based on the KB system (section 3.3.1). Validated and non-validated DfM/DfA rules are displayed to the designer with the aim to keep him/her informed about the feature that are not compliant with the guidelines collected in the repository (section 3.3.2). The proposed methodology is based on an article written in collaboration with other university colleagues (Favi et al., 2020).

The main idea underpinning this research study concerns the possibility to link DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies. It is well known that DfM/DfA design rules are part of the company knowledge (through the experience and the skills of their engineers) whose dissemination among employees and technical departments is a critical issue. As a standard practice, designers usually use DfM/DfA guidelines as a sort of checklist once finished the engineering phase, or even worse. Sometimes, these guidelines are checked by production engineers before starting the production (approval of the technical drawings). This approach increases the time to market and the number of iterations between design and manufacturing departments (design reviews).

Intending to integrate DfM/DfA approach within the 3D CAD modelling, this section describes the materials and method used for this purpose. The method concerns three main aspects:

(i) *3D CAD Model feature recognition* and organization (described in section 3.1.1.1).

(ii) A *Knowledge-Based (KB) System* for DfM/DfA rules classification and deposition.

(iii) A *Rules Validation System* to connect 3D Model feature to DfM/DfA rules contained in the database.

In Figure 19 are represented the overall methodology framework for DfM and DfA methodology.

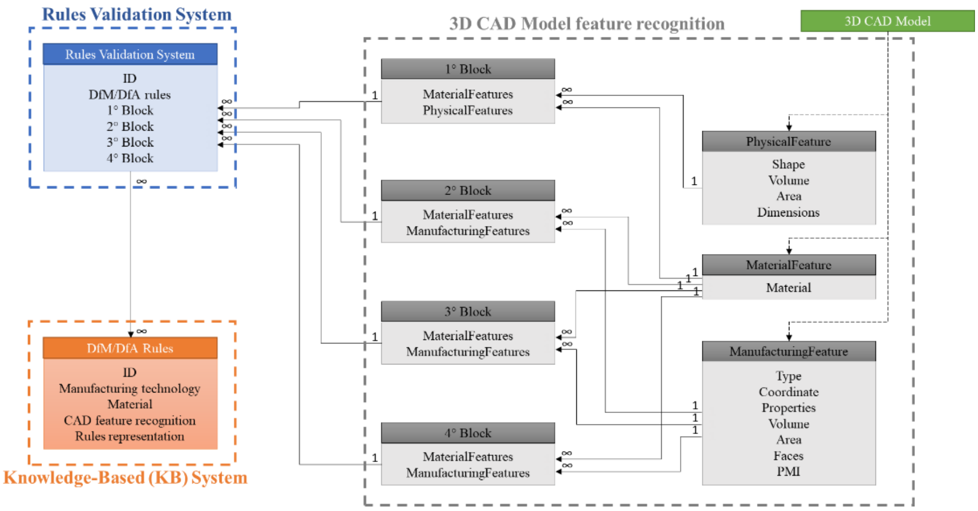


Figure 19 Overall methodology framework for DfM and DfA methodology

3.3.1. Knowledge Based System

A Knowledge Based System is used to classify the DfM/DfA rules. The system for classifying these rules is based on three main fundamentals:

(iv) *Knowledge acquisition*: refers to the literature analysis and industry best practices investigation for the collection of DfM/DfA design rules. This phase could be divided in two main steps: (i) the collection of design rules for several manufacturing and assembly technologies, and (ii) the identification of geometrical entities and numerical parameters involved in the design rules.

(v) *Knowledge processing*: refers to the connection between the DfM/DfA design rules collected in knowledge acquisition phase and the geometrical features of a virtual 3D model (CAD file). This phase is essential to transform the DfM/DfA rules list into a systematic design review of the product (3D CAD Model).

(vi) *Knowledge representation*: refers to the definition of a structured database repository for the collection and the formalization of DfM/DfA knowledge. This phase includes the logical definition of DfM/DfA design guidelines (syntax) and related information, as well as suggestions about design changes to guarantee the corrected product manufacturability and assemblability.

Here now will be explained in detail the previous three main fundamentals.

3.3.1.1. Knowledge acquisition phase

From the manufacturing and assembly perspective, production knowledge represents the groundwork for a proper implementation of DfM/DfA methods (Hoque et al., 2013). Knowledge can be divided into tacit and explicit knowledge (Darai et al, 2010). Tacit knowledge is the knowledge that people carry in their minds. Hence, this knowledge is not formalized and not widely used by an organization. Explicit knowledge, instead, refers to a set of information that can be articulated, codified, and stored in certain media.

Knowledge acquisition phase begins with the analysis of the literature related to the DfM/DfA topic (book, research papers, technical reports, master/Ph.D. thesis). In particular the most interesting authors have been: Boothroyd et al., (Boothroyd et al., 2011), Bralla (Bralla, 1999), Ciambrone (Ciambrone, 2007), Poli (Poli, 2001), Molloy et al. (Molloy et al., 1998) and El Wakil (El Wakil, 2019). Some of the previous authors write DfM/DfA rules as a list of actions about what to do and what is better to avoid during the design phase of a mechanical component realized employing a specific manufacturing technology. On the other hand, for some other authors, the DfM/DfA rules are not explicitly stated, and a more in-depth analysis is necessary to extract applicable design rules. Another essential source for the acquisition of DfM/DfA rules concerns the use and the access to the available documentation of commercial software and tool developed for DfM/DfA analysis.

For example, DFMA® tool from BOOTHROYD DEWHURST Inc. (https://www.dfma.com/) and DFMPro® from HCL Technologies Ltd. (https://dfmpro.com/) are two software tools developed to aid designers and engineers in designing assembly-compliant products. Besides, authors organized several meetings in design departments of manufacturing companies to collect best practices and rules dedicated to given manufacturing technologies.

3.3.1.2. Knowledge processing phase

Knowledge processing phase consist in the definition of the Database Repository of the DfM/DfA knowledge previously acquihired. It starts with the definition and classification of DfM/DfA rules associated with a given manufacturing technology. The repository is composed by three sections:

(i) *Manufacturing technology*, recalling the technological aspects related to a given rule.

(ii) *Material*, providing material information related to a given rule.

(iii) *CAD feature recognition*, identifying geometrical parameters and mathematical equations associated to a given rule.

Manufacturing technology is related to the technological aspects of a given rule and includes: (i) manufacturing technology class, (ii) manufacturing technology type – level I, and (iii) manufacturing technology type – level II. The adoption of these clusters is necessary to classify DfM/DfA rules that are generic for a technology class (e.g. machining, sheet metal stamping, metal forming, metal casting, plastic forming, welding, assembly) or specific for a manufacturing operation of the defined technology class (e.g., drilling). Indeed, a DfM/DfA rule may be valid for the generic manufacturing technology class (e.g., machining) regardless of the specific operation (e.g., turning, milling, drilling). Conversely, a DfM/DfA rule may be valid only for a specific operation (e.g., drilling) and cannot be generalized for the manufacturing technology class that contains the operation (e.g., machining). The identification of two levels for manufacturing technology type allows classifying DfM/DfA rules based on a list of operations (e.g., turning) or for a single operation (e.g., drilling, external cylindrical turning, internal cylindrical turning).

Material section requires the definition of two clusters according to Ashby (Ashby, 2010): (i) material class, and (ii) material type. These two groups allocate a given DfM/DfA rule to a generic class (e.g., carbon steel) or a specific type (e.g., C40) of materials. The identification of these two clusters allows classifying DfM/DfA rules that are valid for any material (N.A. – Not Applicable), for a given material class (e.g., stainless steel) or for a given material type (e.g., AISI 304).

CAD feature recognition classifies the geometrical parameters and mathematical equations with 3D CAD features to recognize in relation with a given DfM/DfA rule. This section is divided in: (i) 3D CAD features, which identifies the type of feature to recognize (e.g., hole, slot), (ii) PMI – Product Manufacturing Information to read (e.g., roughness, tolerances), (iii) dimension/geometry, which is connected to the features properties (e.g., hole diameter, hole length, hole length/diameter ratio), and at the end the rules to verify (e.g. hole length/diameter ratio < 5).

Table 14 presents the overall structure of the repository used for collecting and storing the rule-related information. Two examples facilitate understanding the type of information to store for each section.

Table 14 Overall structure repository example

	Manufacturing technology			**Material**		**CAD features recognition**			
Rule ID	*Manufacturing technology class*	*Manufacturing technology type level 1*	*Manufacturing technology type level 2*	*Material class*	*Material type*	*CAD features to recognize*	*PMI to recognize*	*Dimensions*	*Rules to verify*
M003	Machining	Milling	N.A.	All	N.A.	Pocket and/or contours	N.A.	s: pocket/contours thickness r: inner radii	r <= s/6
A003	Assembly	Bolted	N.A.	All	N.A.	Hole Center or Gravity	N.A.	Center or Gravity coordinates of feature	[X1, Y1, Z1]

						coordin ates		1: [X1, Y1, Z1] Center or Gravity coordinates of feature 2: [X2, Y2, Z2]	= [X2 , Y2, Z2]

3.3.1.3. Knowledge representation phase

Knowledge representation phase has the function of explain correctly the rule to the designer. Then this phase is composed by three main pillars: (i) a predefined syntax, (ii) the type of guideline, and (iii) an explicatory image. Each DfM/DfA rule is defined in a pre-defined form. Then, a taxonomy and a syntax are necessary to keep consistency among different guidelines and to provide the same level of details and information that can be manipulated by the mechanical designer during the product development process. For each DfM/DfA guidelines there are necessary and optional information. Necessary information provides the minimum set of information to perform a design improvement. Then necessary information's are the design action to do (verb), and the subject which requires modification (name). Optional information provides additional data that allows clarifying the context in which the design action is required. These additional data are the manufacturing process, the type of feature involved, the type/family part, and the type of material. The type of guideline classifies the importance of the rules. A rule could be divided in three level of importance:

- Critical: precludes the technological feasibility.
- Warning: generate potential problems or complications during manufacturing or assembly.
- Information: is a suggestion that would be desirable, a nice to have (e.g. for cost reduction).

To give a more detailed understanding of the DfM/DfA design rule, an image explains what to do and what to avoid. Table 15, Figure 20 and Figure 21 summarize examples of the previous DfM and DfA rule of Table 14.

Table 15 Example of DfM/DfA guideline syntax

Action (verb)	**Subject (name)**	**Context (type of feature)**	**Context (type of part)**	**Context (type of material)**	**Context (manufacturing process)**	**Type of guideline**
Necessary	*Necessary*	*Optional*	*Optional*	*Optional*	*Optional*	*Necessary*
Avoid	sharp	internal corners	N.A.	N.A.	in milling operations	Critical
Guarantee	alignment	of hole axes	N.A.	N.A.	in assembly operations	Critical

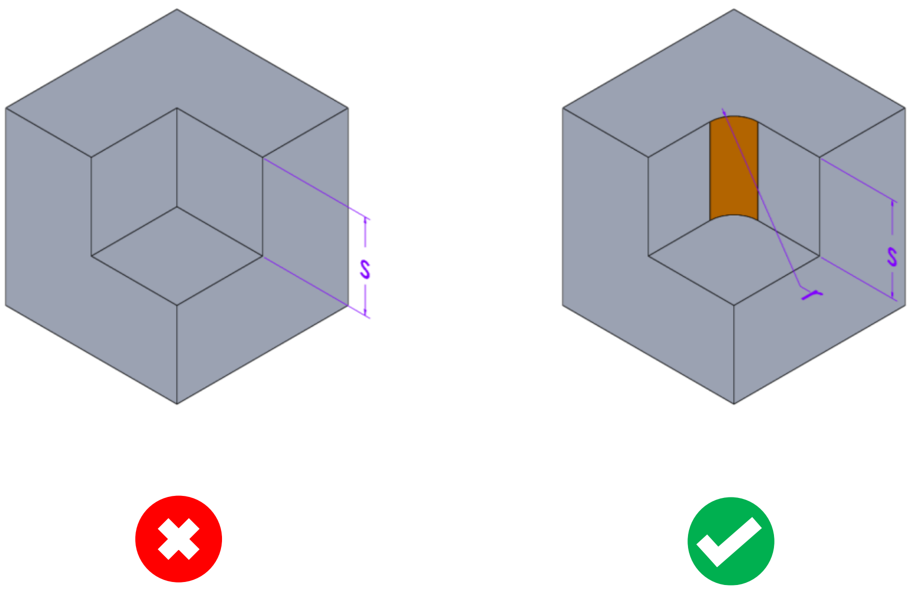


Figure 20 Example of DfM/DfA guideline picture (rule ID M003)

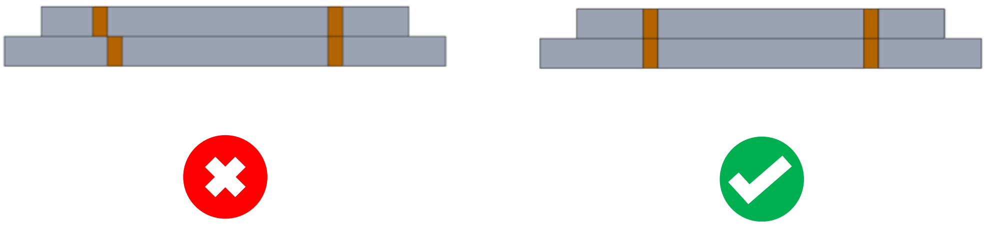


Figure 21 Example of DfM/DfA guideline picture (rule ID A003)

3.3.2. Rules Validation System

Rules Validation System is the core of the entire system with three main purposes: interaction with the 3D CAD Model, extrapolate rules from the DB repository and then evaluate which design rules in 3D CAD Model are respected and which are not.

The interaction module is the link with the CAD environment, and it allows to display in which feature the rule fails, and so where the designer can make design changes on the model. This stage deals with the execution of the DfM/DfA design rules for which any part is analysed to check whether it satisfies or not the rules. The link with the CAD tool allows real-time simulation of the design changes and the possibility to check if the design change is compliant with the manufacturing process.

A dedicated repository (DfM/DfA rules DB) is necessary to collect all the information in a structured manner based on the KB system. The KB system informs the designer about the validated and non-validated DfM/DfA rules to keep him/her informed about those features that are not compliant with the guidelines collected in the repository.

The evaluation consists of mathematical equations and algorithms, and it concerns the possibility to display and generate report of validated and non-validated DfM/DfA design rules. This step allows checking all the design rules stored in the DfM/DfA rules DB with the design features retrieved by the analysis of the 3D model. Mathematical equations are used to verify the compliance of the applicable design guidelines with the information retrieved during the 3D model data reading.

3.3.3. Workflow of DfM/DfA methodology

Starting from 3D CAD Model, the workflow for the definition of DfM/DfA methodology consists of 5 decision steps (Figure 22), each one supported by a combination of databases and knowledge-based rules. The first step of the DfM/DfA process is composed by sub-steps 1a, 1b, 1c, 1d and 1e. In this step the user defines the production information (batch size, production volume and general PMI (roughness, tolerance and coating)) and select the CAD model of an assembly or a part. After that, from 3D CAD model, are extracted material, physical and manufacturing feature (material, shape, ect).

The features extraction is necessary for the feature blocks creation in step 2 (sub-step 2a, 2b, 2c and 2d). In particular material and physical feature compose the first block, while manufacturing feature together with material feature compose the second and the third block. Also, the fourth block is a composition between material and manufacturing features, but in this case, they are interrelated with the assembly.

After features extraction and their grouping in the various blocks, in step 3 the knowledge-based system is instantiated (3a) and rules are extracted from database (3b). The Knowledge Based System is used to classify the DfM/DfA rules through knowledge acquisition, processing and representation.

In the fourth step rules and features are connected together through the Rules Validation System, which interacts with the 3D CAD Model, extrapolate rules from the DB repository and then evaluate which design rules in 3D CAD Model are respected and which are not.

At the end (step 5) the KB system informs the designer about the validated and non-validated DfM/DfA rules, displaying them in 3D CAD Model. In this way the designer could look the features that are not compliant with the guidelines collected in the repository.

Figure 22 summarize the workflow of DfM/DfA methodology.

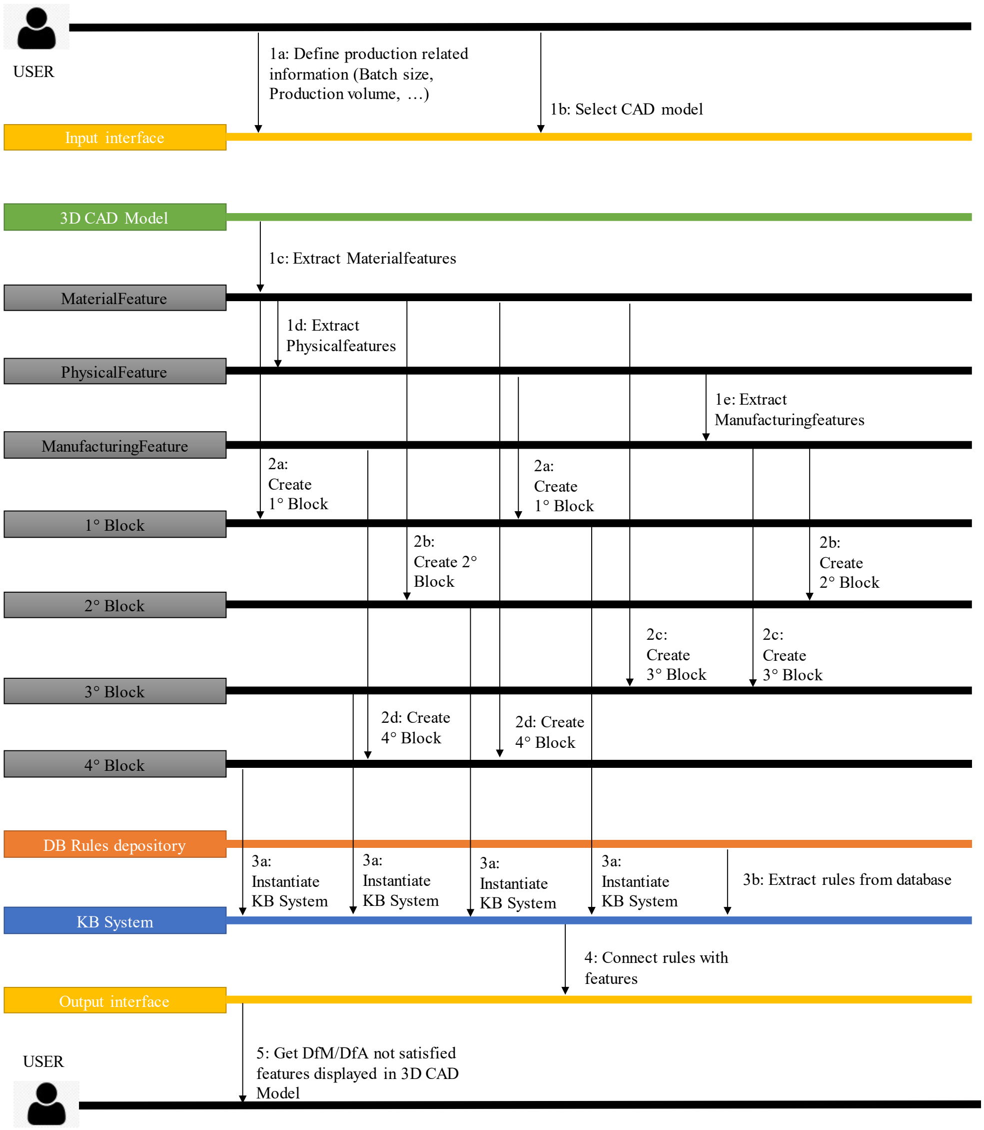


Figure 22 Workflow of DfM/DfA methodology

4. Cost and DfM-DfA tool

Methodology described in previous section 3 has been implemented in a specific software tool. In this section will be described its functionalities and the software structure, but the code and the programming steps are not described, being out of scope of the thesis.

4.1. Cost and DfM-DfA tool description

The Cost and DfM-DfA software tool help designers during the 3D modelling activities in the development phase, through the calculation of the cost of a component and/or assembly and with the identification of design errors occurred in this phase. In this way, designers can understand how their choices affect the design of the product and how select alternative design that better meet manufacturing production without compromising cost or performance. The guided process toward the selection of the best design for the manufacturing of product component starts from the 3D CAD model of the part or assembly.

The tool is integrated with the most popular 3D CAD systems through the use of dedicated DLLs. A DLL contains code and data that can be used by more than one program at the same time. DLLs allow the connection between a CAD system and the tool, extracting the necessary information required for analysis, in particular the parts features needed for cost estimation and for DfM/DfA design rules validation. The CAD connection is not only focused in inputs extracting, but also allows the highlighting of features not compliant with DfM/DfA rules directly in 3D CAD systems interface. In this way the user could visualize directly in 3D model the feature to change.

Prior to go into the detail description of the structure of the software, input and outputs are described.

The inputs of the tool are:

- *3D CAD model of the part or assembly*: from 3D CAD model are extracted information relating to the part such as parts *material*, *shape* (axisymmetric, prismatic, etc.), parts *volumes*, parts *surfaces area*, parts *dimensions* (length, width and height), part *manufacturing features* (holes, slots, fillets, etc.), *PMI – Product Manufacturing Information* (tolerances, roughness, etc.).

- *Production information*: *production volume* and *batch size*. These information's are necessary to determine setup costs (batch size), equipment and tool costs (production volume), but also affect the best process type. In-fact, in function of batch size and production volume, process cost varies and some process are more economical (e.g. for small production volumes a forging process are generally not convenient).

- *Production and assembly strategy*: production and assembly strategies define the manufacturing (e.g. machining: milling from block, machining: turning from block, casting, casting and machining, etc.) and assembly process (e.g. assembly: bolted, assembly: welding, etc.) for the analysis.

- *Treatment and painting*: the treatments and painting of the part or assembly.

The outputs are represented by:

- *Cost analysis*: the analysis of cost includes (i) total cost, (ii) raw material cost, (iii) investment cost and (iv) process cost. At the same time the system provides a more detailed cost breakdown including costs and times for each manufacturing or assembly operation and feature. For each operation are provided information's regarding the machine type selected, machining or assembly direction and roughness/tolerance. These information's are displayed in the GUI of the tool and they could be exported in a dedicated report in excel format.

- *DfM/DfA analysis*: this analysis shows in the GUI of the tool the DfM/DfA rules which are not validated and then the manufacturing features which do not respect the design guidelines are highlighted in the CAD software interface connect to the tool. In the GUI are also displayed the suggestions within the not-validated design guidelines. At the same time the list of the design guidelines involved in analysis, with images of 3D models, are contained in the dedicated excel report.

- *Report in excel format*: report generation contains the export of the history of analyses carried out with images of 3D models and the bill of materials (BOM) of an assembly with indication of the incidence of the cost of each component. Report includes also the type of manufacturing operation associated with each feature, the related performance (i.e. cost of a manufacturing operation), and the list of validated and not validated DfM/DfA rules with the associated images of 3D models features. Following the outcomes stated in the reports, the designer can adjust the 3D model following the suggestions included within the not-validated design guidelines.

The developed tool has been implemented using Microsoft .NET framework as programming environment, which allow to create Windows applications using different programming languages; in this case Visual Basic has been selected.

Part of this work is realized in collaboration of external software house. For these reasons only a preliminary description of the tool software implementation is proposed.

The structure of the software is composed by four main modules:

1. GUI: the Graphical User Interface, with which the user interacts (section 4.1.1).
2. Feature recognition: allow the connection between a CAD system and the tool (section 4.1.2).
3. Database: contains information about materials, machine and the rules for a correct design and cost estimation (section 4.1.3).
4. Analysis framework: module needed for costs calculation and rules validations, continuously interfacing between feature recognition, databases and the GUI. Through the latter it allows the user to view costs and design rules (section 4.1.4).

4.1.1. GUI

The graphical user interface is the series of screens through which the user could be connected with the Cost and DfM-DfA tool.

The tool interface is positioned next to the CAD software (Figure 23) for viewing features and design errors directly in it. During 3D model design, the user can hide the tool and continue the design in CAD software in full screen.

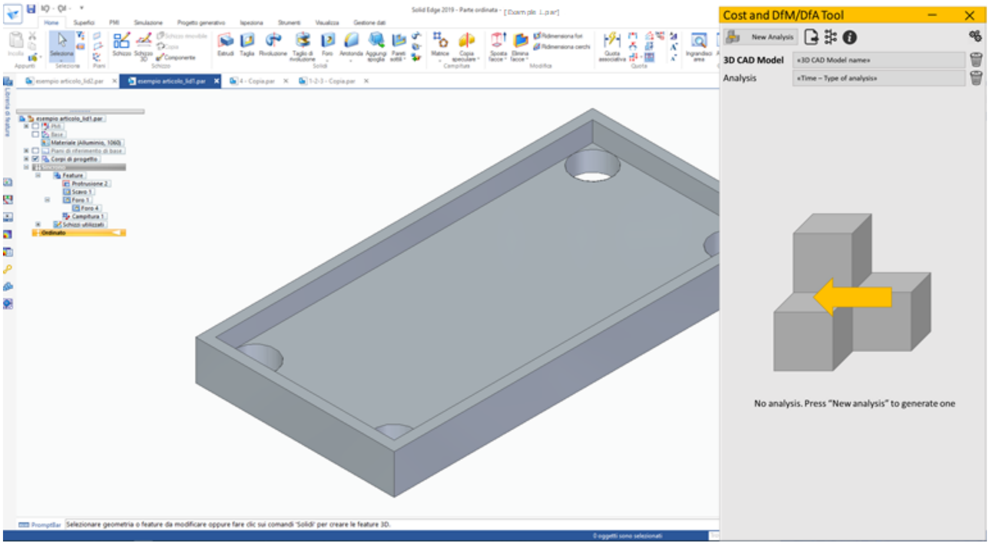


Figure 23 Tool interface prior to analysis

The designer, to start a new analysis, press the "New Analysis" button in the bottom left side of the GUI. In this way 3D CAD model of the part (or 3D models of the assembly) will be loaded in the tool. The user then have to insert the necessary information (Analysis information form (Figure 24)) of the analysis:

- *Production information*: the user set the production volume and batch size needed to determine setup costs (batch size), equipment and tool costs (production volume), but also are necessary to advise the user on the best process type. The tool, in function of batch size and production volume, suggest the best process for the part or assembly analysed.

- *Process type*: through this the user select the "production strategy" in case of components analysis, while in case of assemblies the "assembly strategy" is chosen. In this section the user is conduct by the tool with the suggestion of the best process in function of production information.

- *Material and PMI*: when the user press “New analysis” button in the first tool interface (Figure 23), the system, through the feature recognition, recognize the 3D CAD model’s material and PMI. If the 3D models are lack of these information, or the material are not read from the 3D CAD model, the user can choose material and general PMI (roughness and tolerances).
  In this section are also present the raw material stock type and size. The tool selects the best stock in function of recognized/selected material, PMI and process type, but the user could change it if the default stock doesn’t satisfy his needs

- *Treatment and painting*: the treatments and painting of the part or assembly.

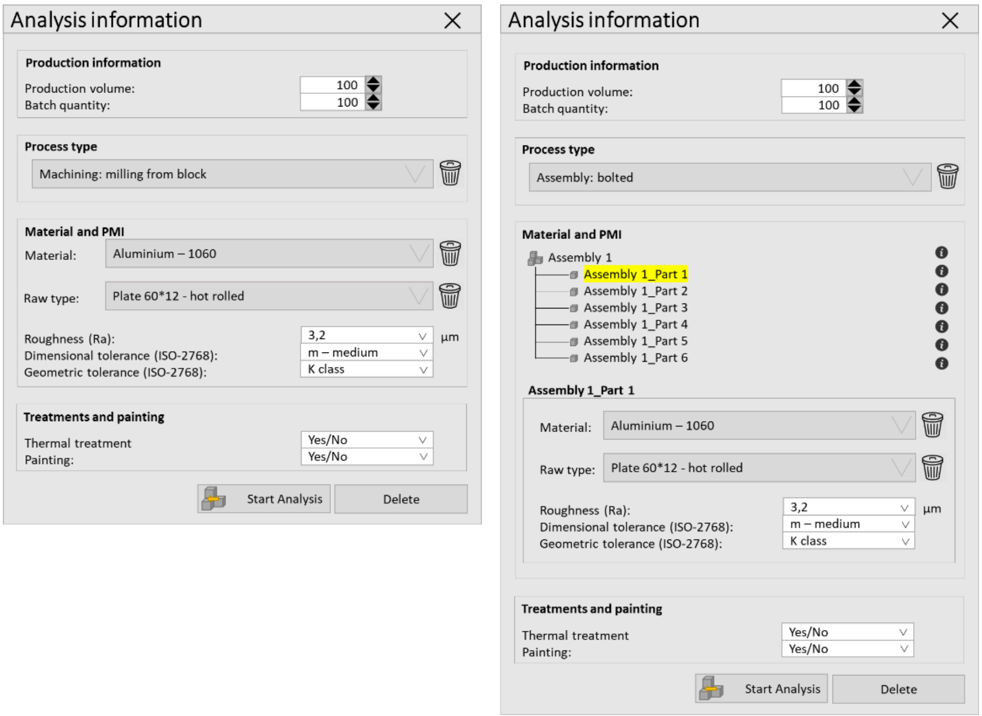


Figure 24 Analysis information screen (left: component; right: assembly)

Once all the information necessary for the analysis has been entered, the analysis can start ("Start analysis" button) and the costs and design errors of the component or assembly analysed can be shown to the user (Figure 25).

The tool interface after the analysis is divided in five main sections:

- *3D CAD Model and Analysis*: collects the information about 3D CAD Model name and analysis type. Also in this section are contained the buttons for the analysis report and the list of modifications made in the component from the beginning of the analysis.

- *Physical and material information*: in this section are collected the information about material, shape, volume and dimensions of the part (or the assembly). User could change these information's using the "i" button in the right, which bring back the user to the analysis information screen (Figure 24).

- *Production information*: production volume and batch quantity information.

- *Cost analysis*: in this interface section cost displayed includes only: (i) total cost, (ii) raw material cost, (iii) investment cost and (iv) process cost. For a more detailed cost breakdown the "i" button in the right of the section will open a new screen and will show more information to the designer. These information's includes costs, machine type, machining or assembly direction and roughness/tolerance for each manufacturing or assembly operation and feature. At the same time the default machine chosen by the tool can be changed selecting them from a list contained in the tool database.

- *DfM/DfA analysis*: this section shows DfM/DfA the rules which are not validated and then the features which do not respect the design guidelines contained in the database. The "i" button in the right of each design guidelines allows the highlighting, in the CAD software, of the features connected to the guideline and also an example image of the error and how to correct it is shown.

Once the designer found his designer error, he can modify the 3D model and repeat the analysis. The analysis can be launched several times to compare the results based on the changes made. Some indicators shown the growth or decrease in costs and in not respected rules (Figure 26).

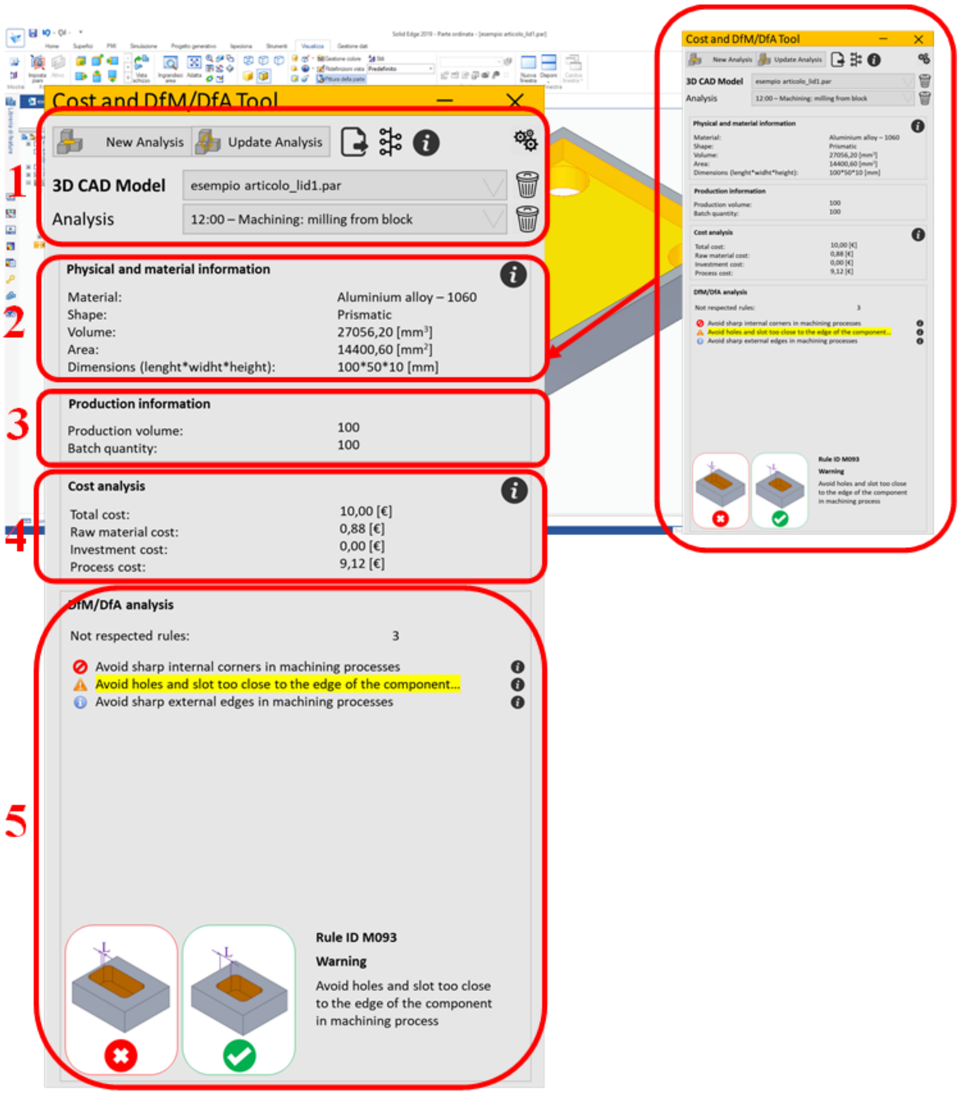


Figure 25 Tool interface after first analysis

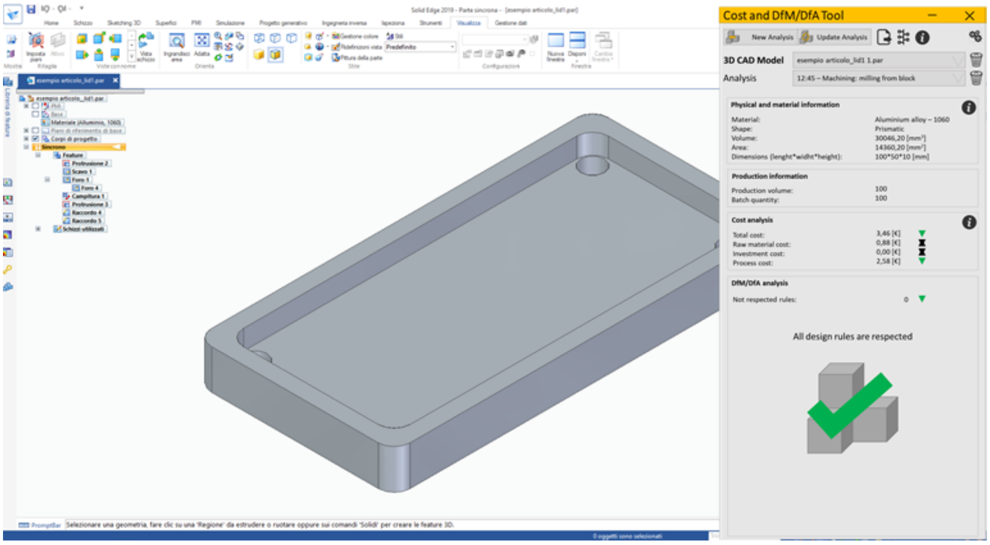


Figure 26 Tool interface after the analysis update

4.1.2. Feature recognition

As said in previous chapters, both cost methodology and DfM/DfA methodology are based on models feature recognition. The main idea underpinning this research study concerns the possibility to link manufacturing/assembly costs and DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies.

Features used in analytical and DfM/DfA methodologies are: (i) material features, (ii) physical features, (iii) manufacturing features and (iv) assembly features. A more detailed description of them are shown in Table 6, describing their information and attributes.

The feature recognition module allows the connection between CAD software and analysis framework.

Material and physical features can be extracted from a 3D geometry (B-rep model – boundary representation) because attributes included in this class are readily available. Manufacturing features can be extracted from a 3D model by using a specific kernel for manufacturing features recognition. Kernel can compute manufacturing features for a comprehensive set of components shapes (e.g.

prismatic, axisymmetric, sheet metal) and assemblies (e.g., welded structures mounted assemblies). For each feature, it is possible to watch the most relevant attributes expected for the further DfM rules processing.

As described in section 3.1.1, *material*, *physical* and *manufacturing* features where organized in 3 blocks, divided in this way:

- *Block 1*: Physical and material features of the model.
- *Block 2*: Manufacturing and material features of the model (isolated).
- *Block 3*: Manufacturing and material features of the model in relation with other feature/s (interrelated for part).

The blocks have the scope to classify and organize the features of a part (or assembly) in order to be read and analysed by the framework which calculate the cost and verify the DfM/DfA rules. The division into several blocks has been implemented cause each block collects different types of features to be associated with specific DfM/DfA rules and specific elements of the manufacturing/assembly cost routing structure.

As described in section 3.1.1, *assembly features* derives from a composition of *handling* and *connection* features. The first type represents assembly information used to handle a component, i.e. handling-specific assembly information on generic level. The second type represents information about the connections between components. The feature recognition module creates handling feature starting from the 1° and 2° blocks introduced before, while the connection features derive from new block, the *block 4*, which represents the manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly).

The eight steps and the workflow activities of the Feature Recognition module are described in detail as follows. In Figure 27 are summarized STEP 1, STEP 2 and STEP 3 of the workflow, while in Figure 28 are summarized STEP 4, STEP 5, STEP 6, STEP 7 and STEP 8 of the workflow.

The first step is the 3D CAD model import from CAD software. In this step the assembly is decomposed in into the parts that compose it, to extract the different features and information of the assembly and of the single parts.

The second step consists in extracting the features of the single parts: material, physical and manufacturing features. Concerning the manufacturing ones, all the single features types (holes, cylinders, surfaces, etc.) present in the parts which compose the assembly are extracted.

In the third step feature parameter are extracted. Feature parameters consist in: (i) material for material features, (ii) shape, volume, area and dimensions of the parts for physical features and (iii), for manufacturing features, type, coordinate, properties, volume, area, faces and PMI of the single type features.

These information's extracted are then used in *fourth step to create of block 1, block 2 and block 3* of the single parts. It's important to underline that in some cases 3D CAD model haven't information's regarding material or PMI. As said before, if the 3D models are lack of these information, or the material are not read from the 3D CAD model, the user can choose material and general PMI (roughness and tolerances).

The fifth step consists in create handling features of a single part from block 1 and 2.

In the sixth step blocks 4 are created. Blocks 4 derive from material features and manufacturing features of the single parts relating them to the features of another part.

From blocks 4 in the *seventh step are create connection features*.

The *last step (8) consists in create assembly features* from handling and connection features.

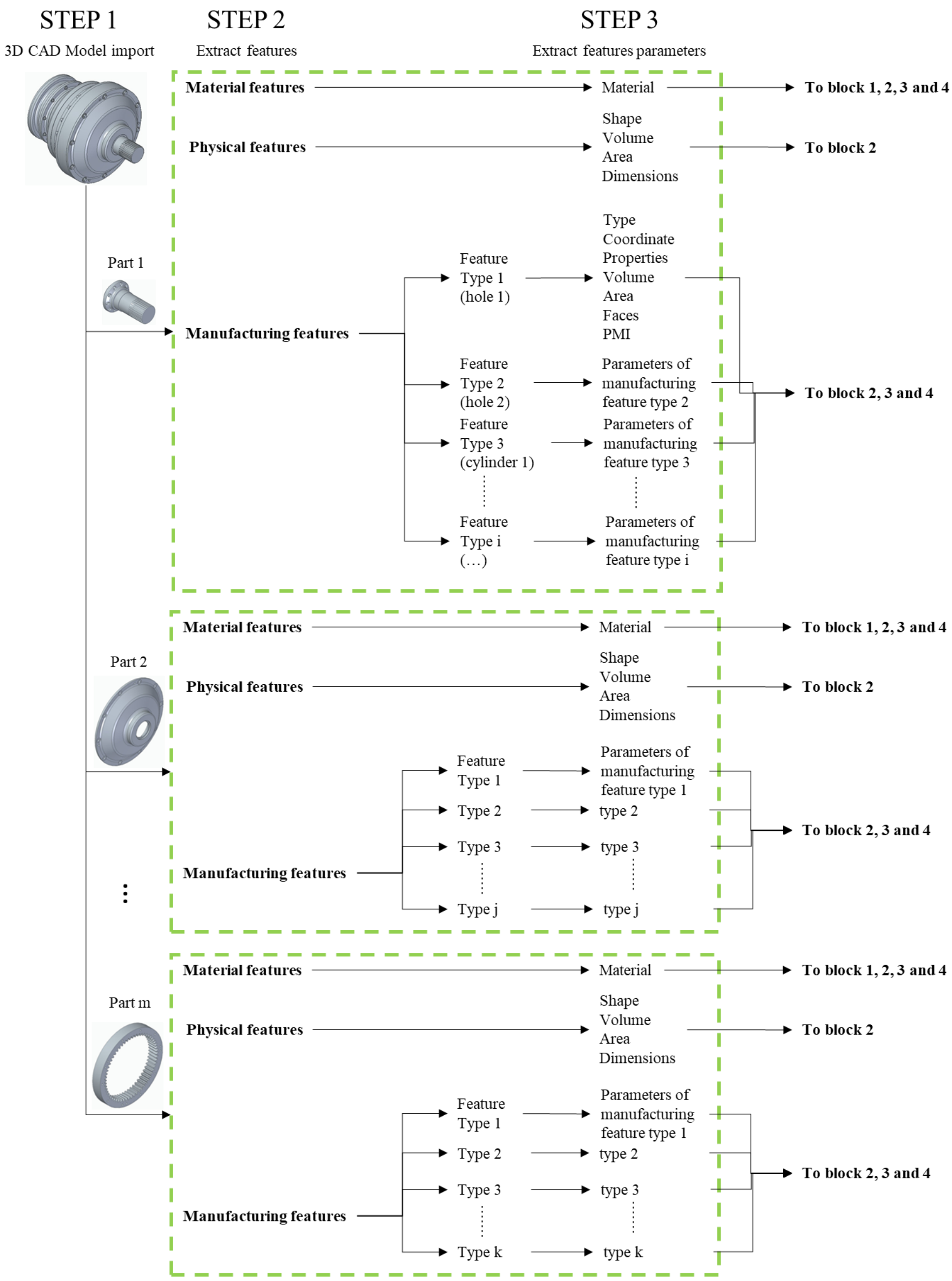


Figure 27 STEP 1, STEP 2 and STEP 3 of the feature recognition module

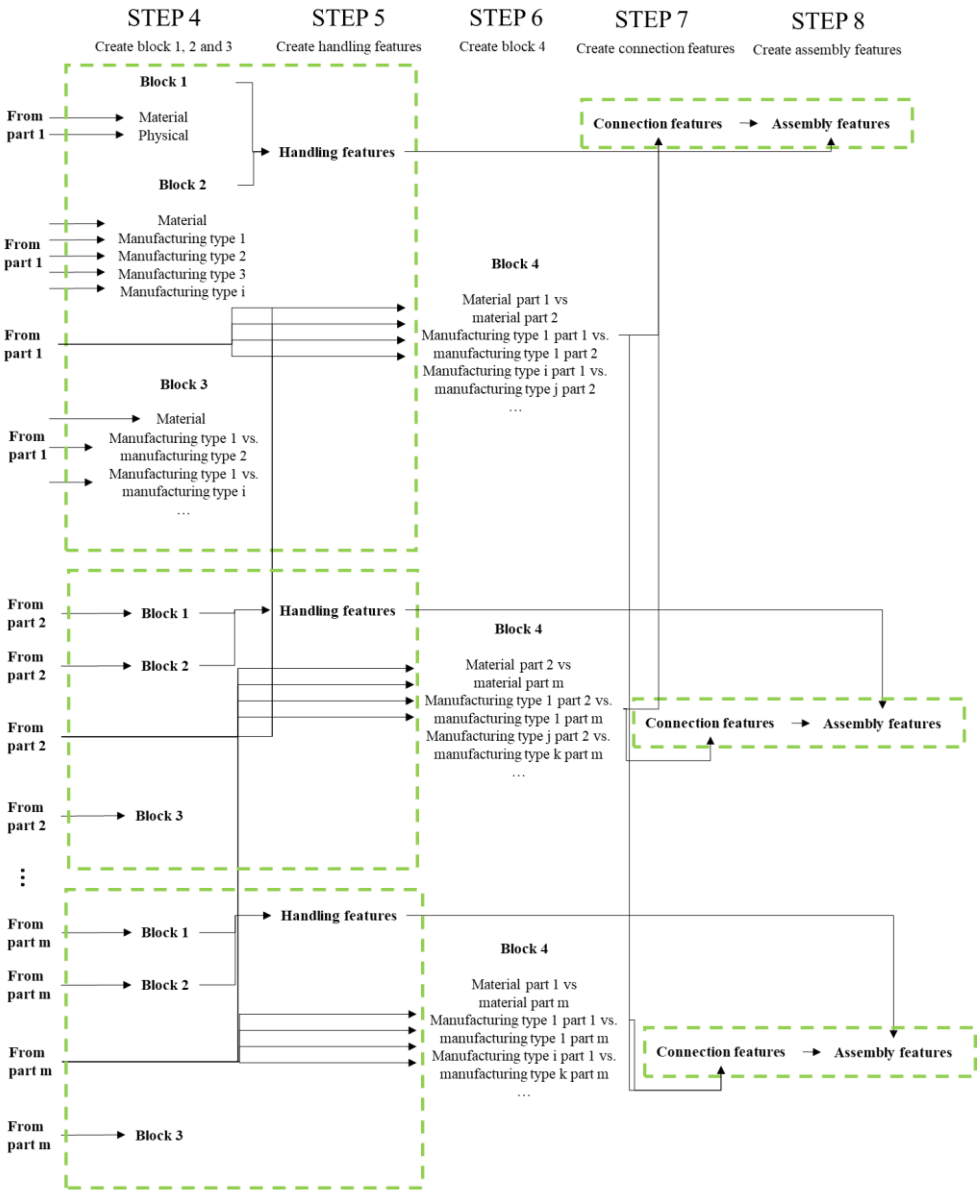


Figure 28 STEP 4, STEP 5, STEP 6, STEP 7 and STEP 8 of the feature recognition module

4.1.3. Databases

The developed tool includes databases to store cost estimation and DfM/DfA knowledge. These databases have been built as Microsoft Access, the reason of this choice lies in its simple implementation and connection with the implemented user interface by the integrated API available for Access in .NET environment. It is important to underline that these databases can be developed with other technologies, in order to obtain improved functionalities and more, just by changing the loading data module in the source code.

The database contains the data needed to guarantee cost calculation and design errors evaluation.

Database are divided in five sub-databases:

1. Material DB
2. Labour DB
3. Machine DB
4. Cost estimation models DB
5. DfM/DfA rules DB

4.1.3.1. Material DB

The material DB (Table 16) contain the information's required to represents the raw material needed to manufacture a specific part/component. Each material is represented by a progressive code for identification.

Material DB is divided in function of *material class* (e.g. aluminium, alloy steel, stainless steel, carbon steel) and each material class is divided in *material type* (e.g. stainless steel AISI 304, stainless steel AISI 306).

Each material type is classified in function of *raw geometry characteristics* and *supply country* (EU, China, etc.).

Raw geometry characteristics are *stock typology* (e.g pipe, round), *condition* (e.g. cold drawn, hot rolled) and *dimensions* (*D1 [mm], D2 [mm], D3 [mm], D4 [mm]* and *Section Area [mm^2]*).

Raw geometry characteristics and supply country affect the *material cost* (*Unitary Cost [<CUR>/kg] and Scrap Value [<CUR>/kg]*) and the *physical characteristics*.

Physical characteristics (Table 17) are *Density [Kg/m^3], Machining factor [-], Ultimate Tensile Strength [Mpa], Ultimate Shear Strength [Mpa], Fusion Latent Heat [kJ/kg], Specific Heat [kJ/(K kg)], Melting Temperature [°C] and Convective Coefficient [W/m^2K]*.

Table 16 Extract of material DB

Material Code	**Material Class**	**Material Type**	**Stock topology**	**Condition**	**D1 [mm]**	**D2 [mm]**	**D3 [mm]**	**D4 [mm]**	**Section [mm^2]**	**Supply country**	**Currency [<CUR>]**	**Unitary Cost [<CUR>/kg]**	**Scrap Value [<CUR>/kg]**
#CSEU00000026	Carbon steel	ASTM 471 Type 2	Round	Hot rolled	20	20	20	20	400	EU	€	2,2	0,14
#CSEU00000059	Carbon steel	ASTM 471 Type 2	Square	Hot rolled	19	19	19	19	284	EU	€	2,4	0,14

Table 17 Material physical characteristics of material #CSEU00000026

Material physical characteristics	**Value**
Material Code	#CSEU00000026
Density [Kg/m^3]	7850
Machining Factor [-]	1
Ultimate Tensile Strength [Mpa]	966
Ultimate Shear Strength [Mpa]	759

Fusion Latent Heat [kJ/kg]	251
Specific Heat [kJ/(K kg)]	0,46
Melting Temperature [°C]	1400
Convective Coefficient [W/m^2 K]	10

4.1.3.2. *Labour DB*

Labour DB contains hourly rate of operators in function of their skills and country (Table 18).

Table 18 Extract of labour DB

Operator Code	**Operator type**	**Country**	**Currency [<CUR>]**	**Hourly rate [<CUR>/h]**
#00025	Welder	Italy	€	40
#00026	CNC operator	Italy	€	25
#00029	Welder	U.K.	£	45
#00030	CNC operator	U.K.	£	30

4.1.3.3. *Machine DB*

Machine DB contain the information’s of machines used for realizing an operation. Each operation has a list of available machines restricted by a list of validity rules (part dimensions, process force required, etc.) and priority rules (e.g. the cheaper machine). Each machine is represented by a progressive code for identification.

Machine DB (Table 19) is divided in function of country dataset (EU, China, etc…), machine category (forging, milling, turning, etc…), machine type (press, CNC milling (4 axis), CNC milling (5axis)) and in each type the classification is based on machine dimensions (CNC milling (4 axis)_Large, CNC milling (4 axis)_Medium, CNC milling (4 axis)_Small).

Each machine dataset contains a set of information’s (Table 20) based on machine use and category:

Geometrical and process related information's: maximum and minimum stock dimension (x, y and z) [mm], maximum and minimum stock weight [kg], machine axes (for milling), etc.

Machine performance information's: e.g maximum spindle rotational speed (for milling tools) or blow per minute (for forging press), minimum tolerance achievable [IT], minimum roughness [µm], etc.

Machine times [min]: setup time [min], changing tool times [min], etc.

Machine unitary costs [<CUR/h>]. Machine costs are affected by many items:

- Number of operators required: each machine, in function on its complexity, needs a specific number of operators.
- Energy vectors: are generally electricity or gas. For each operation could be used one, multiple or no energy vectors. Unitary energy consumption mainly depends on the machine size and type.
- Consumable: consumable are lubricants, cutting tools, etc. Each machine could use one, multiple or no consumables.

Table 19 Extract of machine DB

Machining Code	**Category**	**Machine type**	**Machine dimension**	**Country dataset**	**Currency [<CUR>]**	**Unitary cost [<CUR>/h]**
#2350	Milling	CNC milling 3 Axis	Small	Italy	€	45
#2351	Milling	CNC milling 3 Axis	Medium	Italy	€	50
#2352	Milling	CNC milling 3 Axis	Large	Italy	€	60
#2353	Milling	CNC milling 4 Axis	Small	Italy	€	55
#2355	Milling	CNC milling 4 Axis	Medium	Italy	€	60

#2356	Milling	CNC milling 4 Axis	Large	Italy	€	70

Table 20 Machine information's of machine #2356

Machine information's	Value
Machine Code	#2356
Maximum Stock Dimension – X [mm]	1100
Maximum Stock Dimension – Y [mm]	1200
Maximum Stock Dimension – Z [mm]	1500
Maximum Stock Weight [kg]	4000
Minimum Stock Dimension - X [mm]	0
Minimum Stock Dimension - Y [mm]	0
Minimum Stock Dimension - Z [mm]	0
Minimum Stock Weight [kg]	0
Number of axes [-]	4
Minimum Batch Size [-]	0
Maximum Batch Size [-]	0
Minimum Tolerance Achievable [IT]	6
Minimum Roughness Achievable [µm]	0,8
Maximum spindle rotational speed (for milling tools) [rpm]	4000
Number of pallets [-]	0
Preloaded number of tools [-]	10
Rapid traverse acceleration [m/s^2]	6
Rapid traverse speed [m/min]	15
Milling head change time [min]	0
Milling head rotation time [min]	0,5
Pallet change time [min]	0
Table rotation time [min]	0,05
Setup time (each phase) [min]	30
Tool change time (Piece-piece) [min]	0,5
Tooling time in machine (each tool) [min]	1
Tooling time in tool room (each tool) [min]	5
NC programming time (each tool) [min]	1,5

4.1.3.4. Cost estimation models DB

A cost model is a data model which contain the knowledge necessary for production time and cost estimation for each operation. A cost model could be considered a structured information object.

Cost estimation models DB contains the cost estimation models of the various operations in a structured way. A cost estimation model is divided by geometric cost drivers, process cost drivers and process time and cost calculation

Geometric cost drivers represent the necessary input information of the cost model taken from the 3D CAD model, inserted by user, or taken from Material DB. Geometric cost drivers could be material type (M), part dimensions (L, W, H), part volume (V), production batch (P_b), etc.
Geometric cost drivers have validity and priority rules. Validity rules used for establishing only the feasible manufacturing solutions among all the possible ones, while priority rules used for sorting the feasible solutions, with the aim of selecting the best one (e.g selection of a shearing instead of sawing for cutting billet in forging).

Process cost drivers is the list of the cost driver needed for process cost and time calculation. These ones could be taken from Material DB or Machine DB (e.g. Machine Power (M.P), Maximum Stock Dimension, Material shear stress) or could calculated from equations contained in database (e.g. Shearing Force ($F_{shearing}$)). As Geometric cost drivers also Process cost drivers have validity and priority rules. Validity rules are used for establishing only the feasible machine among all the possible ones, while priority rules are used for sorting the feasible them (e.g using hourly cost).

Process time and cost calculation are the equations used to obtain time and cost of the operations.

In Table 21 are show a cost estimation model of shearing operation for billet cutting in forging process.

Table 21 Cost estimation model of shearing operation

#00256	**Item**	**Reference or calculation form**
Geometric cost driver	Material (M)	User or 3D CAD model
	Billet diameter (d_{raw}) [mm^2]	3D CAD model
	Billet volume (V) [mm^3]	3D CAD model
	Production batch (P_b) [-]	User
	Material density (ρ) [kg/dm3]	Material DB
	Billet weight (W) [kg]	$\rho \cdot V/10^6$
	Billet base area (Abillet)	3D CAD model
	Geometric validity rules	$A_{billet} < 70.000\ mm^2$
	Geometric priority rules	Priority=IF(P_b>100;20;0)
Process cost driver	Machine Power (M.P) [N]	Machine DB
	Maximum Stock Dimension – X (M.X) [mm]	Machine DB

	Maximum Stock Dimension – Y (M.Y) [mm]	Machine DB
	Maximum Stock Dimension – Z (M.Z) [mm]	Machine DB
	Material shear stress (Y_{shear}) [MPa]	Material DB
	Machine forging rate ($M.n_{stroke}$) [min^{-1}]	Machine DB
	Machine Cost rate ($M.C_u$) [<CUR>/hour]	Machine DB
	Shearing Force ($F_{shearing}$) [N]	$1.15 \cdot (\pi \cdot d_{raw}^2)/4 \cdot Y_{shear}$
	Process validity rules	$M.P > F_{shearing}$
		$M.X > d_{raw}$
		$M.Y > d_{raw}$
	Process priority rules	MIN ($M.C_u$)
Process time and cost calculation	Cutting time ($t_{cutting}$) [min]	$1/(M.n_{stroke})$
	Load and unload time ($t_{load/unload}$) [min]	f(W)
	Setup time (t_{setup}) [min]	Machine DB
	Process time (t) [min]	$t_{cutting}+t_{load/unload}+t_{setup}/P_b$
	Total cost [<CUR>]	$t \cdot (M.C_u)/60$

4.1.3.5. DfM/DfA rules DB

DfM/DfA rules DB includes the definition of the repository structure and the link between a given design rule and the involved features (geometrical features of a virtual 3D CAD model) that can be read from the CAD file. The structure of the repository is the semantic (logic) used to switch from tacit knowledge (unstructured) to explicit knowledge (structured). The repository stores rules based on the *rule number*, which is a positive, progressive number and *rule type* which provide a ranking of the compliance for the given feature with the manufacturing process (i.e. info, warning, critical).

The DfM/DfA DB is composed by four main sections, following the "knowledge processing phase" and "knowledge representation phase" schema explained in section 3.3.1: *Manufacturing technology*, *Material*, *CAD feature recognition* and *Guideline*.

Manufacturing technology is related to the technological aspects of a given rule and includes: (i) manufacturing technology *class* (e.g. machining, sheet metal stamping, metal forming, metal casting, plastic forming, welding, assembly), (ii) manufacturing technology *type – level I* (e.g. milling, turning), and (iii) manufacturing technology *type – level II* (e.g., drilling).

Material section provides material information related to a given rule and requires the definition of two clusters according to Ashby (Ashby, 2010): (i) material *class* (e.g., carbon steel, stainless steel) and (ii) material *type* (e.g., AISI 314, AISI 316). These two groups allocate a given DfM/DfA rule to a generic class (e.g., carbon steel) or a specific type (e.g., C40) of materials.

CAD feature and algorithms classifies the geometrical parameters and mathematical equations with 3D CAD features to recognize in relation with a given DfM/DfA rule. This section is divided in: (i) *CAD features to recognize*, which identifies the type of feature to recognize (e.g., hole, slot), (ii) *PMI – Product Manufacturing Information to recognize* (e.g., roughness, tolerances), (iii) *dimension and rules to verify*, which is connected to the features properties (e.g., hole diameter, hole length, hole length/diameter ratio), and at the end the rules to verify (e.g. hole length/diameter ratio < 5).

Guideline section has the function of correctly explain the rule to the designer.

In Table 22 are show an extract of DfM/DfA rules DB.

Table 22 Extract of DfM/DfA rules DB

Rule #	**Rule type**	**Manufacturing Technology**	
		Class	**Type – Level 1**
M001	Warning	Machining	Milling
M002	Warning	Machining	Milling

	Material		CAD features and algorithms			Guideline
Type – Level 2	Class	Type	CAD features to recognize	PMI to recognize	Dimensions and rules to verify	
N.A.	All materials	N.A.	Initial volume of the part (Vi) Final volume of	N.A.	S = Vi / Vf S > 3	Keep limited the ratio between the volume of the raw material (Vi) and the volume of the finished part (Vf)
Drilling	All materials	N.A.	Hole diameter (D) Hole length (L)	Hole roughness (Ra)	Ra ≤ 0,8 μm L/D ≥ 5	Avoid tight roughnesses (Ra ≤ 0.8 μm) for deep holes (L/D ≥ 5) in machining operations

4.1.4. Analysis framework

This module is the main module of the Cost and DfM/DfA tool. Inside it are contained algorithms for organizing a manufacturing process, for cost calculation (cost analysis framework) and for design guidelines validation (DfM/DfA analysis framework).

The module is connected with the GUI, with the feature recognition and with the database. From the GUI receives the information needed for the analysis (process type, material, etc.) and at the same time after the analysis send to the GUI the result of the analysis. From feature recognition receives feature information of the 3D model/s under analysis and at the same time send information for highlining feature faces in CAD software. From the database the analysis framework receives unitary cost, design rules, etc.

The analysis framework is divided in two main sub-frameworks:

1. The cost analysis framework.
2. The DfM/DfA analysis framework.

4.1.4.1. Cost analysis framework

The cost analysis framework has the function to define groups of attributes and rules for generating manufacturing or assembly processes from 3D virtual models of components. Analysis framework is composed by *two cost routing generators*, one for manufacturing processes and the other for assembly processes. A cost routing is defined as a hierarchical data model and is divided by classes, required for the definition of a process by a multi-step approach, which starts from the setting of a production scenario to the calculation of the elementary operations necessary for converting raw materials into finished parts. A cost routing does not contain direct information for computing the cost of a process, while such knowledge is contained in cost models.

Manufacturing processes cost routing generator is divided in five modules:

1. Production/assembly scenario generation module.
2. Production strategy generation module.
3. Raw material strategy generation module.
4. Manufacturing/assembly strategy generation module.

5. Operation bundle generation module.

Production/assembly scenario generation module defines the facilities and production technologies available (the context) in which the manufacturing or assembly process is realized, for example the definition of the production country or make a product internally or buy from a supplier. The production scenario is directly chosen by the user, which define the database country through the setting of the tool, and this will affect material DB (column supply country), labour DB (column country) and machine DB (column country). In each of previous mentioned databases will be considered only the codes belonging to the selected country.

Production strategy generation module defines the overall manufacturing process (e.g., milling from prismatic bar vs. milling from round bar vs. milling from semi-finished casted part) to be used for realizing a component.
Production strategy is defined by the tool user from a list of available production strategies. The production strategy list is composed by a sub-list of raw material and manufacturing strategies. The available production strategies are defined in function of material and physical features of the part (block 1 of the feature recognition module). The tool in function of validity and priority rules suggest the best production strategy for the specific part.

Raw material strategy generation module defines the raw material to be used for realizing the final part. The module calculates the correct raw material (e.g., commercial semi-finished material, casted/forged elements) starting from material features and physical features of the part (block 1 of feature recognition module or from user). The selection of the correct raw material is a process consisting in five steps, which are summarized as follow.
Step 1 of Raw material strategy generation module. From material features are selected a list of material code belonging to a specific material class (e.g. Carbon steel), material type (e.g. C40) and condition (e.g. hot rolled).
Step 2 of Raw material strategy generation module. In step 2 are excluded the stock topologies not compatible with the shape of the part (physical feature information).
Step 3 of Raw material strategy generation module. In step 3 are selected the proper stock topology in function of the production strategy selected before (e.g. billets for forging process, commercial round or commercial square for machining processes).
Step 4 of Raw material strategy generation module. The raw material strategy generation module then calculates the minimum raw dimensions and compare them with dimensions D1, D2, D3 and D4 available in material DB.
Step 5 of Raw material strategy generation module. In this step the material code

with the low unitary cost are then selected from the list of material codes left over from the previous steps. In this way material physical characteristics are then imported in raw material strategy.

Manufacturing/assembly strategy generation module defines the specific manufacturing process to be used for converting a stock into a finished component (e.g., turning vs milling), or for converting a series of components in final assembled product (e.g., welding vs gluing vs bolding) Manufacturing/assembly strategy is chosen by the user and each manufacturing/assembly strategy is composed by a list of operations bundles. The manufacturing/assembly strategies available for a part are defined by validity and priority rules. In case of manufacturing, validity rules evaluate, in function of material and physical features of the part (block 1 of the feature recognition module), the manufacturing strategies compatible with the part (e.g. the injection molding strategy is available only for plastic parts, or milling and turning strategies have limitations in function of part dimensions). In case of assembly strategy, validity rules are used to evaluate the assembly strategies compatible with the parts in function of handling and connection features.
Priority rules suggest the best manufacturing strategy for the specific part in function of batch size and production volume (e.g. for an aluminium part are available machining strategies or die-casting strategies, but the most suitable is defined by the production volume and/or batch size). In manufacturing this module limits the machine category in machine DB.

Operation bundle generation module. An operations bundle is composed by the group of phases needed for the specific features of a product (1°, 2°, 3° block and assembly features of feature recognition module). The operation bundle generation module calculates the list of operations needed for the part or assembly and calculate the cost of each operation. This is a process consisting in two steps, which are summarized as follow.
In Step 1 the list of phases in a bundle is chosen through a series of validity rules, in which are compared product features and raw material with the available machine contained DB.
In the second step, the costs of each single phase (e.g. plasma cutting, milling with 3 axis CNC vertical) are calculated. In case of manufacturing the starting point is the material of the part that allows the identification, from the material DB, of its physical characteristics, which will be used for the cost model calculation.
After that machine type and size of each phase are chosen together whit operator type. The dimensions of the machine depend on the size of the component to be

produced (1° block of feature recognition), while machine type (e.g. 3 axis or 4 axis milling) depends on the feature of the part to be produced (2° and 3° block of feature recognition or by user information), i.e. by the different operations that compose the phase (e.g. drilling holes). The cost of each single operation will then be calculated starting from the cost model contained in DB cost model, which is compiled with the coming from the part (2° and 3° block of feature recognition) and from the other DBs (material DB, labour DB and machine DB).
In case of assembly the operations are chosen and evaluated in function of assembly features of the parts.

At the end the costs are displayed in GUI and include: (i) total cost, (ii) raw material cost, (iii) investment cost and (iv) process cost.

4.1.4.2. DfM/DfA analysis framework

DfM/DfA analysis framework has the function to link design rules with 3D CAD features developed during the engineering design process of parts or assemblies. This framework connects database rules repository, mathematical equations and 3D CAD model feature recognition. The scope of this framework is to examine the features of the part or assembly and verify if they are compliant with the guidelines collected in the repository.

DfM/DfA analysis framework is strictly connected whit cost analysis framework, in-fact production strategy, raw material strategy, manufacturing/assembly strategy and operation bundle generation modules of cost analysis framework are used also in DfM/DfA analysis framework.

DfM/DfA analysis framework is composed by a rules validation system and an interaction module.

Rules Validation System is the core of the entire system with three main purposes: interaction with the 3D CAD Model, extrapolate rules from the DB repository and then evaluate which design rules in 3D CAD Model are respected and which are not. Rules validation system is used with production strategy, raw material strategy, manufacturing/assembly strategy and operation bundle generation modules of cost analysis framework and connect them whit DfM/DfA rules DB. At the same time rules validation system works with features recognition module to verify the guidelines. As described in section 4.1.3 the DfM/DfA rules DB is composed by main sections (Manufacturing technology, Material, CAD feature recognition and Guideline) and they will be defined by these items:

- Manufacturing technology class: defined by production strategy in case of manufacturing and by assembly strategy in case of assembly.

- Manufacturing technology type – level I: manufacturing/assembly strategy.

- Manufacturing technology type – level II: phases and operations.

- Material class and material type: material feature of the parts.

- CAD features to recognize, PMI – Product Manufacturing Information to recognize and dimensions and rules to verify: block 1, block 2, block 3 and assembly features of features recognition module.

At the end the rules validation system displays in GUI the guideline section of the DfM/DfA rules DB to correctly explain the rule to the designer.

The interaction module is the link with the CAD environment, and it allows to display in which feature the rule fails, and so where the designer can make design changes on the model.

In Figure 29 and Figure 30 are shown the tool structure.

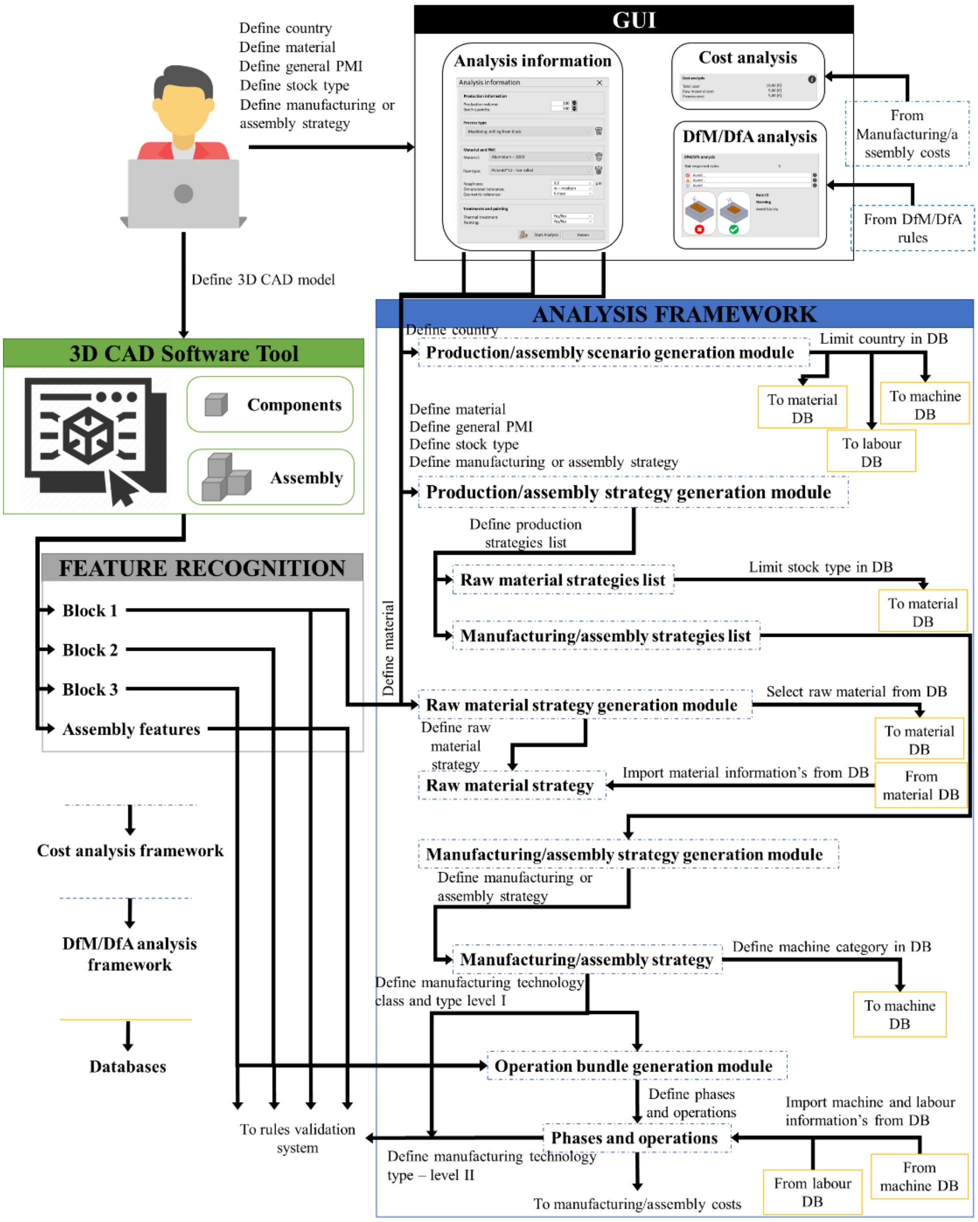


Figure 29 DfM/DfA and cost estimation tool structure (part 1)

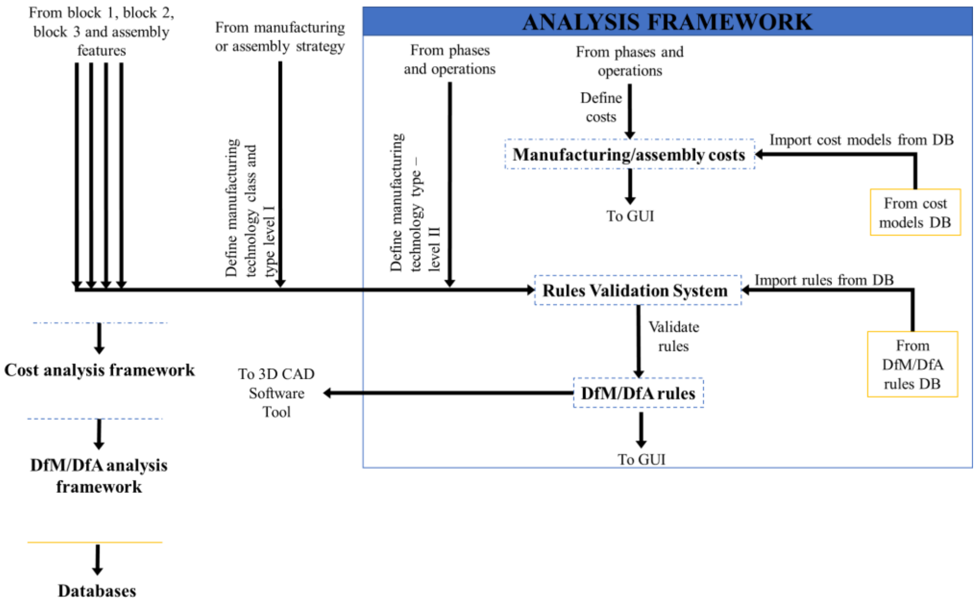


Figure 30 DfM/DfA and cost estimation tool structure (part 2)

5. Case studies

In this section, the proposed CAD-integrated DfM/DfA and cost methodology was used to address possible manufacturing issues in mechanical components and assembled products. In particular, the proposed approach was used to perform DfM/DfA and cost analysis by using 3D CAD models of 4 parts components (parts) and 2 product (assembly). Case studies are divided in 3 main sub-sections, in function of manufacturing process analysed:

- *Forging case study (Section 5.1).*
- *Machining case study (Section 5.2).*
- *Assembly case study (Section 5.3).*

The first two case studies are focused on Design for Manufacturing, while the last one is focused on Design for Assembly.

5.1. Case study – Forging

The forging case study is divided in 6 sub-sections:

- Section 5.1.1 presents a brief introduction of the closed-die forging process.
- Section 5.1.2 is focused on the cost structure of the closed-die forging process.
- Section 5.1.3 presents the cost estimation methodology related to the closed-die forging process.
- Section 5.1.4 describes the design rules involved in closed-die forging.
- Section 5.1.5 presents the first part analysed (Pin).
- Section 5.1.6 presents the second part analysed (Planet carrier).

5.1.1. Closed die forging introduction

The first two parts analysed are focused in forging process.

As described by (Mandolini et al., 2020, and Campi et al., 2020), forging is a manufacturing process which shapes a billet or a bar by applying compressive forces on it. The process temperature, employed during forging operations, classifies the technology in hot-forging and cold-forging (Kalpakjian et al., 2017). Another typical aspect of this process is the use of hammers or presses to squeeze and deform the material into a high strength part. The deformation could be achieved using flat or simple dies that do not completely enclose the material or into complex and shaped dies. In the first case, the process configuration is called open-die forging while in the second one the process configuration is called closed-die forging.

The basic procedure for closed-die forging is relatively straightforward (Figure 31). Metal stock in the form of either ingot or a billet, which is cut from a commercial bar, is first heated into the hot working temperature range to improve ductility. Then the material is squeezed or hammered in a series of tool steel dies to convert the stock into the finished shape. Excess material in the form of flash is produced as a necessary part of forging, and the final processing stage is to remove the flash to yield the finish forged part. Hot forging is a near net shape process, but all forgings require some subsequent machining, in particular for surfaces that must locate with other surfaces during the final assembly of a product (in conventional closed-die forging achievable surface roughness could not overcome 12,5 μm) (Ashby, 2010).

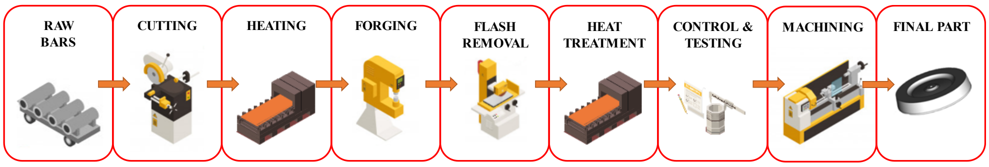


Figure 31 Closed-die forging process phases

5.1.2. Closed die forging process costs structure

According to Figure 17, the workflow for defining a manufacturing process begins by first selecting the *production environment*. Then, the production country or plant is chosen, and the unitary costs of materials and energy and the hourly rates of machines and labour are consequently established. The rules used at this stage do not depend on the process itself but rather depend on the supply strategies of the company that is developing the product.

The selection of the *production strategy* consists of establishing the raw material and manufacturing process (Table 23). All forgeable metals can be employed in closed-die, and a list of forgeable materials is available in (ASM International Handbook Committee, 2005). The production strategy depends on the realized product's variables (i.e., its shape and dimensions) and type of forging precision. Generally, the closed-die forging process variants can be grouped into three categories: (i) *blocker-type*, (ii) *conventional*, and (iii) *close-tolerance* (ASM International Handbook Committee, 2005).

Blocker-type forgings are produced in relatively inexpensive dies, but their weight and dimensions are somewhat greater than those of corresponding conventional closed-die forgings. A blocker-type forging approximates the general shape of the final part, with relatively generous finish allowance and radii.

Conventional closed-die forgings are the most common type and are produced to comply with commercial tolerances. These forgings are characterized by design complexity and tolerances that fall within the broad range of general forging practice.

Close-tolerance forgings are usually held to smaller dimensional tolerances than conventional forgings. Little or no machining is required after forging, because close-tolerance forgings are made with less draft, less material, and thinner walls, webs, and ribs. These forgings cost more and require higher forging pressures per unit of plan area than conventional forgings.

Each of previous categories can be divided in function of billet type (round or prismatic), derived from component shape (axisymmetric or prismatic). Generally a round billet could be used both for axisymmetric and prismatic part, but a prismatic billet could not be used for axisymmetric components.

Table 23. Production strategies for closed-die forging

Production strategy	Raw material strategy	Manufacturing strategy	Validity rules	Priority rules
Blocker closed-die forging from round billet	Round billet	Blocker closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	IF (Piece.Shape = "Axysimmetrical") THEN Score = 10 ELSE Score = 0
Blocker closed-die forging from prismatic billet	Prismatic billet	Blocker closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 Piece.Shape = "Prismatic" NOT (Piece.Shape = "Axysimmetrical") NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	N/A (no alternative production strategy available)
Conventional closed-die forging from round billet	Round billet	Conventional closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 Piece.Shape = "Axysimmetrical" NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal") Piece.GeneralRoughness < 25µm Piece.GeneralTolerance < ±3mm	IF (Piece.Shape = "Axysimmetrical") THEN Score = 10 ELSE Score = 0
Conventional closed-die forging from prismatic billet	Prismatic billet	Conventional closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 Piece.Shape = "Prismatic" NOT (Piece.Shape = "Axysimmetrical")	N/A (no alternative production strategy available)

			NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal") Piece.GeneralRoughness < 25 µm Piece.GeneralTolerance < ±3mm	
Precision closed-die forging from round billet	Round billet	Precision closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal") Piece.GeneralRoughness < 12,5µm Piece.GeneralTolerance < ±1,5mm	IF (Piece.Shape = "Axysimmetrical") THEN Score = 10 ELSE Score = 0
Precision closed-die forging from prismatic billet	Prismatic billet	Precision closed-die	Piece.Material.Category = "Metal" Piece.Volume > 0,025 dm3 AND Piece.Volume ≤ 25 dm3 Piece.Shape = "Prismatic" NOT (Piece.Shape = "Axysimmetrical") NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal") Piece.GeneralRoughness < 12,5µm Piece.GeneralTolerance < ±1,5 mm	N/A (no alternative production strategy available)

The material is closely related to the manufacturing process. However, the manufacturing process also depends on the piece shape (axisymmetric, prismatic, etc.), its dimensions, the tolerances and the surface roughness required.

The *raw material strategy* consists in the initial stock selection and is a function of the quantity of material needed for the final part (Table 24). Material costs usually make more than 50% of the forging costs, and a significant proportion of this material is waste (Knight, 1992). The material cost is determined by the weight of the forged part (RawMaterial.Density*Piece.Volume) and by the wastes generated during the process. Scraps can be divided into (i) waste during billet cutting (Cutting.Waste.Volume), (ii) defected parts (DefectedPiece.Percentage), (iii) scale oxidation losses (ScaleLoss.Percentage), and (iv) the machining allowance loss for chip forming (Machining.Volume).

The waste losses (scraps) depend on the "production strategy" adopted and on the size of the component.

Due to the heating of the material, scale loss is always present in hot forging. The outer surface of the hot metal is generally oxidized, and during the deformation, the oxidized film breaks and falls down in the form of scale. Scale is generally a percentage of total volume and is a function of the material forged. Machining loss should be considered only if a chip forming process (milling, turning etc.) is present after the hot forging. The amount of machining loss is function of the part dimensions.

The amount of raw material depends on the volume of the component and therefore on the amount of material necessary for the entire process (from billet cutting to final machining). The stock is a billet cut from a commercial bar. In case of axisymmetric components, the round billet diameter (RawMaterial.Width) is generally ¾ of the piece width (Piece.Width). Billet height (RawMaterial.Length) is calculated starting from necessary volume for forging the part (RawMaterial.Volume).

Table 24. "Round billet" raw material strategy

Validity rules	Calculation rule
NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	IF (Piece.Shape = "Axysimmetric" THEN RawMaterial.CrossSectionType = "Circular" ELSE RawMaterial.CrossSectionType = "Prismatic") RawMaterial.Material = Piece.Material RawMaterial.Volume = (Piece.Volume + Cutting.Waste.Volume + Flash.Volume + Machining.Volume) * (1 + ScaleLoss.Percentage/100) * (1 + DefectedPiece.Percentage/100) RawMaterial.Width = Round(3/4 * Piece.Witdh; -1)

	RawMaterial.Length = (RawMaterial.Volume * 4) / (π * RawMaterial.Width^2) RawMaterial.Cost = RawMaterial.Volume * RawMaterial.Density * RawMaterial.UnitaryCost – ((Machining.Volume + Cutting.Waste.Volume +Flash.Volume) * (1 + DefectedPiece.Percentage/100)) * RawMaterial.Density * Scrap.UnitaryRevenue

Once defined the stock strategy, the *manufacturing strategy* should be selected (Table 25). A manufacturing strategy covers all the bundles available for a given strategy. For the closed-die forging process, the shape of component (axisymmetric parts and prismatic parts) affects the manufacturing strategies.

Table 25. "Precision Closed-Die Forging" manufacturing strategy

Manufacturing strategy validity rules	**Operations bundles**	**Bundles validity rules**	**Bundles priority rules**
NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal") Piece.GeneralRoughness < 12,5µm Piece.GeneralTolerance < ±1,5mm	Precision Closed-die forging	Always valid	N/A (no alternative bundles available)
	Non-destructive test	Piece.NDTRequested	N/A (no alternative bundles available)
	Heat treatment	Always valid	N/A (no alternative bundles available)
	Turning with Multitasking lathe	Piece.GeneralRoughness < 6,3µm Piece.GeneralTolerance < ±0,5mm	IF (Production.BatchQuantity < 10) THEN Score = 5 ELSE Score = 20
	Turning + Milling	Piece.GeneralRoughness < 6,3µm Piece.GeneralTolerance < ±0,5mm	IF (Production.BatchQuantity ≥ 10) THEN Score = 10 ELSE Score = 0

Table 26 shows an analysis of a conventional closed-die forging of an axisymmetrical component. The forging process is completed whit chip-forming operations to achieve the final dimensional tolerances and surface roughness. For precision closed-die forging manufacturing strategy (Table 25), there are 5 bundles: (i) closed-die forging, (ii) non-destructive test, (iii) heat treatment, (iv) turning with the multitasking lathe. and (v) turning plus milling. The precision closed-die forging bundle is composed by the following four principal operations:

- Billet cutting (sawing is alternative to shearing);
- Billet heating;
- Forging;
- Flash removal (sawing or trimming in function of component characteristics).

Table 26. "Precision Closed Die Forging" operations bundle

Operations	**Operation validity rules**	**Product parameters**
Billet sawing	`RawMaterial.CrossSectionDimension1 > 300 mm`	`Operation.Area = RawMaterial.CrossSectionArea`
Billet shearing	`RawMaterial.CrossSectionDimension1 ≤ 300 mm`	`Operation.Area = RawMaterial.CrossSectionArea`
Billet heating	`Always valid`	`Operation.Width = Piece.Width * Furnace.BachtSize` `Operation.Height = Piece.Height`

Forging	`Always valid`	`Operation.Length = Piece.Length`
		`Operation.Width = Piece.Width`
		`Operation.Height = Piece.Height`
		`Operation.ProjectedArea = Piece. ProjectedArea + Flash.ProjectedArea`
		`Operation.Volume = Piece.Volume`
		`Operation.PartingLine = Piece.PartingLine`
		`Operation.MainAxis = Piece.MainAxis`
		`Operation.SideDepression = Piece.SideDepression`
		`Operation.NumberSurfaces = Piece. NumberSurfaces`

Flash trimming	Piece.ThroughHoles.Number $\geq$ 1 Piece.ThroughHole.Area $\geq$ 8 E03 mm^2	Operation.Length = Piece.Length Operation.Width = Piece.Width Operation.Height = Piece.Height Operation.ProjectedArea = Piece. ProjectedArea + Flash.ProjectedArea Operation.Perimeter = Piece.PerimeterOutside + Piece.PerimeterInside
Flash sawing	Piece.ThroughHoles.Number $\leq$ 1 OR Piece.ThroughHole.Area < 8 E03 mm^2	Operation.Length = Piece.Length Operation.Width = Piece.Width Operation.Height = Piece.Height Operation.ProjectedArea = Piece. ProjectedArea + Flash.ProjectedArea Operation.Perimeter = Piece.PerimeterOutside

5.1.3. Closed die forging cost calculation

For the sake of brevity, this section focuses only on the forging process for an axisymmetrical component, which represents the case studies analysed in this section.

Once the operations that constitute the overall forging process are established, the following variables are calculated for each operation:

- Raw material required.
- Operation, setup and idle time for machines and labour.
- Equipment required.
- Solid, liquid and gas consumables consumption.
- Energy consumption for the employed vectors.

The cost of forged components is calculated by first summing the cost of each operation included within the *closed-die forging* bundle (Eq. 1).

$$C_{precision\ closed-\ die\ forging\ bundle} = C_{billet\ cutting} + C_{billet\ heating} + C_{forging} + C_{flash\ trimming} \quad (1)$$

The cost of the overall manufacturing process is calculated by summing the cost of each bundle (Eq. 2).

$$C_{precision\ closed-\ die\ forging} = C_{precision\ closed-\ die\ forging\ (bundle)} + C_{chip\ forming\ (bundle)} + C_{control\ and\ treatment\ (bundle)} \quad (2)$$

Finally, the cost of the forged component is calculated by summing the raw material and the process cost (Eq. 3).

$$C_{forged\ component} = C_{precision\ closed-\ die\ forging} + C_{raw\ material} \quad (3)$$

5.1.4. Closed die forging design rules

The design of any forging process begins with the geometry of the finished part. Consideration is given to the shape of the part, the material to be forged, the type of forging, the equipment to be used, the number of parts to be forged, the application of the part and the forging type (blocker, conventional and precision). The design of forging part could be summarized in 8 main points (ASM 14A, 2005):

1. Parting Line: projected line around the periphery of a forging that is defined by the adjacent and mating faces of the forging dies when the dies are closed. The parting line design involve its inclination and position in relation of forging part.

2. Draft: describe the taper commonly applied to or inherent in the vertical sides of elements or features of a hammer or press forging. Its function is to facilitate removal of the workpiece from the die. Draft design rules are generally focused on draft angles in function of forging part material.

3. Ribs and bosses: are integral functional elements or features of a forging that project outward from a web in a direction parallel to the ram stroke. The

design of ribs and bosses is necessary to ensure their suitability for performing their functions, then the design rules are focused on ribs and bosses dimensions and characteristics.

4. Corners and fillets: are curved connecting surfaces on closed-die forgings that unite smoothly the converging or intersecting sides of forged elements, such as ribs, bosses, and webs. Then the design rules involving corners and fillets are focused on their values according to the features in which they are located.

5. Webs: are the relatively thin elements of the forging that lies between, and serves to connect, ribs, bosses, and other forged elements projecting from surfaces of the web. The design of webs must be considered along with the design of ribs and bosses, the location of the parting line, the assignment of draft, and the selection of corner and fillet radii.

6. Cavities and holes: cavities are pockets, recesses, or indentations of regular or irregular contour that are impressed into a portion of a closed-die forging. Holes are prolongations of cavities that perforate, or penetrate completely, some portion of the forging elements. Their design involves distances, radii, thickness and draft.

7. Flash: it is metal in excess of that required to fill the impression. Flash design are strictly connected with parting line design.

8. Dimensions and tolerances: dimensions describe the overall length, width and height, the location and amount of draft, and the location and size of forging features (ribs, bosses, cavities, holes) and they define the interconnecting fairing, or fillet radii, and the outside edge or corner radii. Dimensions and tolerances limits are function of the feature involved, forging material and forging type (blocker, conventional and precision).

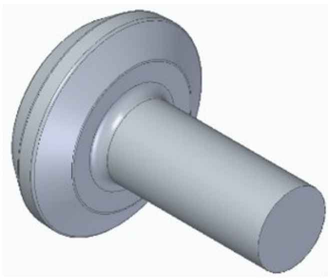
In appendix A. (Table 64) are reported a set of rules dedicated to the closed-forging process. It is worth noting that this is not a complete list of rules but only part of it.

5.1.5. *Case study - Forging closed die (part 1 – pin)*

The first part analysed is a pin manufactured by precision closed-die forging process. The part is manufactured in C40 carbon steel with a production volume of 50000 components and a batch size of 500 parts.

General roughness of the part is 6,3 μm and the tolerances doesn't exceed ±1,5mm.

In Figure 32 are show the component and its properties.



- → Material: C40 Carbon Steel
- → Production volume: 50000
- → Batch size: 500
- → General roughness: 6,3 μm
- → General tolerances: +1,5mm

Figure 32 Forging closed die (part 1 - pin)

By following the proposed methodology (Section 3), the first step (*Step 1: 3D CAD Model*) concerns the 3D model data reading as described in the methodology workflow (Figure 8). The described CAD feature recognition system was used to retrieve information from the 3D CAD model under development and to connect product feature with the DfM/DfA guidelines and cost estimation algorithms (*Step 2: Feature recognition and extraction)*. In Appendix B. Features of components analysed in case studies, Table 67, are summarized the *physical and material features of the model (Features of 1° block)* while in Table 68 are summarized the *manufacturing and material features of the model (isolated) (Features of 2° block)*. Block 3 (Manufacturing and material features of the model in relation with other feature/s (interrelated for part)) and block 4 (Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly)) are not interested in this case study.

Once identified the features belonging to the blocks, DfM/DfA rules analysis was performed as described in the methodology workflow (S*tep 4: DfM/DfA analysis*) (Figure 8). For the part analysis, only the set of DfM rules referring to the closed-die forging technology, in particular precision forging, was selected (Table 64 in Appendix A. DfM/DfA rules repositories). Then, mathematical equations characterizing each DfM rule are checked with the feature identified in the feature recognition phase.

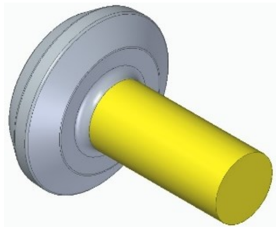
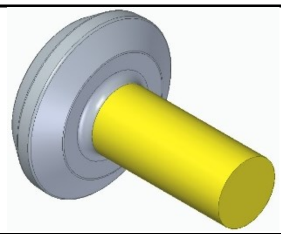
In this first case study are identified 2 design problems regarding the part, both related to the second block of geometric feature recognition.

The first issue concerns the absence of draft angle of "Feature_10 – CYLINDER". Draft is the term used to describe the taper commonly applied to or inherent in the vertical sides of elements or features of a hammer or press forging. Its function is to facilitate removal of the workpiece from the die. Although the surfaces of die cavities normally are polished and lightly coated with a lubricating film, the absence of draft, or of sufficient draft, causes the forging to stick in the dies, making removal impossible or difficult (workpieces designed with no taper on vertical sides (zero draft) require special forceful means for ejection from die cavities). The minimum draft angle in precision closed-die forging of steel cannot be lower than 3°. This issue can be classified as a critical since it affects the technological feasibility of the feature.

The second design issue is related to the absence of fillets at the base of "Feature_10 – CYLINDER", cause in closed-die forging of steel minimum value of corner fillet radii is 1,5mm. Fillet and corner are curved connecting surfaces on closed-die forgings that unite smoothly the converging or intersecting sides of forged elements, such as ribs, bosses, and webs. Their radii provide a smooth, gradual connection rather than an abrupt angular junction. Minimum values for corner and fillet radii provide a series of advantages including a lower concentration of stress but also a less die costs, time savings and reduction of processing waste. Indeed, sharp edges cannot be obtained by forging and is required a machining operation.

Table 27 summarize the identified design problem.

Table 27 Design problems identified for the component (part 1 – pin original design)

Knowledge processing			Knowledge representation	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**
Class: Metal forming Type - level 1: Closed-die forging Type - level 2: Precision	Class: Metals Type: Steel	Recognize: Outside draft angle (αdo) PMI: N.A. Dimensions/geometry: αdo ≥3°	Action: Guarantee Subject: An outside draft angle higher than 3° Context: In precision closed-die forging of steel	
Class: Metal forming Type - level 1: Closed-die forging Type - level 2: N.A.	Class: Metals Type: Steel	Recognize: Corner radius (r) PMI: N.A. Dimensions/geometry: r ≥ 1,5mm	Action: Guarantee Subject: A minimum corner radius of 1,5 mm Context: In closed-die forging of steels	

At the same time with DfM/DfA rules analysis, an analytical cost estimation has been done starting from the identified features (*Step 3: Cost analysis*). It is important to notice that the manufacturing cost estimation is not applicable in the original design due to the impossibility to produce the part cause the draft angle and corner radius absence.

Based on the mentioned analyses (3D Model Data, Feature recognition and extraction DfM/DfA analysis and Cost estimation) two report (one for cost analysis and one for DfM/DfA analysis) was generated. This report keeps track of the changes did about the CAD model and its evolutions over time. At this step, the previously highlighted issues will be fixed and then the 3D model is updated *(Step 5: Update 3D CAD Model)* by changing the model features according to the design guideline.

The changes consisted of:

- Feature_10 – CYLINDER: substituted with a cone having a 3° draft angle (Feature_12 – TRUNCATED_CONE_NEW).

- Feature_10 – CYLINDER: elimination of sharp corner at the base using a 1,5 mm corner radius (Feature_13 - FILLET_NEW).

In Appendix B. Features of components analysed in case studies, are summarized only the modified *physical and material features of the updated model (Features of 1° block)* while in Table 70 are summarized the *manufacturing and material features of the updated model (isolated) (Features of 2° block)*. It's important to notice that the component will then undergo a machining operation to obtain the Feature_10 – CYLINDER 10, necessary for the assembly of the component. The component after machining operation will be the same of the original design, therefore, regarding the other features the information are the same represented in previous tables (Table 67 and Table 68).

Table 28 and Table 29 report the cost-sharing for the component manufacturing after the design update. Analysing the breakdown of cost can be notice that the "Precision closed-die forging (bundle)" is the most impacting in term of costs, while the heat treatment and control impact only in a small percentage in the total costs.

Table 28 Cost analysis (part 1 – pin updated design) – Raw material

Raw material information	**Type [ad.]**	**Dimensions [mm]**	**Volume [dm^3]**	**Total [€]**
Raw material (net+waste)	*Round billet*	*70*70*104*	*0,40*	*2,48*

Table 29 Cost analysis (part 1 – pin updated design) – Operations

Cost breakdown (bundles)	**Setup/idle**		**Active**		**Total**		**Tooling [€]**
	Cost [€]	**Time [s]**	**Cost [€]**	**Time [s]**	**Cost [€]**	**Time [s]**	
Precision closed-die forging (manufacturing strategy) (tot.)	*1,95*	*43*	*8,25*	*512*	*10,20*	*556*	*13850,22*
Precision closed-die forging (bundle) (tot.)	*1,83*	*38*	*5,64*	*434*	*7,47*	*472*	*13850,22*
100 ton billet shearing press (55 €/h)	*0,14*	*9*	*0,02*	*1*	*0,16*	*10*	*-*
750 ton hydraulic press (210 €/h)	*1,69*	*29*	*2,35*	*40*	*4,04*	*69*	*13850,22*

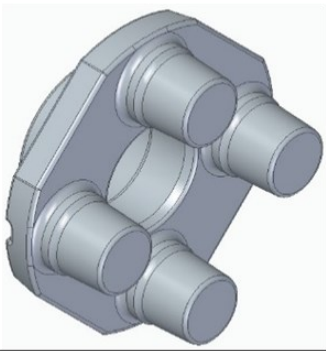
Bandsaw trim (30 €/h)	-	-	*3,27*	*392*	*3,27*	*392*	-
Heat treatment + control (bundle) (tot.)	*0,03*	*1*	*0,35*	*15*	*0,38*	*16*	-
Furnace heat treatment (135 €/h)	*0,03*	*1*	*0,22*	*6*	*0,25*	*7*	-
Visual control (50€/h)	-	-	*0,13*	*9*	*0,13*	*9*	-
Chip forming (bundle) (tot.)	*0,06*	*5*	*0,84*	*63*	*0.90*	*68*	-
Generic CNC turret lathe (tot.) (48 €/h):	*0,06*	*5*	*0,84*	*63*	*0,90*	*68*	-
→ Rough cylindrical turn on Feature_10 - CYLINDER: → Cylindrical_face_10.01	-	-	0,84	63	-	-	-

5.1.6. *Case study - Forging closed die (part 2 – planet carrier)*

Using the same procedure as in the first case study, the second part analysed is a planet carrier manufactured also in this case by precision closed-die forging process. The part is manufactured in C40 carbon steel with a production volume of 50000 components and a batch size of 500 parts.

General roughness of the part is 6,3 μm and the tolerances doesn't exceed ±1,5mm.

In Figure 33 are show the component and its properties.



- → Material: C40 Carbon Steel
- → Production volume: 50000
- → Batch size: 500
- → General roughness: 6,3 μm
- → General tolerances: +1,5mm

Figure 33 Forging closed die (part 2 - planet carrier)

Following the methodology (SECTION 3) in Appendix B. Features of components analysed in case studies, Table 71, are summarized the *physical and material features of the model (Features of 1° block)* while in Table 72 are summarized the *manufacturing and material features of the model (isolated) (Features of 2° block)*. Block 3 (Manufacturing and material features of the model in relation with other feature/s (interrelated for part)) and block 4 (Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly)) also in this case study are not interested in the analysis.

Once identified the features belonging to the blocks, DfM/DfA rules analysis was performed and mathematical equations characterizing each DfM rule are checked with the feature identified in the feature recognition phase.

In this second case study are identified 4 design problems regarding the part, all of them related to the second block of geometric feature recognition:

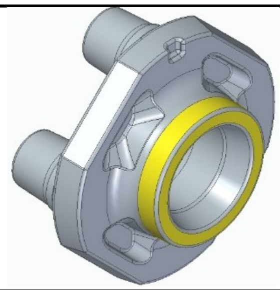
All the issues are related to the too low draft angle of some features:

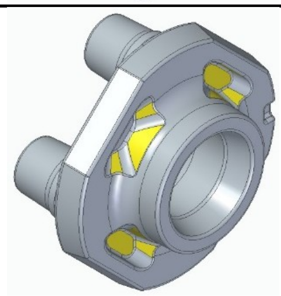
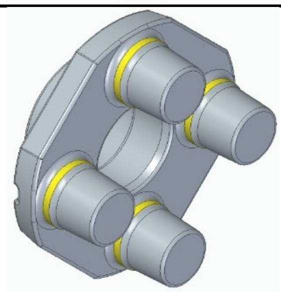
- “Feature_1 - TRUNCATED CONE_1”: too low draft angle (2°) Critical issue.
- “Feature_10 – CYLINDER”: absence of draft angle. Critical issue.
- “Feature_12 – SLOTS”: absence of draft angle. Critical issue.
- “Feature_18 – CYLINDER_CIRCULAR PATTERN”: absence of draft angle. Critical issue.

The minimum draft angle in precision closed-die forging of steel cannot be lower than 3° and in this case is only 2° for the first feature and absent for the other ones. As described in the previous case study this issue can be classified as a critical since it affects the technological feasibility of the feature.

Table 30 summarize the identified design problem.

Table 30 Design problems identified for the component (part 2 – planet carrier original design)

Knowledge processing			**Knowledge representation**	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**
Class: Metal forming Type - level 1: Closed-die forging Type - level 2: Precision	Class: Metals Type: Steel	Recognize: Outside draft angle (αdo) PMI: N.A. Dimensions/geometry: αdo ≥3°	Action: Guarantee Subject: An outside draft angle higher than 3° Context: In precision closed-die forging of steel	

Class: Metal forming Type - level 1: Closed-die forging Type - level 2: Precision	Class: Metals Type: Steel	Recognize: Inside draft angle (αdi) PMI: N.A. Dimensions/geometry: αdi ≥5°	Action: Guarantee Subject: An inside draft angle higher than 5° Context: In precision closed-die forging of steel	
Class: Metal forming Type - level 1: Closed-die forging Type - level 2: Precision	Class: Metals Type: Steel	Recognize: Inside draft angle (αdi) PMI: N.A. Dimensions/geometry: αdi ≥5°	Action: Guarantee Subject: An inside draft angle higher than 5° Context: In precision closed-die forging of steel	
Class: Metal forming Type - level 1: Closed-die forging Type - level 2: Precision	Class: Metals Type: Steel	Recognize: Outside draft angle (αdo) PMI: N.A. Dimensions/geometry: αdo >3°	Action: Guarantee Subject: An outside draft angle higher than 3° Context: In precision closed-die forging of steel	

Also in this case study is important to notice that the manufacturing cost estimation is not applicable in the original design due to the impossibility to produce the part cause the draft angle absence.

Then, starting from the previous analyses (3D Model Data, Feature recognition and extraction DfM/DfA analysis and Cost estimation) and from the report generated, the highlighted issues will be fixed and then the 3D model is updated by changing the model features according to the design guidelines.

The changes consisted of:

- Feature_1 - TRUNCATED CONE_1: increasing the draft angle from 2° to 3° (Feature_1 - TRUNCATED CONE_1_MOD).

- Feature_10 – CYLINDER: elimination of this feature for forging operation. The feature will be obtained using a chip forming process.

- Feature_12 – SLOTS: adding a draft angle of 3° (Feature_12 – SLOTS_MOD).

- Feature_16 - TRUNCATED CONE_3: changing height (from 9,33 mm to 20 mm) and reduced the diameter (from 88 mm from 82,28 mm).

- Feature_26 - FILLET_NEW: adding a fillet (radius 3mm) at the base of the Feature_16 - TRUNCATED CONE_3_MOD.

- Feature_18 – CYLINDER_CIRCULAR PATTERN: substitution of this feature with a truncated cone with a 3° draft angle (Feature_18 – TRUNCATED_CONE_CIRCULAR PATTERN_NEW).

In Appendix B. Features of components analysed in case studies, Table 73, are summarized only the modified *physical and material features of the updated model (Features of 1° block)* while in Table 74 are summarized the *manufacturing and material features of the updated model (isolated) (Features of 2° block)*. It's important to notice that the component will then undergo a machining operation to obtain the Feature_10 – CYLINDER, necessary for the correct working of the component in the assembly. The component after machining operation, except for previously edited features, will be the same of the original design, therefore, regarding the other features the information are the same represented in previous tables (Table 71 and Table 72)

Table 31 and Table 32 reports the cost-sharing for the component manufacturing after the design update. Analysing the costs breakdown can be notice also in this case study that the "Precision closed-die forging (bundle)" is the most impacting in term of costs, while the heat treatment and control impact only in a small percentage in the total costs.

Table 31 Cost analysis (part 2 – planet carrier updated design) – Raw material

Raw material informations	**Type [ad.]**	**Dimensions [mm]**	**Volume [dm^3]**	**Total [€]**
Raw material (net+waste)	*Round billet*	*190*190*104*	*2,96*	*18,49*

Table 32 Cost analysis (part 2 – planet carrier updated design) – Operations

Cost breakdown (bundles)	**Setup/idle**		**Active**		**Total**		**Tooling [€]**
	Cost [€]	**Time [s]**	**Cost [€]**	**Time [s]**	**Cost [€]**	**Time [s]**	
Precision closed-die forging (manufacturing strategy) (tot.)	*6,55*	*69*	*27,00*	*1241*	*33,55*	*1310*	*47301,09*
Precision closed-die forging (bundle) (tot.)	*6,44*	*62*	*19,21*	*665*	*25,65*	*727*	*47301,09*
500 ton billet shearing press (115 €/h)	*0,52*	*16*	*0,06*	*2*	*0,58*	*18*	-
5000 ton hydraulic press (470 €/h)	*5,92*	*46*	*14,55*	*111*	*20,47*	*157*	*47301,09*
Bandsaw trim (30 €/h)	-	-	*4,60*	*552*	*4,60*	*552*	-
Heat treatment + control (bundle) (tot.)	*0,03*	*1*	*1,24*	*52*	*1,27*	*53*	-
Furnace heat treatment (135 €/h)	*0,03*	*1*	*0,98*	*26*	*1,01*	*27*	-
Visual control (50 €/h)	-	-	*0,36*	*26*	*0,36*	*26*	-
Chip forming (bundle) (tot.)	*0,08*	*6*	*6,55*	*524*	*6,63*	*530*	-
Generic CNC machining center (tot operations) (45 €/h):	*0,08*	*6*	*6,55*	*524*	*6,63*	*530*	-
→ Drill single hole on Feature_10 - CYLINDER: → Cylindrical_face_10.01	-	-	6,55	524	-	-	-

5.2. Case study – machining/chip forming

The machining/chip forming case study is divided in 6 sub-sections:

- Section 5.2.1 presents a brief introduction of the machining/chip forming process.
- Section 5.2.2 is focused on the cost structure of the machining/chip forming process.
- Section 5.2.3 presents the cost estimation methodology related to the machining/chip forming process.
- Section 5.2.4 describes the design rules involved in machining/chip forming.
- Section 5.2.5 presents the first part analysed (milled late).
- Section 5.2.6 presents the second part analysed (turned haft).

5.2.1. Machining introduction

In this section the case study is focused in chip forming process.

Machining is a term that covers a large collection of manufacturing processes designed to remove unwanted material, usually in the form of chips, from a workpiece. Machining is used to convert castings, forgings, or preformed blocks of metal into desired shapes, with size and finish specified to fulfil design requirements (ASM International Handbook Committee, 1989).

Machining process number is huge and each process could be performed on one or more machine tools. For example, drilling can be performed on drill presses, milling machines, lathes, and some boring machines. The main chip forming processes are listed below:

- Turning (boring, facing, cutoff, taper turning, form cutting, chamfering, recessing, thread cutting).
- Shaping (planing, vertical shaping).

- Milling (hobbing, generating, thread milling).
- Drilling (reaming, tapping, spot facing, counterboring, countersinking).
- Sawing (filing).
- Abrasive machining (grinding, honing, lapping).
- Broaching (internal and surface).
- Processes can be combined into multiple capability machines, known as machining centers.

In machining process achievable surface roughness is generally less than 3,2 μm up to very accurate values (0,01 μm). Also, for tolerance the values achievable are extremely accurate, varying between ±1 mm to ±0,01 mm (Ashby, 2010).

5.2.2. Machining process costs structure

According to Figure 8 and in the same way as forging (Section 5.1) the workflow for defining a manufacturing process begins by first selecting the *production environment* (Table 33) in the same way as described in previous chapters.

In machining the raw material could be a bar (round or prismatic), a tube (round or prismatic) or a sheet metal, in function of the realized product's shape (Axysimmetrical, Prismatic, Hollow Axysimmetrical, Hollow Prismatic and Sheet Metal). Also, in chip forming raw material could be a semi-finished part produced by forming processes, such as forging or casting.

The manufacturing strategy depends on the realized product's variables (i.e., its shape and dimensions) and could be classified in *Milling, Turning* (limited for axysimmetrical and hollow axysimmetrical components) and a combination of previous two: *Milling and Turning* for axysimmetrical and hollow axysimmetrical parts which need turning but also milling operations.

Table 33 Production strategies for machining

Production strategy	**Raw material strategy**	**Manufacturing strategy**	**Validity rules**	**Priority rules**

Milling from prismatic bar	Prismatic bar	Milling	`Piece.Length < 1800 mm`
			`Piece.Width < 500 mm`
			`Piece.Height < 160 mm`
			`Piece.Weight < 4000 kg`
			`NOT (Piece.Shape = "SheetMetal")`
			`NOT (Piece.Shape = "Axysimmetrical")`
			`NOT (Piece.Shape = "HollowAxysimmetrical")`
				`N/A (no alternative production strategy available)`

Milling from round bar	Round bar	Milling	`Piece.Length < 1800 mm`
			`Piece.Width < 500 mm`
			`Piece.Height < 500 mm`
			`Piece.Weight < 4000 kg`
			`NOT (Piece.Shape = "SheetMetal")`
			`NOT (Piece.Shape = "Prismatic")`
			`NOT (Piece.Shape = "Hollow Prismatic")`
				`N/A (no alternative production strategy available)`

Milling from prismatic tube	Prismatic tube	Milling	`Piece.Length < 1800 mm`
			`Piece.Width < 500 mm`
			`Piece.Height < 300 mm`
			`Piece.Thickness< 14,2 mm`
			`Piece.Weight < 4000 kg`
			`Piece.Shape = "Hollow Prismatic"`
			`NOT (Piece.Shape = "SheetMetal")`
			`NOT (Piece.Shape = "Prismatic")`
			`NOT (Piece.Shape = "Axysimmetrical")`
				`N/A (no alternative production strategy available)`

			NOT (Piece.Shape = "HollowAxysimmetrical")	
Milling from round tube	Round tube	Milling	Piece.Length < 1800 mm Piece.Width < 1200 mm Piece.Height < 1200 mm Piece.Thickness< 12,5 mm Piece.Weight < 4000 kg Piece.Shape = "Hollow Axysimmetrical" NOT (Piece.Shape = "SheetMetal") NOT (Piece.Shape = "Prismatic") NOT (Piece.Shape = "Axysimmetrical") NOT (Piece.Shape = "HollowPrismatic")	N/A (no alternative production strategy available)
Milling from sheet metal	Sheet metal	Milling	Piece.Length < 1800 mm Piece.Width < 1200 mm Piece.Height < 700 mm Piece.Weight < 4000 kg Piece.Shape = "SheetMetal" NOT (Piece.Shape = "Prismatic") NOT (Piece.Shape = "Axysimmetrical") NOT (Piece.Shape = "HollowPrismatic") NOT (Piece.Shape = "HollowAxysimmetrical")	N/A (no alternative production strategy available)
Milling from semi-finished	Semi-finished	Milling	Piece.Length < 1800 mm Piece.Width < 1200 mm Piece.Height < 1200 mm Piece.Weight < 4000 kg	N/A (no alternative production strategy available)

Turning from round bar	Round bar	Turning	Piece.Length < 1910 mm
			Piece.Width < 500 mm
			Piece.Height < 500 mm
			Piece.Weight < 4000 kg
			Piece.Shape = "Axysimmetrical"
			Piece.Shape = "HollowAxysimmetrical"
			NOT (Piece.Shape = "SheetMetal")
			NOT (Piece.Shape = "Prismatic")
			NOT (Piece.Shape = "Hollow Prismatic")
				IF (Piece.Shape = "Axysimmetrical" AND Production.BatchQuantity > 10) THEN Score = 10
				IF (Piece.Shape = "Axysimmetrical" AND Production.BatchQuantity ≤ 10) THEN Score = 5
				ELSE Score = 0

Turning from round tube	Round tube	Turning	Piece.Length < 1910 mm
			Piece. Width < 630 mm
			Piece.Height < 630 mm
			Piece.Thickness< 12,5 mm
			Piece.Weight < 4000 kg
			Piece.Shape = "HollowAxysimmetrical"
			NOT (Piece.Shape = "SheetMetal")
			NOT (Piece.Shape = "Prismatic")
			NOT (Piece.Shape = "Axysimmetrical")
			NOT (Piece.Shape = "HollowPrismatic")
				IF (Piece.Shape = "HollowAxysimmetrical" AND Production.BatchQuantity > 10) THEN Score = 10
				IF (Piece.Shape = "HollowAxysimmetrical" AND Production.BatchQuantity ≤ 10) THEN Score = 5
				ELSE Score = 0

Turning from semi-finished	Semi-finished	Turning	Piece.Length < 1910 mm Piece.Width < 630 mm Piece.Height < 630 mm Piece.Weight < 4000 kg NOT (Piece.Shape = "SheetMetal") NOT (Piece.Shape = "Prismatic") NOT (Piece.Shape = "HollowPrismatic")	N/A (no alternative production strategy available)

Turning and milling from round bar	Round bar	Turning + Milling	Piece.Length < 1910 mm
			Piece.Width < 500 mm
			Piece.Height < 500 mm
			Piece.Weight < 4000 kg
			Piece.Shape = "Axysimmetrical"
			Piece.Shape = "HollowAxysimmetrical"
			NOT (Piece.Shape = "SheetMetal")
			NOT (Piece.Shape = "Prismatic")
			NOT (Piece.Shape = "Hollow Prismatic")
				IF (Piece.Shape = "Axysimmetrical" AND Production.BatchQuantity ≤ 10) THEN Score = 10
				IF (Piece.Shape = "Axysimmetrical" AND Production.BatchQuantity > 10) THEN Score = 5
				ELSE Score = 0

Turning and milling from round tube	Round tube	Turning + Milling	Piece.Length < 1910 mm
			Piece. Width < 630 mm
			Piece.Height < 630 mm
			Piece.Thickness< 12,5 mm
			Piece.Weight < 4000 kg
			Piece.Shape = "HollowAxysimmetrical"
			NOT (Piece.Shape = "SheetMetal")
			NOT (Piece.Shape = "Prismatic")
			NOT (Piece.Shape = "Axysimmetrical")
			NOT (Piece.Shape = "Hollow Prismatic")
				IF (Piece.Shape = "HollowAxysimmetrical" AND Production.BatchQuantity ≤ 10) THEN Score = 10
				IF (Piece.Shape = "HollowAxysimmetrical" AND Production.BatchQuantity > 10) THEN Score = 5
				ELSE Score = 0

Turning and milling from semi-finished	Semi-finished	Turning + Milling	Piece.Length < 1910 mm Piece.Width < 630 mm Piece.Height < 630 mm Piece.Weight < 4000 kg NOT (Piece.Shape = "SheetMetal") NOT (Piece.Shape = "Prismatic") NOT (Piece.Shape = "Hollow Prismatic")	N/A (no alternative production strategy available)

The material is closely related to the manufacturing process. However, the manufacturing process also depends on the piece shape (axisymmetric, prismatic, etc.), its dimensions, the tolerances and the surface roughness required.

The *raw material strategy* consists in the initial stock selection and is a function of the quantity of material needed for the final part (Table 34). Material costs importance in total cost breakdown of chip forming is extremely variable and affected by raw material unitary cost and by part complexity. In-fact in complex part the manufacturing cost outclasses the material cost. The material cost is determined by the final part dimensions (`Piece.Length`, `Piece.Width`, `Piece.Height`) and by the allowance of material (`Piece.Length.Allowance`, `Piece.Width.Allowance`, `Piece.Height.Allowance`) required to obtain the final roughness and tolerances of the part.

In raw material cost must be considered also the defected parts (`DefectedPiece.Percentage`). Generally the scrap, defined as the difference between raw material volume (`RawMaterial.Volume`) and piece volume (`Piece.Volume`), could be resold to obtain some revenues.

Table 34 "Prismatic bar" raw material strategy

Validity rules	**Calculation rule**
Piece.Dimension2 < 500 mm Piece.Dimension3 < 160 mm	RawMaterial.Material = Piece.Material RawMaterial.Dimension1 ≥ Piece.Length + Piece.Length.Allowance RawMaterial.Dimension2 ≥ Piece.Width + Piece.Width.Allowance RawMaterial.Dimension3 ≥ Piece.Height + Piece.Height.Allowance RawMaterial.Volume = (RawMaterial.Dimension1 * RawMaterial.Dimension2 * RawMaterial.Dimension3) * (1 + DefectedPiece.Percentage/100) RawMaterial.Cost = RawMaterial.Volume * RawMaterial.Density * RawMaterial.UnitaryCost – (RawMaterial.Volume – Piece.Volume) * (1 + DefectedPiece.Percentage/100) * RawMaterial.Density * Scrap.UnitaryRevenue

Once defined the stock strategy, the *manufacturing strategy* should be selected (Table 35). For the milling process, the dimensions of component (space limits in machining centers) and the movements required at the machining centers (3 axis, 4 axis and 5 axis) affects the manufacturing strategies.

Table 35 "Milling" manufacturing strategy

Manufacturing strategy validity rules	Operations bundles	Bundles validity rules	Bundles priority rules
Piece.Length < 1800 mm Piece.Width < 1200 mm Piece.Height < 1200 mm Piece.Weight < 4000 kg	Milling with 3 axis CNC vertical	NMax movements required: X axis ("left to right") AND Y axis ("front to back") AND Z axis ("up and down")	IF NMax movements required: X axis AND Y axis AND Z axis THEN Score = 15 ELSE Score = 15
	Milling with 4 axis CNC horizontal	NMax movements required: X axis AND Y axis AND Z axis AND "180° rotation around the X axis"	IF NMax movements required: X axis AND Y axis AND Z axis THEN Score = 10 IF NMax movements required: X axis AND Y axis AND Z axis AND "180° rotation around the X axis" THEN Score = 10 ELSE Score = 10
	Milling with 5 axis CNC	NMax movements required: X axis AND Y axis AND Z axis AND (("180° rotation around the X axis" AND "180° rotation around the Y axis") OR (AND "180° rotation around the X axis" AND "180° rotation around the Z axis") OR (AND "180° rotation	IF NMax movements required: X axis AND Y axis AND Z axis THEN Score = 5 IF NMax movements

		around the Y axis" AND "180° rotation around the Z axis"))	required: X axis AND Y axis AND Z axis AND "180° rotation around the X axis" THEN Score = 5 ELSE Score = 5
	Broaching	Piece.BroachingRequest	N/A (no alternative bundles available)
	EDM	Piece.MinFilletRadius $\leq$ 3 mm	N/A (no alternative bundles available)
	Non-destructive test	Piece.NDTRequested	N/A (no alternative bundles available)
	Painting	Piece.PaintRequest	N/A (no alternative bundles available)
	Chrome plating	Piece.ChromeRequest	N/A (no alternative bundles available)

Table 36 shows an analysis of a milling using a vertical 3 axis CNC. The milling process is completed whit operations to achieve the final dimensional tolerances, surface roughness or painting. For milling (Table 35) there are 8 bundles in function of machine required to achieve the final part shape: (i) milling with 3 axis CNC vertical, (ii) milling with 4 axis CNC horizontal, (iii) milling with 5 axis CNC, (iv) broaching, (v) EDM, (vi) non-destructive test and (vii) painting and chrome plating. The milling with 3 axis CNC vertical bundle is composed by the following operations:

- Raw material cutting, which could be achieved by laser, plasma or in case of large section, by bandsaw.
- The milling process using a vertical 3 axis CNC.

Table 36 "Milling with 3 axis CNC vertical" operations bundle

Operations	Operation validity rules	Product parameters
Laser cutting	`RawMaterial.Dimension3` ≤ `20 mm`	`Operation.Height = RawMaterial.Dimension3` `Operation.Perimeter = RawMaterial.Perimeter`
Plasma cutting	`RawMaterial.Dimension3` ≤ `160 mm`	`Operation.Height = RawMaterial.Dimension3` `Operation.Perimeter = RawMaterial.Perimeter`
Bandsaw cutting	`RawMaterial.Dimension3` ≥ `160 mm`	`Operation.CrossSectionalArea = RawMaterial.CrossSectionalArea`
Milling with 3 axis CNC vertical	`Always valid`	`Operation.MaxLength = Piece.Length` `Operation.MaxWidth = Piece.Width` `Operation.MaxHeight = Piece.Height`

5.2.3. Machining cost calculation

Once the operations that constitute the overall process are established, the following variables are calculated for each operation:

- Raw material required.
- Operation, setup and idle time for machines and labour.
- Equipment required.
- Solid, liquid and gas consumables consumption.
- Energy consumption for the employed vectors.

The cost of machined parts is calculated by first summing the cost of each operation included within the *Milling with 3 axis CNC vertical* bundle (Eq. 4).

$$C_{milling\ with\ 3\ axis\ CNC\ vertical\ (bundle)} = C_{raw\ material\ cutting} + C_{milling\ with\ 3\ axis\ CNC\ vertical} \quad (4)$$

The cost of the overall manufacturing process is calculated by summing the cost of each bundle required (Eq. 5).

$$C_{milling} = C_{milling\ with\ 3\ axis\ CNC\ vertical\ (bundle)} + C_{broaching} + C_{EDM} + C_{non-destructive\ test} + C_{painting} + C_{chrome\ plating} \quad (5)$$

Finally, the cost of the final component is calculated by summing the raw material and the process cost (Eq. 6).

$$C_{machined\ component} = C_{raw\ material} + C_{milling} \quad (6)$$

5.2.4. Machining design rules

The design of a machined components includes limitations about drilling operation, hole diameters, achievable and recommended surface finish and tolerances, achievable radii, ect.

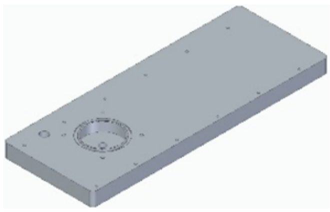
A set of rules dedicated for machining (milling and turning in particular) are reported in Appendix A. DfM/DfA rules repositories, Table 65. It is worth noting that this is not a complete list of rules but only part of it.

5.2.5. Case study- Machining (part 1 – milled plate)

The first part analysed is a plate manufactured by “milling from sheet metal” production strategy. The part is manufactured in Aluminium - AC 100 with a production volume of 100 components and a batch size of 10 parts.

General roughness of the part is 3,2 μm and the tolerances are classified as medium.

In Figure 34 are show the component and its properties.



- → Material: Aluminium - AC 100
- → Production volume: 100
- → Batch size: 10
- → General roughness: 3,2 μm
- → General tolerances: medium

Figure 34 Machining (part 1 – milled plate)

As in the previous case study, also in this one is followed methodology (Section 3), starting from "*Step 1: 3D CAD Model*" (Figure 8), and "*Step 2: Feature recognition and extraction*", in Appendix B. Features of components analysed in case studies, Table 75, are summarized the *physical and material features of the model (Features of 1° block)*, in Table 76 are summarized the *manufacturing and material features of the model (isolated) (Features of 2° block)*, while in Table 77 are summarized the *Block 3 (Manufacturing and material features of the model in relation with other feature/s (interrelated for part))*. *Block 4 (Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly))* is not interested in this case study.

Once identified the features belonging to the blocks, DfM/DfA rules analysis was performed as described in the methodology workflow (S*tep 4: DfM/DfA analysis*) (Figure 8). For the part analysis, only the set of DfM rules referring to the machining process, was selected (Appendix A. DfM/DfA rules repositories, Table 65). Then, mathematical equations characterizing each DfM rule are checked with the feature identified in the feature recognition phase.

In this case study are identified 3 design problems regarding the part, two related to the second block of geometric feature recognition, while the latest is related to the third block.

The first design issue is classified as critical and it affects the technological feasibility of the feature. This issue refers to the internal corners of "Feature_9 - SLOT_1" which must be rounded in milling processes. Rounded corner issue is divided in three rules in function of radius of the pocket/contours edge (r) and the ratio between this radius and pocket/contours thickness (s). The rule is classified as critical if the radius is zero and is classified as warning or information in function of the r/s ratio (warning: r <= s/6; information r <= s/4).

The use of rounded internal corners provides a series of advantages including a lower concentration of stress but also all fewer machine operations, time savings and reduction of processing waste. Indeed, sharp internal edges cannot be obtained by milling, and they require more complicated and expensive technologies such as Electrical Discharge Machining (EDM).

The second and third design issues are classified as warning since they do not negatively affect component manufacturability but generate waste of manufacturing time and cost.

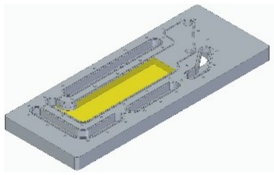
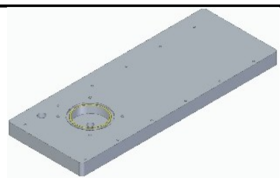
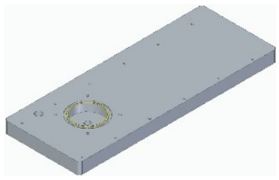
The second issue is related to the "Feature_5 – THREADED_HOLES_PATTERN_1", "Feature_6 – THREADED_HOLES_PATTERN_2" and "Feature_25 – THREADED_HOLES_PATTERN_3" holes which have flat bottom. Holes with a flat bottom require special tools instead of traditional ones such as the drill bit. This cause an increase in costs and times, and problems for any subsequent processing such as reaming. The drill bit makes holes with a conical bottom, more suitable for subsequent processing.

The third issue is related to the "Feature_3 – CYLINDRICAL_SLOT_1 vs. Feature_3 – CYLINDRICAL_SLOT_2". Narrow wall must be avoided, since cavities with too thin wall thicknesses are subjected to the stresses due to milling operations, are at high risk of breaking

Table 37 summarize the identified design problem.

Table 37 Design problems identified for the component (part 1 – plate original design)

Knowledge processing			Knowledge representation	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**

Class: Machining Type - level 1: Milling Type - level 2: N.A.	Class: N.A. Type: N.A.	Recognize: Pocket/contours thickness (s); Inner radius (r) PMI: N.A. Dimensions/geometry: r <= s/6	Action: Avoid Subject: Sharp internal corners Context: In milling operations	
Class: Machining Type - level 1: Milling Type - level 2: Drilling	Class: N.A. Type: N.A.	Recognize: Hole base angle (αwb) PMI: N.A. Dimensions/geometry: αwb > 90°	Action: Avoid Subject: Holes whit flat bottom Context: In drilling operations	
Class: Machining Type - level 1: N.A. Type - level 2: N.A.	Class: N.A. Type: N.A.	Recognize: Slot wall distance (ds); Slot height (hs) PMI: N.A. Dimensions/geometry: ds ≥ hs	Action: Avoid Subject: Slot wall distance (ds) lower than slot height (hs) Context: In machining process	

At the same time with DfM/DfA rules analysis, an analytical cost estimation has been done starting from the identified features (*Step 3: Cost analysis*).

Table 38 and Table 39 report the cost-sharing for the component manufacturing. Analysing the breakdown of cost can be notice that the rough and finish single slot end mill on "GASKET_SLOT_1", "GASKET_SLOT_2", "GASKET_SLOT_3", "GASKET_SLOT_4" and "GASKET_SLOT_5" are the most impacting in term of costs, while the others operation regarding the generic CNC machining center (tot.) impact only in a small percentage in the total costs. Is also important to notice that another important cost item is the sinker EDM on "Feature_9 - SLOT_1" needed to obtain the sharp internal corners.

Table 38 Cost analysis (part 1 – plate original design) – Raw material

Raw material informations	**Type [ad.]**	**Dimensions [mm]**	**Volume [dm^3]**	**Total [€]**
Raw material (net+waste)	*Sheet metal plate*	*351*137*25*	*1,20*	*13,78*

Table 39 Cost analysis (part 1 – plate original design) – Operations

Cost breakdown (bundles)	Setup/idle		Active		Total		Tooling [€]
	Cost [€]	Time [s]	Cost [€]	Time [s]	Cost [€]	Time [s]	
Milling with 3 axis CNC vertical (bundle) (tot.)	*31,34*	*2342*	*135,58*	*10710*	*180,72*	*13051*	-
Plasma cutting (tot.) (30 €/h):	*1,18*	*142*	*0,71*	*85*	*1,89*	*227*	-
→ Plasma cutting on Feature_1 – PAD_1: → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06	-	-	0,71	85	-	-	-
Generic CNC machining center (tot.) (45 €/h):	*22,71*	*1817*	*129,09*	*10327*	*151,80*	*12144*	-
→ Rough and finish perimetral end mill on Feature_1 – PAD_1 and Feature_2 - FILLET_1: → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06 → Cylindrical_face_02.01*4	-	-	0,72	58	-	-	-
→ Rough and finish face milling on Feature_1 – PAD_1: → Rectangular_face_01.01 → Rectangular_face_01.02	-	-	1,56	125	-	-	-
→ Drill and thread single hole on Feature_8 – THREADED_HOLE_2: → Cylindrical_face_08.01	-	-	0,14	11	-	-	-
→ Drill single hole on Feature_7 - HOLE_1: → Cylindrical_face_07.01	-	-	0,11	9	-	-	-
→ Counterbore single hole on Feature_3 – CYLINDRICAL_SLOT_1 → Circular_face_03.01 → Circular_face_03.02 → Cylindrical_face_03.01	-	-	1,02	82	-	-	-
→ Drill and thread multiple holes on Feature_25 – THREADED_HOLES_PATTERN_3: → Cylindrical_face_25.01*40	-	-	3,76	301	-	-	-
→ Drill and thread multiple holes on Feature_6 – THREADED_HOLES_PATTERN_2: → Cylindrical_face_06.01*4	-	-	0,36	29	-	-	-

→ Drill and thread multiple holes on Feature_5 – THREADED_HOLES_PATTERN_1: → Cylindrical_face_05.01*12	-	-	1,04	83	-	-	-
→ Rough and finish single slot end mill on Feature_20 – GASKET_SLOT_4: → Polygonal_face_20.02 → Polygonal_face_20.03 → Polygonal_face_20.04	-	-	12,48	998	-	-	-
→ Rough and finish single slot end mill on Feature_14 – GASKET_SLOT_2: → Polygonal_face_14.02 → Polygonal_face_14.03 → Polygonal_face_14.04	-	-	23,04	1843	-	-	-
→ Rough and finish single slot end mill on Feature_24 – GASKET_SLOT_5: → Polygonal_face_24.02 → Polygonal_face_24.03 → Polygonal_face_24.04	-	-	10,89	871	-	-	-
→ Rough and finish single slot end mill on Feature_12 – GASKET_SLOT_1: → Polygonal_face_12.02 → Polygonal_face_12.03 → Polygonal_face_12.04	-	-	41,40	3312	-	-	-
→ Rough and finish single slot end mill on Feature_18 – GASKET_SLOT_3: → Polygonal_face_18.02 → Polygonal_face_18.03 → Polygonal_face_18.04	-	-	20,84	1667	-	-	-
→ Rough single pocket end mill on Feature_19 - SLOT_4: → Poligonal_face_19.02 → Rectangular_face_19.01 → Rectangular_face_19.02 → Semicircular_face_19.01 → Semicircular_face_19.01	-	-	0,19	15	-	-	-
→ Rough single pocket end mill on Feature_9 - SLOT_1, Feature_10 – FILLET_2 and Feature_11 – FILLET_3: → Poligonal_face_09.02 → Rectangular_face_09.01 → Rectangular_face_09.02 → Rectangular_face_09.03 → Rectangular_face_09.04 → Rectangular_face_09.05 → Semicircular_face_09.01 → Cylindrical_face_10.01 → Cylindrical_face_11.01	-	-	4,35	348	-	-	-

→ Rough single pocket end mill on Feature_13 - SLOT_2: → Poligonal_face_13.02 → Rectangular_face_13.01 → Rectangular_face_13.02 → Semicircular_face_13.01 → Semicircular_face_13.01	-	-	0,33	26	-	-	-
→ Rough single pocket end mill on Feature_15 - SLOT_3, Feature_16 – FILLET_4 and Feature_17 – FILLET_5: → Poligonal_face_15.02 → Rectangular_face_15.01 → Rectangular_face_15.02 → Rectangular_face_15.03 → Rectangular_face_15.04 → Semicircular_face_15.01 → Semicircular_face_15.02 → Cylindrical_face_16.01 → Cylindrical_face_17.01	-	-	0,76	61	-	-	-
→ Rough single pocket end mill on Feature_21 - SLOT_5, Feature_22 – FILLET_6 and Feature_23 – FILLET_7: → Poligonal_face_21.02 → Rectangular_face_21.01 → Rectangular_face_21.02 → Rectangular_face_21.03 → Rectangular_face_21.04 → Semicircular_face_21.01 → Semicircular_face_21.02 → Cylindrical_face_22.01 → Cylindrical_face_23.01	-	-	0,29	23	-	-	-
→ Rough and finish single slot end mill on Feature_4 – CYLINDRICAL_SLOT_2: → Circular_face_04.02 → Cylindrical_face_04.01 → Cylindrical_face_04.02	-	-	5,83	466	-	-	-
EDM machine (bundle) (tot.) (70 €/h):	*7,45*	*383*	*5,78*	*297*	*13,23*	*680*	-
→ Sinker EDM on Feature_9 - SLOT_1: → Poligonal_face_09.02 → Rectangular_face_09.01 → Rectangular_face_09.02 → Rectangular_face_09.03	-	-	5,78	297	-	-	-

At this step, the previously highlighted issues will be fixed and then the 3D model is updated *(Step 5: Update 3D CAD Model)* by changing the model features according to the design guideline.

The changes consisted of:

- Feature_9 - SLOT_1: elimination of sharp corner using a 3,00 mm corner radius (Feature_26 - FILLET_8).
- Feature_5 – THREADED_HOLES_PATTERN_1: elimination of holes flat base substituted with a conical one (Feature_5 – THREADED_HOLES_PATTERN_1_MOD).
- Feature_6 – THREADED_HOLES_PATTERN_2: elimination of holes flat base substituted with a conical one (Feature_6 – THREADED_HOLES_PATTERN_2_MOD).
- Feature_25 – THREADED _HOLES_PATTERN_3: elimination of hole flat base substituted with a conical one (Feature_25 – THREADED_HOLES_PATTERN_3_MOD).
- Feature_3 – CYLINDRICAL_SLOT_1 vs. Feature_4 – CYLINDRICAL_SLOT_2: increasing of slot wall thickness from 1,5 mm to 3 mm in way to avoid a slot wall distance lower than wall thickness. The slot distance increasing is obtained through the modification of the internal and external diameter of Feature_4 – CYLINDRICAL_SLOT_2 (internal diameter from 52,50 mm to 55,50 mm and external diameter from 59,50 mm to 62,50 mm).

In Appendix B. Features of components analysed in case studies, Table 78, are summarized only the modified *features of 1° block*, in Table 79 are summarized the *features of 2° block* and in Table 80 are summarized *features of 3° block*. The component after machining operation will be the same of the original design, therefore, regarding the other features the information are the same represented in previous tables (Appendix B. Features of components analysed in case studies, Table 75 Table 76 and Table 77).

Table 40 and Table 41 reports the cost-sharing for the component manufacturing after the design update. Could be noticed that the costs for plasma cutting and CNC machining center are approximatively the same of the original design, while the EDM isn’t present in this updated design. Thanks to the elimination of sharp corner at the “Feature_9 - SLOT_1”, using a 3,00 mm corner radius (Feature_26 - FILLET_8) there is a cost reduction of 13,25€.

Table 40 Cost analysis (part 1 – plate updated design) – Raw material

Raw material informations	**Type [ad.]**	**Dimensions [mm]**	**Volume [dm^3]**	**Total [€]**
Raw material (net+waste)	*Sheet metal plate*	*351*137*25*	*1,20*	*13,78*

Table 41 Cost analysis (part 1 – plate updated design) – Operations

Cost breakdown (bundles)	**Setup/idle [€]**		**Active [€]**		**Total [€]**		**Tooling [€]**
	Cost [€]	**Time [s]**	**Cost [€]**	**Time [s]**	**Cost [€]**	**Time [s]**	
Milling with 3 axis CNC vertical (bundle) (tot.)	*23,92*	*1961*	*130,12*	*10438*	*154,14*	*12399*	-
Plasma cutting (tot operations) (30 €/h):	*1,18*	*142*	*0,71*	*85*	*1,89*	*227*	-
→ Plasma cutting on Feature_1 – PAD_1: → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06	-	-	0,71	85	-	-	-
Generic CNC machining center (tot operations) (45 €/h):	*22,74*	*1819*	*129,41*	*10353*	*152,15*	*12172*	-
→ Rough and finish perimetral end mill on Feature_1 – PAD_1 and Feature_2 - FILLET_1: → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06 → Cylindrical_face_02.01*4	-	-	0,72	58	-	-	-
→ Rough and finish face milling on Feature_1 – PAD_1: → Rectangular_face_01.01 → Rectangular_face_01.02	-	-	1,56	125	-	-	-

→	Drill and thread single hole on Feature_8 – THREADED_HOLE_2: → Cylindrical_face_08.01	-	-	0,14	11	-	-	-
→	Drill single hole on Feature_7 - HOLE_1: → Cylindrical_face_07.01	-	-	0,11	9	-	-	-
→	Counterbore single hole on Feature_3 – CYLINDRICAL_SLOT_1 → Circular_face_03.01 → Circular_face_03.02 → Cylindrical_face_03.01	-	-	1,02	82	-	-	-
→	Drill and thread multiple holes on Feature_25 – THREADED_HOLES_PATTERN_3_MOD: → Cylindrical_face_25.01*40	-	-	3,78	302	-	-	-
→	Drill and thread multiple holes on Feature_6 – THREADED_HOLES_PATTERN_2_MOD: → Cylindrical_face_06.01*4	-	-	0,36	29	-	-	-
→	Drill and thread multiple holes on Feature_5 – THREADED_HOLES_PATTERN_1_MOD: → Cylindrical_face_05.01*12	-	-	1,04	83	-	-	-
→	Rough and finish single slot end mill on Feature_20 – GASKET_SLOT_4: → Polygonal_face_20.02 → Polygonal_face_20.03 → Polygonal_face_20.04	-	-	12,48	998	-	-	-
→	Rough and finish single slot end mill on Feature_14 – GASKET_SLOT_2: → Polygonal_face_14.02 → Polygonal_face_14.03 → Polygonal_face_14.04	-	-	23,04	1843	-	-	-
→	Rough and finish single slot end mill on Feature_24 – GASKET_SLOT_5: → Polygonal_face_24.02 → Polygonal_face_24.03 → Polygonal_face_24.04	-	-	10,89	871	-	-	-
→	Rough and finish single slot end mill on Feature_12 – GASKET_SLOT_1: → Polygonal_face_12.02 → Polygonal_face_12.03 → Polygonal_face_12.04	-	-	41,40	3312	-	-	-
→	Rough and finish single slot end mill on Feature_18 – GASKET_SLOT_3: → Polygonal_face_18.02 → Polygonal_face_18.03 → Polygonal_face_18.04	-	-	20,84	1667	-	-	-

→ Rough single pocket end mill on Feature_19 - SLOT_4: → Poligonal_face_19.02 → Rectangular_face_19.01 → Rectangular_face_19.02 → Semicircular_face_19.01 → Semicircular_face_19.01	-	-	0,19	15	-	-	-
→ Rough single pocket end mill on Feature_9 - SLOT_1, Feature_10 – FILLET_2, Feature_11 – FILLET_3 and Feature_26 – FILLET_8: → Poligonal_face_09.02 → Rectangular_face_09.01 → Rectangular_face_09.02 → Rectangular_face_09.03 → Rectangular_face_09.04 → Rectangular_face_09.05 → Semicircular_face_09.01 → Cylindrical_face_10.01 → Cylindrical_face_11.01 → Cylindrical_face_26.01*2	-	-	4,33	346	-	-	-
→ Rough single pocket end mill on Feature_13 - SLOT_2: → Poligonal_face_13.02 → Rectangular_face_13.01 → Rectangular_face_13.02 → Semicircular_face_13.01 → Semicircular_face_13.01	-	-	0,33	26	-	-	-
→ Rough single pocket end mill on Feature_15 - SLOT_3, Feature_16 – FILLET_4 and Feature_17 – FILLET_5: → Poligonal_face_15.02 → Rectangular_face_15.01 → Rectangular_face_15.02 → Rectangular_face_15.03 → Rectangular_face_15.04 → Semicircular_face_15.01 → Semicircular_face_15.02 → Cylindrical_face_16.01 → Cylindrical_face_17.01	-	-	0,76	61	-	-	-
→ Rough single pocket end mill on Feature_21 - SLOT_5, Feature_22 – FILLET_6 and Feature_23 – FILLET_7: → Poligonal_face_21.02 → Rectangular_face_21.01 → Rectangular_face_21.02 → Rectangular_face_21.03 → Rectangular_face_21.04 → Semicircular_face_21.01 → Semicircular_face_21.02 → Cylindrical_face_22.01	-	-	0,29	23	-	-	-

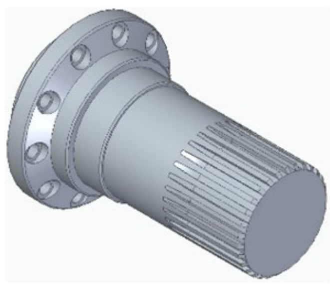
→ Cylindrical_face_23.01							
→ Rough and finish single slot end mill on Feature_4 – CYLINDRICAL_SLOT_2_MOD: → Circular_face_04.02 → Cylindrical_face_04.01 → Cylindrical_face_04.02	-	-	6,14	491	-	-	-

5.2.6. *Case study - Machining (part 2 – turned shaft)*

Using the same procedure as in the first case study, the second part analysed is a shaft manufactured by turning and milling with motorized lathe process. The part is manufactured in C40 carbon steel with a production volume of 5000 components and a batch size of 50 parts.

General roughness of the part is 3,2 µm and the general tolerance could be classified as medium (IT7).

In Figure 35 are show the component and its properties.



→ Material: C40 Carbon Steel
→ Production volume: 5000
→ Batch size: 50
→ General roughness: 3,2 µm
→ General tolerances: medium (IT7)

Figure 35 Machining (part 2 – turned shaft)

Following the same methodology of the previous case study (Section 5.2.5), in Appendix B. Features of components analysed in case studies, Table 81, are summarized the *physical and material features of the model (Features of 1° block)* while in Table 82 are summarized the *manufacturing and material features of the model (isolated) (Features of 2° block)*. Block 3 (Manufacturing and material features of the model in relation with other feature/s (interrelated for part)) and block 4 (Manufacturing and material features of the model in relation with feature/s of other model/s (interrelated for assembly)) in this case study are not interested in the analysis.

Once identified the features belonging to the blocks, DfM/DfA rules analysis was performed and mathematical equations characterizing each DfM rule are checked with the feature identified in the feature recognition phase.

In this case study are identified 2 design problems regarding the part, all of them related to the second block of geometric feature recognition.

The first design issue is classified as warning and it refers to the "Feature_6 - TRUNCATED CONE_1" and "Feature_10 - HOLE CIRCULAR PATTERN_1". The issue is caused by the partial holes which do not involve at least 80% of material area. Making partial holes causes loss of tool control, deviation from the hole axis and consequent damage. If these holes cannot be avoided, the surface affected by the hole must be 80% of the material to be machined.

The second issue is classified as warning since it does not negatively affect component manufacturability but generate waste of manufacturing time and cost.

The second issue is already related to the "Feature_6 - TRUNCATED CONE_1" and "Feature_10 - HOLE CIRCULAR PATTERN_1", but in this case is caused by the surface inclination. In the case of holes (through or blind) on curved surfaces, may arise problems of control of the tool and is not guaranteeing the precision required in the operation. For this reason, it is good practice level the surface and make the surface affected by the hole flat. Furthermore, in the case of through holes, the exit hole in the curved surface could have irregular burrs difficult to remove.

Table 42 summarize the identified design problem.

Table 42 Design problems identified for the component (part 2 – shaft original design)

Knowledge processing			**Knowledge representation**	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**

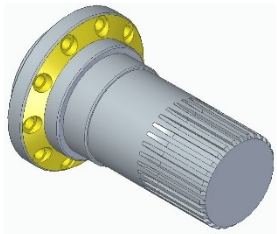
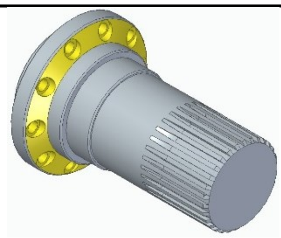
Class: Machining Type - level 1: Milling Type - level 2: Drilling	Class: All materials Type: N.A.	Recognize: Hole cylinder area (A) Hole radius (R) Hole height (H) PMI: N.A. Dimensions/geometry: $A \geq 2\pi * R * H * 0{,}8$	Action: Avoid Subject: Partial holes which do not involve at least 80% of the area of the material to be processed Context: In drilling operations	
Class: Machining Type - level 1: Milling Type - level 2: Drilling	Class: All materials Type: N.A.	Recognize: Hole circular surface (A1) Hole circular surface (A2) Hole radius (R) PMI: N.A. Dimensions/geometry: $A1 \neq A2 \neq \pi R^2$	Action: Avoid Subject: Starting hole from the non-flat surface Context: In drilling operations	

Table 43 and Table 44 report the cost-sharing for the component manufacturing. Analysing the breakdown of costs can be notice that the rough side and slot milling on Feature_16 - SPLINED PROFILE, rough external turning on Feature_4 - CYLINDER_3 and Feature_6 - TRUNCATED CONE_14 are the most impacting in term of costs, while the others operation regarding the motorized lathe (tot.) impact only in a small percentage in the total costs. Is also important to notice that another important costs item are the grinding operations on Feature_16 - SPLINED PROFILE and Feature_1- CYLINDER_1 needed to obtain the narrow-required roughness and tolerances on these features.

Table 43 Cost analysis (part 2 – shaft original design) – Raw material

Raw material informations	Type [ad.]	Dimensions [mm]	Volume [dm^3]	Total [€]
Raw material (net+waste)	*Round bar*	*250*250*333*	*16,35*	*110,16*

Table 44 Cost analysis (part 2 – shaft original design) – Operations

Cost breakdown (bundles)	Setup/idle	Active	Total	

	Cost [€]	Time [s]	Cost [€]	Time [s]	Cost [€]	Time [s]	Tooling [€]
Turning and milling with motorized lathe (bundle) (tot.)	*12,70*	*887*	*212,59*	*15447*	*225,29*	*16334*	-
Bandsaw cutting (tot.) (25 €/h):	*0,08*	*12*	*13,96*	*2010*	*14,04*	*2022*	-
→ Bandsaw cutting on Feature_1 – CYLINDER_1: → Circular_face_01.02	-		13,96	2010	-		-
Motorized lathe (tot.) (53 €/h):	*5,48*	*372*	*173,76*	*11803*	*179,24*	*12175*	-
→ Rough and finish face milling on Feature_11 - CYLINDER_5: → Circular_face_11.01	-		2,10	143	-		-
→ Rough and finish external turning on Feature_11 - CYLINDER_5 and Feature_7 - CYLINDER_4: → Circular_face_07.01 → Cylindrical_face_11.01	-		4,27	290	-		-
→ Rough external conical turning on Feature_12 - CHAMFER_5: → Conical_face_12.01	-		0,06	4	-		-
→ Rough external turning on Feature_7 - CYLINDER_4: → Cylindrical_face_07.01	-		14,75	1002	-		-
→ Rough external turning on Feature_4 - CYLINDER_3 and Feature_6 - TRUNCATED CONE_14: → Cylindrical_face_04.01 → Conical_face_06.01	-		21,54	1463	-		-
→ Rough external turning on Feature_4 - CYLINDER_3 and Feature_2 - CYLINDER_2: → Circular_face_04.02 → Cylindrical_face_02.01	-		6,27	426	-		-
→ Rough and finish external turning on Feature_1- CYLINDER_1: → Circular_face_01.01	-		3,44	234	-		-
→ Rough external conical turning on Feature_8 - CHAMFER_3: → Conical_face_08.01	-		0,08	5	-		-
→ Rough external conical turning on Feature_9 - CHAMFER_4: → Conical_face_09.01	-		0,08	5	-		-
→ Rough external conical turning on Feature_5 - CHAMFER_2: → Conical_face_05.01	-		0,06	4	-		-
→ Rough external conical turning on Feature_2 - CHAMFER_1: → Conical_face_02.01	-		0,05	3	-		-

→ Rough and finish internal turning on Feature_13 - SLOT_1: → Circular_face_13.02 → Cylindrical_face_13.01	-		1,36	92	-		-
→ Rough internal conical turning on Feature_14 - CHAMFER_6: → Conical_face_14.01	-		0,06	4	-		-
→ Rough and finish internal turning on Feature_15 - SLOT_2: → Circular_face_15.02 → Cylindrical_face_15.01	-		2,93	199	-		-
→ Rough side and slot milling on Feature_16 - SPLINED PROFILE: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30	-		101,29	6880	-		-
→ Drill multiple holes on Feature_10 - HOLE CIRCULAR PATTERN: → Circular_face_10.01*10 → Circular_face_10.02*10 → Circular_face_10.03*10 → Cilindrical_face_10.01*10 → Cilindrical_face_10.02*10	-		15,31	1040	-		-
Tangential grinding machine (tot.) (50 €/h):	*6,24*	*449*	*11,31*	*814*	*17,55*	*1263*	-
→ Slot grinding on Feature_16 - SPLINED PROFILE: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30	-		*11,31*	*814*	-		-
External round grinding machine (tot.) (60 €/h):	*0,90*	*54*	*13,67*	*820*	*14,57*	*874*	-
→ Rough grinding on Feature_1- CYLINDER_1: → Circular_face_01.01	-	887	13,67	820,2	-		-

Then, starting from the previous analyses (3D Model Data, Feature recognition and extraction DfM/DfA analysis and Cost estimation) and from the report generated, the highlighted issues will be fixed and then the 3D model is updated by changing the model features according to the design guidelines.

The changes consisted of:

- Feature_6 - TRUNCATED CONE_1: elimination.
- Feature_4 - CYLINDER_3_MOD: increasing of height to 24,08 mm to 25 mm.
- Feature_7 - CYLINDER_4_MOD: increasing of height to 25 mm to 35 mm.
- Feature_10 - HOLE CIRCULAR PATTERN_MOD: changing of spotface height (10,92 mm to 10 mm).

In Appendix B. Features of components analysed in case studies, Table 83, are summarized only the modified *physical and material features of the updated model (Features of 1° block)* while in Table 84 are summarized the *manufacturing and material features of the updated model (isolated) (Features of 2° block)*. It's important to notice that the other features are the same represented in previous tables (Table 81 and Table 82)

Table 45 and Table 46 report the cost-sharing for the component manufacturing after the design update. Analysing the breakdown of cost can be notice a decreasing in costs of "motorized lathe machine" operations (170,52 € vs. 173,76 €). The costs of the other machines remained the same of the original design.

Table 45 Cost analysis (part 2 – shaft updated design) – Raw material

Raw material informations	**Type [ad.]**	**Dimensions [mm]**	**Volume [dm^3]**	**Total [€]**
Raw material (net+waste)	*Round bar*	*250*250*333*	*16,35*	*110,16*

Table 46 Cost analysis (part 2 – shaft updated design) – Operations

Cost breakdown (bundles)	**Setup/idle**		**Active**		**Total**		**Tooling [€]**
	Cost [€]	**Time [s]**	**Cost [€]**	**Time [s]**	**Cost [€]**	**Time [s]**	
Turning and milling with motorized lathe (bundle) (tot.)	*12,62*	*882*	*209,46*	*15226*	*222,08*	*16108*	-
Bandsaw cutting (tot.) (25 €/h):	*0,08*	*12*	*13,96*	*2010*	*14,04*	*2022*	-
→ Bandsaw cutting on Feature_1 – CYLINDER_1: → Circular_face_01.02	-		13,96	2010	-		-
Motorized lathe (tot.) (53 €/h):	*5,4*	*367*	*170,52*	*11582*	*175,92*	*11949*	-
→ Rough and finish face milling on Feature_11 - CYLINDER_5: → Circular_face_11.01	-		1,09	74	-		-
→ Rough external turning on Feature_4 - CYLINDER_3_MOD and Feature_7 - CYLINDER_4_MOD: → Cylindrical_face_04.02 → Circular_face_07.01	-		32,55	2211	-		-
→ Rough external turning on Feature_2 - CYLINDER_2 and Feature_4 - CYLINDER_3_MOD: → Circular_face_02.01 → Cylindrical_face_07.01	-		6,27	426	-		-
→ Rough and finish external turning on Feature_1- CYLINDER_1: → Circular_face_01.01	-		3,44	234	-		-
→ Rough external conical turning on Feature_5 - CHAMFER_2: → Conical_face_05.01	-		0,06	4	-		-
→ Rough external conical turning on Feature_2 - CHAMFER_1: → Conical_face_02.01	-		0,05	3	-		-
→ Rough external turning on Feature_7 - CYLINDER_4_MOD: → Cylindrical_face_07.01	-		3,06	208	-		-
→ Rough and finish external turning on Feature_11 - CYLINDER_5 and Feature_7 - CYLINDER_4_MOD: → Circular_face_07.01 → Cylindrical_face_11.01	-		2,89	196	-		-
→ Rough external conical turning on Feature_9 - CHAMFER_4: → Conical_face_09.01	-		0,08	5	-		-

→ Rough external conical turning on Feature_8 - CHAMFER_3: → Conical_face_08.01	-		0,08	5	-		-
→ Rough external conical turning on Feature_12 - CHAMFER_5: → Conical_face_12.01	-		0,06	4	-		-
→ Rough and finish internal turning on Feature_13 - SLOT_1: → Circular_face_13.02 → Cylindrical_face_13.01	-		1,36	92	-		-
→ Rough internal conical turning on Feature_14 - CHAMFER_6: → Conical_face_14.01	-		0,06	4	-		-
→ Rough and finish internal turning on Feature_15 - SLOT_2: → Circular_face_15.02 → Cylindrical_face_15.01	-		2,93	199	-		-
→ Rough side and slot milling on Feature_16 - SPLINED PROFILE: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30	-		101,29	6880	-		-
→ Drill multiple holes on Feature_10 - HOLE CIRCULAR PATTERN: → Circular_face_10.01*10 → Circular_face_10.02*10 → Circular_face_10.03*10 → Cilindrical_face_10.01*10 → Cilindrical_face_10.02*10	-		15,25	1036	-		-
Tangential grinding machine (tot.) (50 €/h):	*6,24*	*449*	*11,31*	*814*	*17,55*	*1263*	-
→ Slot grinding on Feature_16 - SPLINED PROFILE: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30	-		11,31	814	-		-

External round grinding machine (tot.) (60 €/h):	*0,90*	*54*	*13,67*	*820*	*14,57*	*874*	-
→ Rough grinding on Feature_1-CYLINDER_1: → Circular_face_01.01	-		13,67	820	-		-

5.3. Case study – Assembly

The assembly case study is divided in 6 sub-sections:

- Section 5.3.1 presents a brief introduction of the assembly process.
- Section 5.3.2 is focused on the cost structure of the assembly process.
- Section 5.3.3 presents the cost estimation methodology related to the assembly process.
- Section 5.3.4 describes the design rules involved in assembly.
- Section 5.3.5 presents the first assembly analysed (Centrifugal pump).
- Section 5.3.6 presents the second assembly analysed (Jib crane).

5.3.1. Assembly introduction

In this section the case study is focused on assembly process. Assembly could be divided in two main groups:

- Removable assemblies: bolted/rivetted.
- Permanent assemblies: welded and adhesively bonded.

The assembly process involves the placement and fastening of one or more parts in or on another. Often, the operation is manual, although increasingly it is being performed by automatic equipment, particularly when production volumes are large.

Bolted/rivetted mechanical assemblies may consist of only two parts (e.g., a kitchen saltshaker) or thousands of parts (e.g., an automobile). They can have components of metal, wood, rubber, paper, plastics, ceramics, or a combination of these materials.

In case of permanent assembly, welding consists in a homogeneous joint produced through the melting and fusing together of adjacent portions of the originally separate pieces. The final welded joint has unit strength approximately equal to that of the base material. Intense heat is applied to the joint by means of an electric arc that passes between a welding rod and the work.

Adhesives are compounds capable of holding objects together in a useful fashion by surface attraction. Adhesive joints are often less costly, more easily produced, or better able to resist fatigue and corrosion than mechanical fasteners or welds. In some cases, adhesives are the only practical means of assembly. Although adhesively bonded joints can be engineered for high strength, adhesive bonding may not be suitable if strength requirements or temperature variations are extreme. Other fastening methods also may be indicated if provision must be made for disassembly and reassembly of the component. (Bralla, 1998)

5.3.2. Assembly process costs structure

According to Figure 18 the workflow for defining an assembly process begins by first selecting the *assembly environment* (Table 47).

For the assembly process, the production volume of the assembly and the need to be able to disassemble it in the future define the assembly strategy. In-fact we could have a permanent link between components (e.g. welding or gluing) or a removable connection between the parts of the assembly (e.g. bolted/rivetted). At the same time the production volume affects the methods of assembly of components (e.g. manual, automatic or robotized) (Section 2.4.1.2).

Table 47. Assembly strategies

Operations bundles	**Bundles validity rules**	**Bundles priority rules**
Manual bolted/rivetted	`N/A (no alternative bundle available)`	`IF (Production.Volume ≤ 100) THEN Score = 10 ELSE Score = 5`
Automatized bolted/rivetted	`Production.Volume ≥ 100`	`IF (100 ≤ Production.Volume ≤ 500) THEN Score = 10 ELSE Score = 5`
Robotized bolted/rivetted	`Production.Volume ≥ 200`	`IF (Production.Volume ≥ 500) THEN Score = 10 ELSE Score = 5`

Manual welded	`NOT (Piece.Material = "Plastic")`	`N/A (no alternative bundle available)`
Automatized welded	`NOT (Piece.Material = "Plastic")`	`N/A (no alternative bundle available)`
Robotized welded	`NOT (Piece.Material = "Plastic")`	`N/A (no alternative bundle available)`
Adhesively bonded	`N/A (no alternative bundle available)`	`N/A (no alternative bundle available)`
Manual welded + manual bolted	`NOT (Piece.Material = "Plastic")`	`N/A (no alternative bundle available)`
Adhesively bonded + manual bolted	`N/A (no alternative bundle available)`	`N/A (no alternative bundle available)`
Turning with Multitasking lathe	`Assembly.TurningRequest`	`N/A (no alternative bundles available)`
Turning + Milling	`Assembly.Turning+MillingRequest`	`N/A (no alternative bundles available)`
Non-destructive test	`Piece.NDTRequested`	`N/A (no alternative bundles available)`
Painting	`Piece.PaintRequest`	`N/A (no alternative bundles available)`
Chrome plating	`Piece.ChromeRequest`	`N/A (no alternative bundles available)`

Table 48 shows an analysis of an assembly manual bolted/rivetted. In function of assembly and components weights the number of people needed in assembly varies. In case of manual bolted/rivetted assembly the operation is unique and only the workers required change.

Table 48 "Manual bolted assembly" operations bundle

Operations	**Operation validity rules**	**Assembly parameters**
Manual bolted/rivetted with one person	`Components.Weight` $\leq$ `10 kg`	`Operation.Weight = Components.Weight`
Manual bolted/rivetted with two people	`Components.Weight` $\leq$ `20 kg`	`Operation.Weight = Components.Weight`
Manual bolted/rivetted with	`Components.Weight` $\geq$ `20 kg`	`Operation.Weight = Components.Weight`

two or more people and specific tools		

5.3.3. Assembly cost calculation

Once the operations that constitute the overall process are established, the following variables are calculated for each operation:

- Operation, setup and idle time for labour.
- Equipment required.
- Solid, liquid and gas consumables consumption.
- Energy consumption for the equipment used.

The cost of machined parts is calculated by first summing the cost of each operation included within the *Manual bolted assembly* bundle (Eq. 7).

$$C_{manual\ bolted\ assembly(bundle)} = C_{manual\ bolted/rivetted\ with\ one\ person} \quad (7)$$

The cost of the overall assembly process is calculated by summing the cost of each bundle required (Eq. 8).

$$C_{assembly} = C_{manual\ bolted\ assembly(bundle)} + C_{non-destructive\ test} + C_{painting} + C_{chrome\ plating} \quad (8)$$

5.3.4. Assembly design rules

Very often, the most significant benefits with design for manufacturability (DFM) come from designing for assembly (DFA), simplifying the product so that it has fewer parts and its assembly is easier and faster.

In case of bolted/rivetted assemblies each component of assembly should be designed to reduce the number of manufacturing and assembly operations to a minimum. Reducing the number of parts is the first approach in the improvement of an assembly, far overshadowing in impact any other changes in design that improve manufacturability and further other important design objectives. Other recommendations are standardizing the designs (e.g. standard fasteners), the use of modular subassemblies, the use of not-flexible parts, the use of easily handled parts, etc..

Also for welded assemblies the number of part should be maintained low as possible. Other design examples of improvements for welded assemblies are the maintaining an easy access of the welding nozzle, the designing for assembly to maintain the welded joint as horizontal and avoid the welding of different materials.

In case of adhesive joint is recommended a design for shear, tension and compression but not cleavage or peel. Adhesive bonds resist shear, tensile, and compressive forces better than cleavage or peel. Other design rules are focused on type of surface characteristics (guarantee clean and smooth surfaces for joints).

A set of rules dedicated for assembly (bolted and rivetted in particular) are reported in appendix. (Table 66) It is worth noting that this is not a complete list of rules but only part of it.

5.3.5. Case study - Assembly (assembly 1 – centrifugal pump)

The first assembly analysed is a centrifugal pump. The production strategy used is "manual bolted assembly". The assembly is composed by 68 parts components (parts) and one product (assembly) with a production volume of 10000 components and a batch size of 100 parts. In Figure 36 is shown the exploded view and in Table 49 is shown the BoM of the case study.

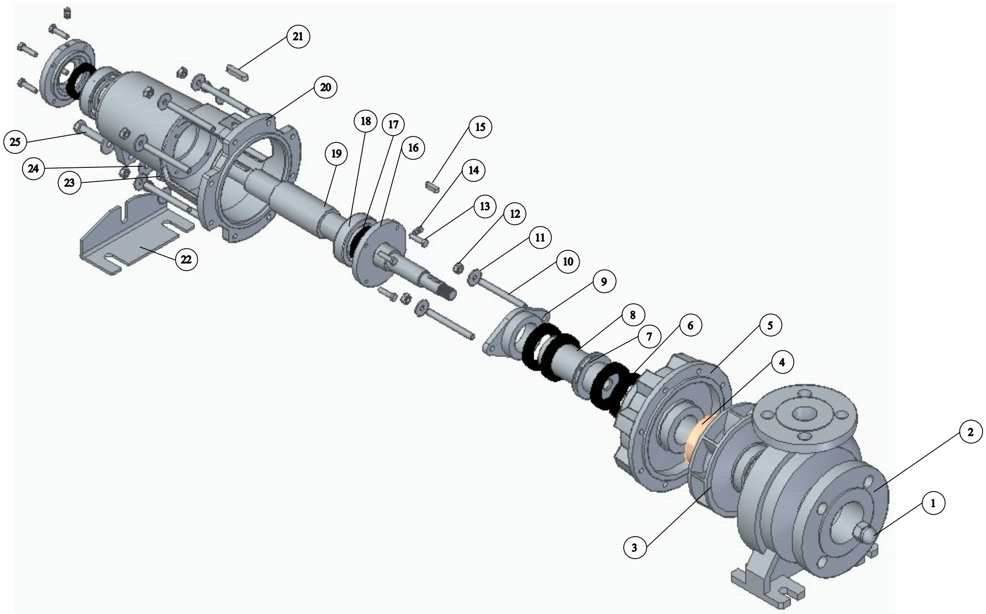


Figure 36 Exploded view (assembly 1 - centrifugal pump original design)

Table 49 Bill of material (assembly 1 - centrifugal pump original design)

No.	Component	Quantity	Material
1	Cup nut M16	1	39NiCrMo3
2	Casing	1	Grey cast iron
3	Impeller	1	Grey cast iron
4	Wear ring	2	CuAl10Fe5Ni5

5	Coupling	1	Grey cast iron
6	Packing set	4	Rubber
7	Lantern ring	1	Aisi 316
8	Seal chamber	1	Aisi 316
9	Packing gland	1	Grey cast iron
10	Stud ISO 888 M8 x 85	10	39NiCrMo3
11	Plain washer ISO 7089 M8	10	Aisi 316
12	Nut DIN ISO 4032 M8	10	39NiCrMo3
13	Hex head screw ISO 4017 M6 x 25	8	39NiCrMo3
14	Taper type grease nipple DIN 71412 A - M6	2	39NiCrMo3
15	Key IS 2048 6 x 6 x 22	1	Aisi 316
16	Bearing cover	2	Aisi 316
17	Lip seal DIN 3760 A 35 x 50 x 7	2	NDR rubber
18	7207 Radial ball bearing	2	Bearing steel
19	Shaft	1	Aisi 316
20	House bearing	1	Grey cast iron
21	Key IS 2048 7 x 8 x 36	1	Aisi 316
22	Support	1	Aisi 316
23	Nut DIN ISO 4032 M10	1	39NiCrMo3
24	Plain washer ISO 7089 M10	2	Aisi 316
25	Hex head screw ISO 4016 M10 x 45	1	39NiCrMo3

Once identified the features of the parts and the assembly ("*Step 1: 3D CAD Model*" (Figure 8) and "*Step 2: Feature recognition and extraction*"), DfM/DfA rules analysis was performed as described in the methodology workflow (S*tep 4: DfM/DfA analysis*) (Figure 8). For the assembly analysis, only the set of DfA rules was selected (Appendix A. DfM/DfA rules repositories, Table 66). Then, mathematical equations characterizing each DfA rule are checked with the feature identified in the feature recognition phase.

In this case study are identified 11 design problems regarding the assembly, related to the fourth block of geometric feature recognition.

The first design issue is classified as critical and it affects the assembly feasibility. In particular, the issue refers to a minimum diameter gap required between screw and hole of non-threaded parts of bolted connection. This minimum gap is necessary to facilitate screw insertion and avoid possible stuck in manual assembly operations. A minimum diameter gap varies in function of screw dimensions, and it can be assessed by the difference between the hole diameter and the external screw diameter. This issue involved the following features:

- Feature_1 - HOLE CIRCULAR PATTERN (Bearing cover) and Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25). Minimum required diameter gap: 0,4 mm. Actual diameter gap: 0 mm.
- Feature_1 - HOLE BASE (House bearing) and Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45). Minimum required diameter gap: 0,5 mm. Actual diameter gap: 0 mm.
- Feature_2 - HOLE CIRCULAR PATTERN (House bearing), Feature_1 - HOLE CIRCULAR PATTERN (Coupling) and Feature_1 – CYLINDRICAL PAD (Stud ISO 888 M8 x 85). Minimum required diameter gap: 0,4 mm. Actual diameter gap: 0 mm.
- Feature_1 - HOLE LINEAR PATTERN (Packing gland) and Feature_1 – CYLINDRICAL PAD (Stud ISO 888 M8 x 85). Minimum required diameter gap: 0,4 mm. Actual diameter gap: 0 mm.

The second design issue is classified as warning since it doesn't affect the assembly feasibility but increase time and difficulty. This issue is referred to the absence of bevels around the holes to facilitate screw insertion. In order to make easier the screw insertion, it is always advisable to provide entry holes with chamfered/countersunk ends. This facilitates the insertion and entry of the screw into the fixing hole itself.

This issue involved the following features:

- Feature_1 – HOLE CIRCULAR PATTERN (Bearing cover), Feature_3 – THREADED HOLE CIRCULAR PATTERN (House bearing) and Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25).

- Feature_1 – HOLE BASE (House bearing) and Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45).

- Feature_2 – HOLE CIRCULAR PATTERN (House bearing), Feature_1 – HOLE CIRCULAR PATTERN (Coupling), Feature_1 – HOLE CIRCULAR PATTERN (Casing) and Feature_1 – CYLINDRICAL PAD (Stud ISO 888 M8 x 85).

- Feature_1 – HOLE LINEAR PATTERN (Packing gland), Feature_2 – THREADED HOLE LINEAR PATTERN (Coupling) and Feature_1 – CYLINDRICAL PAD (Stud ISO 888 M8 x 85).

The third design issue is classified as information and is referred to the use of combined fasteners, e.g. screws with integrated washers to reduce assembly times.

This issue involved the following components:

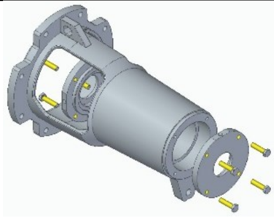
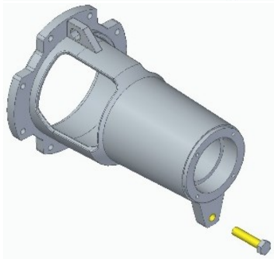
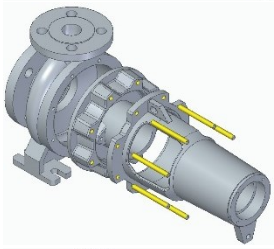
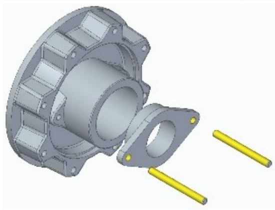
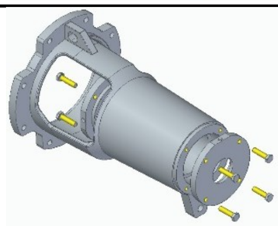
- Stud ISO 888 M8 x 85, plain washer ISO 7089 M8 and nut DIN ISO 4032 M8 in the connection between casing (2) and coupling (5).

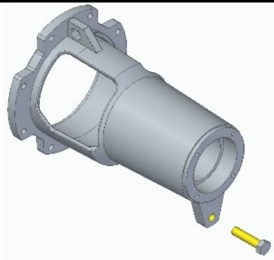
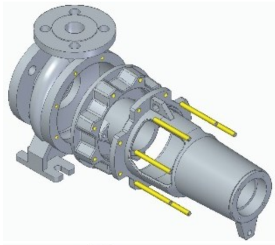
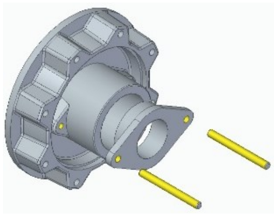
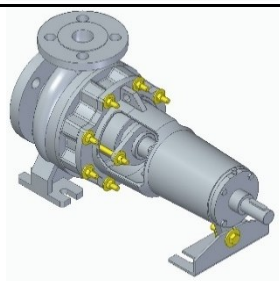
- Stud ISO 888 M8 x 85, plain washer ISO 7089 M8 and nut DIN ISO 4032 M8 in the connection between packing gland (9) and coupling (5).

- Nut DIN ISO 4032 M10, plain washer ISO 7089 M10 and hex head screw ISO 4016 M10 x 45 in the connection between house bearing (20) and support (22).

Table 50 summarize the identified design problem.

Table 50 Design problems identified for the assembly (assembly 1 - centrifugal pump original design)

Knowledge processing			Knowledge representation	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**
Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Hole diameter (Dh); Screw diameter (Ds); Diameter gap (G = Dh - Ds) PMI: N.A. Dimensions/geometry: $G \geq f(Ds)$ Ah = As	Action: Guarantee Subject: Minimum diameter gap between screw and hole of non-threaded parts Context: In the manual assembly process of bolted components	   
Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Hole chamfer; Screw chamfer PMI: N.A. Dimensions/geometry: N.A.	Action: Guarantee Subject: Chamfered/countersunk insertion holes and chamfered screw ends Context: In the manual assembly process of bolted components	

				  
Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Screw; Washer; Nut PMI: N.A. Dimensions/geometry: N.A.	Action: Prefer Subject: The use of combined fasteners Context: In the manual assembly process of bolted components	

In Appendix B. Features of components analysed in case studies, Table 85, Table 86, Table 87, Table 88, Table 89, Table 90, Table 91, Table 92, Table 93, Table 94 and Table 95 are summarized the features of the parts of the assembly involved in design issues.

At the same time with DfM/DfA rules analysis, an analytical cost estimation has been done starting from the identified features (*Step 3: Cost analysis*). It is important to notice that the assembly cost estimation is not applicable in the original design due to the interference between screws and holes of the parts. Thus, it is not possible to insert the screws and complete the assembly.

At this step, the previously highlighted issues will be fixed and then the 3D model is updated *(Step 5: Update 3D CAD Model)* by changing the model features according to the design guideline.

The changes consisted of:

- Feature_2 – CHAMFER CIRCULAR PATTERN: new feature needed for an easier screw insertion.
- Feature_2 - HOLE CIRCULAR PATTERN (House bearing): increasing of hole diameters from 8 mm to 8,4 mm (Feature_2 - HOLE CIRCULAR PATTERN_MOD (House bearing)).
- Feature_5 – CHAMFER HOLE CIRCULAR PATTERN: new feature needed for an easier screw insertion.
- Feature_1 - HOLE CIRCULAR PATTERN (Coupling): increasing of hole diameters from 8 mm to 8,4 mm (Feature_1 - HOLE CIRCULAR PATTERN_MOD (Coupling)).
- Feature_3 – CHAMFER HOLE CIRCULAR PATTERN: new feature needed for an easier screw insertion.
- Feature_1 - HOLE BASE (House bearing): increasing of hole diameters from 10 mm to 10,5 mm (Feature_1 - HOLE BASE_MOD (House bearing)).
- Feature_4 – CHAMFER HOLE BASE: new feature needed for an easier screw insertion.
- Feature_1 - HOLE CIRCULAR PATTERN (Bearing cover): increasing of hole diameters from 6 mm to 6,6 mm (Feature_1 - HOLE CIRCULAR PATTERN_MOD (Bearing cover)).

- Feature_2 – CHAMFER CIRCULAR PATTERN: new feature needed for an easier screw insertion.

- Feature_1 - HOLE LINEAR PATTERN (Packing gland): increasing of hole diameters from 8 mm to 8,5 mm (Feature_1 - HOLE LINEAR PATTERN (Packing gland_MOD).

- Feature_2 – CHAMFER HOLE LINEAR PATTERN: new feature needed for an easier screw insertion.

- Replacement of the nuts (Nut DIN ISO 4032 M8), washers (Plain washer ISO 7089 M8) and studs (Stud ISO 888 M8 x 85) with flanged screws (Hex head screw DIN 6921 M8 x 65 and Hex head screw DIN 6921 M8 x 60).

- Replacement of the nut (Nut DIN ISO 4032 M10), washer (Plain washer ISO 7089 M10) and screw (Hex head screw ISO 4016 M10 x 45) with a flanged nut (Nut DIN ISO 4161 M10) and a flanged screw (Hex head screw DIN 6921 M10 x 40)).

In Appendix B. Features of components analysed in case studies, Table 96, Table 97, Table 98, Table 99, Table 100, Table 101, Table 102, Table 103, Table 104 and Table 105 are summarized only the modified *features of 1° block* and the *features of 2° block* of the modified parts. In Table 106 are summarized *features of 4° block*.

Table 51 reports the cost-sharing for the assembly after the design update. Could be noticed that the major costs are related to the screw insertion and bearing mounting (1,47 € + 4,40 €+ 4,40 € +1,10 €).

Table 51 Cost analysis (assembly 1 – centrifugal pump updated design)

List of operations		Cost [€]	Time [s]
→	7207 Radial ball bearing positioning, alignment and mounting with Shaft and House bearing (x2) (30 €/h)	1,47	177
→	Lip seal DIN 3760 A 35 x 50 x 7 positioning, alignment and mounting with Shaft (x2) (30 €/h)	0,10	12
→	Bearing cover positioning, alignment and mounting with House bearing and Shaft (x2) (30 €/h)	0,10	12
→	Hex head screw ISO 4017 M6 x 25 positioning, alignment and screwing with Bearing cover and House bearing (x8) (30 €/h)	4,40	528
→	Taper type grease nipple DIN 71412 A - M6 positioning, alignment and screwing with Bearing cover (x2) (30 €/h)	1,10	132
→	Packing set positioning, alignment and mounting with Seal chamber (x4) (30 €/h)	0,20	24
→	Seal chamber positioning, alignment and mounting with Shaft (30 €/h)	0,05	6
→	Lantern ring positioning, alignment and mounting with Seal chamber (30 €/h)	0,05	6
→	Packing gland positioning, alignment and mounting with Shaft (30 €/h)	0,05	6
→	Wear ring positioning, alignment and mounting with Impeller (30 €/h)	0,05	6
→	Coupling positioning and alignment with House bearing and Shaft (30 €/h)	0,05	6
→	Key IS 2048 6 x 6 x 22 positioning, alignment and mounting with Shaft (30 €/h)	0,05	6
→	Impeller positioning, alignment and mounting with Shaft and Coupling (30 €/h)	0,38	45
→	Casing positioning, alignment and mounting with Shaft, Coupling and House bearing (30 €/h)	0,25	30
→	Hex head screw DIN 6921 M8 x 65 positioning, alignment and screwing with House bearing, Coupling and Casing (x8) (30 €/h)	4,40	528
→	Cup nut M16 positioning, alignment and screwing with Shaft and Impeller (30 €/h)	0,55	66
→	Hex head screw DIN 6921 M8 x 60 positioning, alignment and screwing with Packing gland and Coupling (x2) (30 €/h)	1,10	132
→	Hex head screw DIN 6921 M10 x 40 positioning, alignment and mounting with Support and House bearing (30 €/h)	0,05	6
→	Nut DIN ISO 4161 M10 positioning, alignment and screwing with Hex head screw DIN 6921 M10 x 40 (30 €/h)	0,55	66
→	Key IS 2048 7 x 8 x 36 positioning, alignment and mounting with Shaft (30 €/h)	0,05	6
→	Total	15,00	1800

5.3.6. Case study - Assembly (assembly 2 – jib crane)

Using the same procedure as in the first case study, the second part analysed is a jib crane assembled as "welded and bolted assembly".

The assembly is composed by 91 parts components (parts) and one product (assembly) with a production volume of 10000 components and a batch size of 100 parts. In Figure 37 is shown the exploded view and in Table 52 is shown the BoM of the case study.

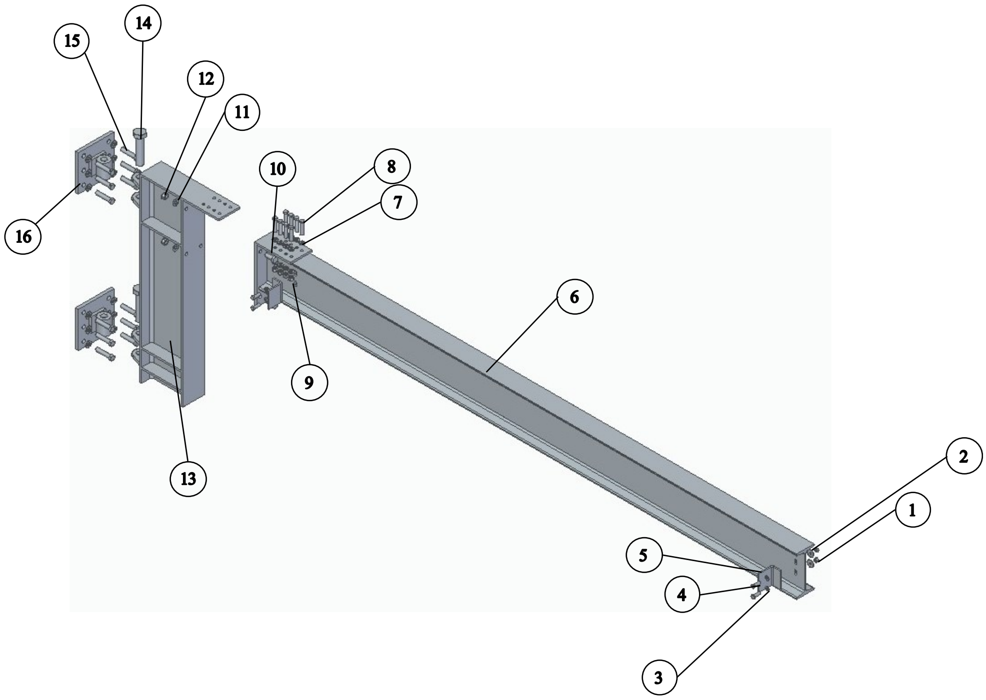


Figure 37 Exploded view (assembly 2 – jib crane original design)

Table 52 Bill of material (assembly 2 – jib crane original design)

No.	Component	Quantity	Material
1	Hex nut ISO 4034 M10	4	39NiCrMo3

2	Plain washer Xlarge ISO 7094 M10	4	Aisi 316
3	Plain washer ISO 7089 M10	4	Aisi 316
4	Hex head screw ISO 4016 M10 x 35	4	39NiCrMo3
5	Stopper	2	Aisi 316
6	Arm	1	S275 JR
7	Plain washer ISO 7089 M12	16	Aisi 316
8	Hex head screw ISO 4018 M12 x 60	8	39NiCrMo3
9	Hex nut ISO 7417 M12	8	39NiCrMo3
10	Hex head screw ISO 4012 M16 x 45	4	39NiCrMo3
11	Plain washer ISO 7089 M16	16	Aisi 316
12	Hex nut ISO 4034 M16	4	39NiCrMo3
13	Column	1	S275 JR
14	Hex head screw ISO 7412 M30 x 140	2	39NiCrMo3
15	Hex head screw ISO 4018 M16 x 80	12	39NiCrMo3
16	Pivot wall	1	S275 JR

Once identified the features of the parts and the assembly ("*Step 1: 3D CAD Model*" (Figure 8), "*Step 2: Feature recognition and extraction*"), DfM/DfA rules analysis was performed as described in the methodology workflow (S*tep 4: DfM/DfA analysis*) (Figure 8).

In this case study are identified 6 design problems regarding the assembly, related to the fourth block of geometric feature recognition. Is important to notice that the design issues are related only to the bolding and not to the welding. Then the case study will be focused only on the features related to bolding.

The first design issue is classified as critical and it affects the assembly feasibility. In particular, the issue refers to the need to have flat surfaces for the insertion holes for screws and rivets. Connections on non-flat surfaces don't allow correct assembly of the components causing the instability of the assembly. This issue involved the following features:

- Feature_1 - HOLE RECTANGUALAR PATTERN (Column), Feature_1 - HOLE RECTANGUALAR PATTERN (Arm), Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60), Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60), Feature_1 – CYLINDRICAL HOLE (Plain washer ISO 7089 M12) and Feature_1 – CYLINDRICAL HOLE (Hex nut ISO 7417 M12). Angle required: 90°. Actual angle: 97,97°.

The second design issue is classified as critical too since it could affect the assembly feasibility, but in general increase time and difficulty. This issue is referred to the minimum distance between the axis of two or more screw. In the case of bolted connections, it is necessary to maintain a certain distance between two adjacent screws equal to 1.2 D (diameter of the first screw) plus 1.2 d (diameter of the second screw) to avoid assembly problems. In fact, if the screws used for assembly have a head with an overall dimension greater than the diameter of the screw itself (for example hexagonal head or hexagon socket screws) these could interfere during the assembly phase, making assembly impossible. Furthermore, this rule could be applied considering the load constrains, which suggest the minimum distance between two consecutive screws in function of load direction: in case of parallel load direction this distance is 2.4 times the diameter of the screw, while in the direction perpendicular to the load this distance must be 3 times the diameter.

This issue involved the same features of previous one:

- Feature_1 - HOLE RECTANGUALAR PATTERN (Column), Feature_1 - HOLE RECTANGUALAR PATTERN (Arm), Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60), Feature_1 – CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60), Feature_1 – CYLINDRICAL HOLE (Plain washer ISO 7089 M12) and Feature_1 – CYLINDRICAL HOLE (Hex nut ISO 7417 M12). Minimum required diameter gap: 31,2 mm. Actual diameter gap: 30 mm.

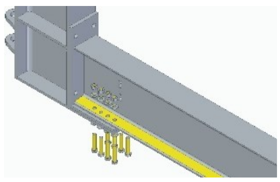
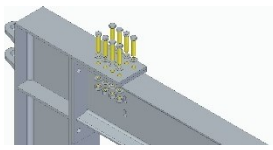
The third design issue is classified as information and is referred to use of combined fasteners, e.g. screws with integrated washers to reduce assembly times.

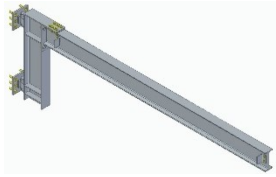
This issue involved the following components:

- Hex nut ISO 4034 M10, plain washer Xlarge ISO 7094 M10, plain washer ISO 7089 M10 and Hex head screw ISO 4016 M10 x 35 in the connection between stopper (5) and arm (6).
- Plain washer ISO 7089 M12, hex head screw ISO 4018 M12 x 60 and hex nut ISO 7417 M12 in the connection between packing column (13) and arm (6).
- Hex head screw ISO 4012 M16 x 45, plain washer ISO 7089 M16 and Hex nut ISO 4034 M16 in the connection between column (13) and arm (6).
- Hex head screw ISO 7412 M30 x 140 and hex head screw ISO 4018 M16 x 80 in the connection between pivot wall (16) and wall.

Table 53 summarize the identified design problem.

Table 53 Design problems identified for the assembly (assembly 2 – jib crane original design)

Knowledge processing			**Knowledge representation**	
Manufacturing technology	**Material**	**CAD feature recognition**	**DfM/DfA guideline syntax**	**DfM/DfA guideline picture**
Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Angle between hole axis and surface (α) PMI: N.A. Dimensions/geometry: α = 90°	Action: Guarantee Subject: Flat surfaces for the insertion holes for screws Context: In the manual assembly process of bolted components	
Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Diameter of first screw (Ds); Diameter of second screw (ds); Distance between the screw axis (La) PMI: N.A. Dimensions/geometry: La > 1,2Ds + 1,2ds	Action: Guarantee Subject: Minimum distance between the axis of two or more screw Context: In the manual assembly process of bolted components	

Class: Manual assembly Type - level 1: Bolted Type - level 2: N.A.	Class: All materials Type: N.A.	Recognize: Screw; Washer; Nut PMI: N.A. Dimensions/geometry: N.A.	Action: Prefer Subject: The use of combined fasteners Context: In the manual assembly process of bolted components	

In Appendix B. Features of components analysed in case studies, Table 107, Table 108, Table 109, Table 110 and Table 111 are summarized the features of the parts of the assembly involved in design issues.

Then an analytical cost estimation has been done starting from the identified features (*Step 3: Cost analysis*). It is important to notice that the assembly cost estimation is not applicable in the original design due to the non-flat surfaces for the insertion holes for screws and rivets, which cause the instability of the assembly.

At this step, the previously highlighted issues will be fixed and then the 3D model is updated *(Step 5: Update 3D CAD Model)* by changing the model features according to the design guideline.

The changes consisted of:

- Feature_1 – HOLE RECTANGULAR PATTERN (Column): increasing of hole distance from 30 mm to 50 mm and new coordinates to avoid non-flat surface between Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) and Feature_2 – T-EXTRUSION (Arm) (Feature_1 – HOLE RECTANGULAR PATTERN_MOD (Column)).
- Feature_2 – RECTANGULAR PAD (Column): changing feature dimensions cause new feature coordinates of Feature_1 – HOLE RECTANGULAR PATTERN (Column) (Feature_2 – PAD (Column)).
- Feature_1 – HOLE RECTANGULAR PATTERN (Arm): increasing of hole distance from 30 mm to 50 mm and new coordinates to avoid non-flat surface between Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw

ISO 4018 M12 x 60) and Feature_2 – T-EXTRUSION (Arm) (Feature_1 – HOLE RECTANGULAR PATTERN_MOD (Arm)).

- Feature_2 – RECTANGULAR PAD (Arm): changing feature dimensions cause new feature coordinates of Feature_1 – HOLE RECTANGULAR PATTERN (Column) (Feature_2 – RECTANGULAR PAD_MOD (Column)).
- Replacement of the screws (Hex head screw ISO 4018 M12 x 60) and washers (Plain washer ISO 7089 M12) with flanged screws (Hex head screw DIN 6921 M12 x 40).
- Replacement of the nuts (Hex nut ISO 7412 M12) and washers (Plain washer ISO 7089 M12) with flanged nuts (Hex nut DIN ISO 6923 M12).
- Replacement of the nuts (Hex nut ISO 4034 M16) and washers (Plain washer ISO 7089 M16) with flanged nuts (Hex nut DIN ISO 4161 M16).
- Replacement of the screws (Hex head screw ISO 4016 M10 x 35) and washers (Plain washer ISO 7089 M10) with flanged screws (Hex head screw DIN 4162 M10 x 35).
- Replacement of the screws (Hex head screw ISO 4018 M16 x 80) and washers (Plain washer ISO 7089 M16) with flanged screws (Hex head screw DIN 4162 M16 x 80).

In Appendix B. Features of components analysed in case studies, Table 112, Table 113, Table 114 and Table 115, are summarized only the modified *features of 1° block* and the *features of 2° block* of the modified parts. In Table 116 are summarized *features of 4° block*.

Table 54 reports the cost-sharing for the assembly after the design update. Could be noticed that the major costs are related to the welds and screw insertion.

Table 54 Cost analysis (assembly 2 – jib crane updated design)

List of operations		Material cost [€]	Operations		Total	
			Cost [€]	Time [s]	Cost [€]	Time [s]
→	Column welds (40 €/h)	6,92	64,74	4893	71,66	4893
→	Arm welds (40 €/h)	2,12	18,6	1149	20,72	1149
→	Pivot welds (40 €/h)	1,70	15,84	1357	17,54	1357
→	Hex head screw DIN 4162 M16 x 80 positioning, alignment and mounting with Pivot and Wall (x12) (30 €/h)	-	6,70	804	6,70	804
→	Column positioning and alignment with Pivot (40€/h)	-	1,00	90	1,00	90
→	Hex head screw ISO 7412 M30 x 140 positioning, alignment and mounting with Pivot and Column (x2) (30 €/h)	-	1,10	132	1,10	132
→	Column positioning and alignment with Arm (70 €/h)	-	4,67	240	4,67	240
→	Hex head screw ISO 4012 M16 x 45 positioning, alignment and mounting with Arm and Column (x4) (30 €/h)	-	0,20	24	0,20	24
→	Hex nut DIN ISO 4161 M16 positioning, alignment and screwing with Hex head screw ISO 4012 M16 x 45 (x4) (30 €/h)	-	2,20	264	2,20	264
→	Hex head screw DIN 6921 M12 x 40 positioning, alignment and mounting with Arm and Column (x8) (30 €/h)	-	0,40	48	0,40	48
→	Hex nut DIN ISO 6923 M12 positioning, alignment and screwing with Hex head screw DIN 6921 M12 x 40 (x8) (30 €/h)	-	4,40	528	4,40	528
→	Stopper positioning, alignment and mounting with Arm (x2) (30 €/h)	-	0,10	12	0,10	12
→	Hex head screw DIN 4162 M10 x 35 positioning, alignment and mounting with Stopper and Arm (x4) (30 €/h)	-	0,20	24	0,20	24
→	Plain washer Xlarge ISO 7094 M10 positioning, alignment and mounting with Hex head screw DIN 4162 M10 x 35 and Arm (x4) (30 €/h)	-	0,20	24	0,20	24
→	Hex nut ISO 4034 M10 positioning, alignment and screwing with Hex head screw DIN 4162 M10 x 35 (x4) (30 €/h)	-	2,20	264	2,20	264
→	Total	10,74	122,55	9853	133,29	9853

6. Results

This chapter resumes the results of the methodology and the tool. The chapter is divided in two main section.

The first one (6.1) discuss about the results related to the methodology, highlighting the advantages and disadvantages in relation with case studies.

The second section (6.2) is focused in software evaluation through two different questionnaires which were submitted to the users after extensive use (more than 6 months) of the tool.

6.1. Methodology results

The presented approach has been used to evaluate 6 different products, 4 parts and 2 assemblies. The proposed methodology has been used for modelling the manufacturing knowledge related to three process: (i) closed-die forging, (ii) machining (milling and turning) and (iii) bolted assembly. However, the methodology can be extended to other forming traditional processes, such as casting, sheet metal or assemblies process such as welding.

Focusing in cost estimation framework of the specific case studies, the constructs (cost breakdown, cost routing, cost model and workflow) have been evaluated based on a set of requirements defined within the literature analysis and the findings of the specific case studies. For each requirement, Table 55 presents the results achieved in this thesis and relative comments. The outcomes identified for each cost item are two: (i) the requirement was addressed, or (ii) the requirement needs to be addressed.

(i) In the first case the requirement was addressed considering the existing state-of-the-art barriers, then the proposed framework is complete and more comprehensive than the one proposed in the literature.

(ii) In the second case the requirement needs to be addressed considering the existing state-of-the-art barriers: based on the requirements obtained from the literature review and the analyses of the results, in future research, improvements for this item need to be made.

Table 55 reports also if the outcomes resulting from the analysis of the case studies can be extended to other processes as well as to a general manufacturing process and indicates the additional actions that are required. In particular for emerging technologies (i.e. additive manufacturing) are required new study to adapt the described ontology on these technologies. Feature recognition for additive manufacturing processes will be a challenging task due to the nature of this process. Indeed, traditional manufacturing processes consist of multiple and different operations (e.g., milling, drilling), which are connected to relative manufacturing features (e.g., hole, pocket, slot). A 3D printing process cannot be split down in multiple manufacturing features.

The positive outcomes are highlighted in relation to the cost breakdown structure and cost model, where the most important requirements were addressed. Some future improvements are required for the cost routing and, in particular, for the management of different objectives, variables and constraints of an optimization problem, as well as for the management of rules to be used for sorting operations. Looking at the workflow for components and assemblies, a positive outcome is its possible extension to other processes such as casting, sheet metal or assemblies process such as welding.

Table 55 Outcomes of the methodology implementation

Requirement	Context	Outcome	Comment	Additional action
Detailed cost breakdown structure to be used for an in-depth cost analysis	Cost breakdown (both manufacturing and assembly)	Addressed	The material, machine and labour cost items are more detailed in this thesis than they are in the literature. For example, the differentiation between contaminated and uncontaminated waste was not observed in the literature. Equipment, consumable and energy cost items have the same structure as that shown in the literature. (Ben-Arieh et al, 2003; Chen at al., 2011;	None

			Chougule et al., 2006; Knight, 1992; Ou-Yang et al., 1997)	
General cost breakdown structure to be used for manufacturing processes	Cost breakdown (manufacturing)	Addressed	The cost breakdown presented in this thesis is general and has been tested for closed-die forging and chip forming (milling and turning case studies). Cost breakdown can be used also for other forming processes (e.g., injection moulding, casting). Many cost breakdown schemas are found in the literature, but all of these refer to specific manufacturing processes: machining (Ben-Arieh et al, 2003), forging (Knight, 1992) and casting (Chougule et al., 2006).	None
General cost breakdown structure to be used for assembly processes	Cost breakdown (assembly)	Addressed	The cost breakdown presented in this thesis is general and has been tested for bolted assembly process (case study). Cost breakdown can be used also for other assembly processes (e.g., welding, gluing). Many cost breakdown schemas are found in the literature, but all of these refer to specific manufacturing processes: machining (Ben-Arieh et al, 2003), forging (Knight, 1992) and casting (Chougule et al., 2006).	None
Workflow for defining manufacturing processes from 3D virtual prototypes of components	Workflow (manufacturing)	Addressed	The workflow presented in this thesis may be used for all the traditional forming processes. All the workflows available in the literature refer to specific manufacturing processes: machining (Ou-Yang et al., 1997; Shehab et al., 2002), assembly products (Streppel et al., 2003), forging (Kulon et al., 2006), injection moulding (Streppel et al., 2003).	None

Workflow for defining manufacturing processes from 3D virtual prototypes of assemblies	Workflow (assembly)	Addressed	The workflow presented in this thesis may be used for defining the cost of assemblies. All the workflows available in the literature refer to specific manufacturing processes: machining (Ou-Yang et al., 1997; Shehab et al., 2002), assembly products (Streppel et al., 2003), forging (Kulon et al., 2006), injection moulding (Streppel et al., 2003).	None
Workflow for defining manufacturing processes from 3D virtual prototypes of additive manufactured components	Workflow (additive manufacturing)	To be addressed	The workflow presented in this thesis cannot be used for defining the cost of additive manufacturing processes Feature recognition for additive manufacturing processes will be a challenging task due to the nature of this process.	Need to devise a new feature concept applicable to these additive manufacturing technologies.
General structure for collecting knowledge-based rules for defining a manufacturing process	Cost routing (manufacturing)	Addressed	The cost routing structure presented in this thesis can be easily used for collecting the knowledge required for defining the manufacturing process and the related cost of single components. Various examples of cost routing are available in the literature, but they generally refer to specific manufacturing processes: machining (Feng et al., 1996; Bouaziz et al., 2006; Grabowik et al., 2003; Garcia-Crespo et al., 2011), casting (Maciol, 2017) and forging (Kulon et al., 2006).	None
General structure for collecting knowledge-based rules for defining an assembly process	Cost routing (assembly)	Addressed	The cost routing structure presented in this thesis can be easily used for collecting the knowledge required for defining the assembly process and the related cost of assembly. Various examples of cost routing are available	None

			in the literature, but they generally refer to specific manufacturing processes: machining (Feng et al., 1996; Bouaziz et al., 2006; Grabowik et al., 2003; Garcia-Crespo et al., 2011), casting (Maciol, 2017) and forging (Kulon et al., 2006).	
General structure for collecting knowledge-based rules for defining an additive manufacturing process	Cost routing (additive manufacturing)	To be addressed	The cost routing structure presented in this thesis cannot be used for collecting the knowledge for a 3D printing process, because it cannot be split down in multiple manufacturing features.	A cost routing for additive manufacturing should be defined.
Optimization methods for cost routing	Cost routing (both manufacturing and assembly)	To be addressed	The cost optimization of a manufacturing or an assembly process should evaluate multiple and alternative solutions to find the best one. For example, the best production strategy should be defined after the evaluation of all the other valid strategies. In this case, priority rules will be neglected.	The cost routing structure for managing objectives, variables and the constraints of an optimization problem should be improved.
Process yield	Cost routing (both manufacturing and assembly)	To be addressed	The cost routing structure does not provide a method for managing process yield. Each operation should be characterized by a success rate. If an operation is not correctly performed, all the cost encountered until that operation performs correctly should be considered as extra-costs.	The cost routing structure must manage the yield for each operation within the process.
Sorting of process operations	Cost routing (both manufacturing and assembly)	To be addressed	The cost routing structure does not provide a method for sorting operations within a manufacturing process. Only validity and priority rules are managed. The operations order may depend on the process; thus, specific rules should be defined.	The cost routing structure for managing rules to be used for sorting operations should be improved.
General cost model to be used	Cost model (manufacturing)	Addressed	Cost models have been tested for closed-die forging and chip	None

for manufacturing processes			forming (milling and turning) (case studies). New cost models for other forming processes (e.g., injection moulding) could be adapted starting from structure identified. In the literature, there are many cost models, but all of these refer to specific manufacturing processes: forging (Knight, 1992), casting (Chougule et al., 2006), high-pressure die casting (Favi et al., 2017).	
General cost model to be used for assembly processes	Cost model (assembly)	Addressed	A cost model has been tested for bolted assembly process (case study). New cost models for other assembly processes (e.g., welding, gluing) could be adapted starting from structure identified. In the literature, there are many cost models, but all of these refer to specific manufacturing processes: forging (Knight, 1992), casting (Chougule et al., 2006), high-pressure die casting (Favi et al., 2017).	None
General cost model to be used for additive manufacturing processes	Cost model (additive manufacturing)	To be addressed	A cost model has not been tested for 3D printing process.	A cost model for additive manufacturing should be defined.
Cost model to provide cost breakdown according to the structure proposed	Cost model (both manufacturing and assembly)	Addressed	The calculation rules of a cost model may be organized for computing the cost in accordance to the cost breakdown. Some authors organize cost model rules in accordance with their idealized cost breakdown (Ben-Arieh et al., 2003; Chougule et al., 2006, Knight, 1992).	None
Optimization methods at cost model	Cost model (both manufacturing and assembly)	To be addressed	The cost model structure does not provide a method for optimizing the cost of each operation by changing technological parameters (e.g.,	The cost model structure for managing objectives, variables and

			machine, equipment, consumables) and respecting constraints. For example, the best machine may not be the cheapest one but the one that guarantees the minimum manufacturing cost.	constraints of an optimization problem should be improved.

Concerning the implementation of the proposed framework, a qualitative evaluation procedure is presented. This evaluation facilitates the understanding of the applicability of the presented framework for daily use and possible grey areas requiring improvement. The evaluation criteria have been derived from March et al (1995) and are presented together with their explanations and related scores in Table 56. Regarding the evaluation method, according to the definition proposed by Prat et al. (2014), the authors performed a qualitative evaluation by using a three-grade scale (low, medium and high). Qualitative feedback on the identified criteria have been derived from two groups of participants: (i) four university professors with experience in the engineering design and cost engineering and (ii) four engineers/designer from the company involved in the implementation of the case studies. The framework was first presented to professors and cost engineers. Second, cost engineers used the proposed framework for process analysis and knowledge formalization. The evaluation results show a satisfactory assessment of the framework as a whole. Considering the criteria described in the evaluation table, the highest scores are registered for "completeness" and "efficacy", which both receive a high score. Conversely, "understandability", "ease of use" and "impact to user" shows the lowest score (medium); however, the scores were far from the lower bound.

Table 56 Qualitative evaluation of the methodology

Criteria	**Explanation of criteria**	**Available scores**	**Result**
Completeness	Completeness addresses whether the cost model and the data structure lack some items or whether its usage requires customization	High Medium Low	High

Understandability	Understandability addresses whether the whole structure of the cost model and the and data arrangement (cost breakdown) are easy to understand	High Medium Low	Medium
Ease of use	Ease of use addresses the capability of the user to use the implemented framework without external training/help	High Medium Low	Medium
Fidelity with real world phenomena	Fidelity addresses whether the model reflects relationships that occur in real world	High Medium Low	Medium/High
Efficacy	Efficacy addresses whether the workflow and cost model produce the desired effect (i.e., whether it achieves its goal)	High Medium Low	High
Effectiveness and generality	Generality addresses whether the overall framework can cover different applications and technologies	High Medium Low	Medium/High
Impact to user	Impact addresses whether the use of the proposed workflow including the cost routing affects the environment (organization) and the users' jobs (daily practice)	High Medium Low	Medium

The case studies analysed in the previous chapter made it possible to draw up DfM/DfA rules for closed-die forging process, chip removal and bolted/rivetted assembly processes. Each guideline is classified in function of the importance of the rules: (i) critical, (ii) warning and (iii) information. As previously described, the criticality of each rule was defined on the basis of how much its non-compliance affected the technological feasibility (critical indicate a preclusion, warning generate potential problems and information is a suggestion).

Concerning the forging process, the design process begins with the geometry of the finished part. Consideration is given to the shape of the part, the material to be forged, the type of forging, the equipment to be used, the number of parts to be forged, the application of the part and the forging type (blocker, conventional and precision). The design of forging takes in consideration 8 main items (ASM 14A, 2005): parting line, draft, ribs and bosses, corner and fillets, webs, cavities and holes, flash and dimensions with tolerances.
For closed-die forging process 194 DfM rules are draw up. 17 of which are critical rules, 160 are warning and 17 are information type rules. In Appendix A. DfM/DfA rules repositories, (Table 64), are reported a set of rules dedicated to the closed-forging process. It is worth noting that this is not a complete list of rules but only

part of it.
In forging case studies are identified design problems related to the second block of geometric feature recognition. The main issues for both parts analysed regards the minimum draft angle and fillet absence. In precision closed-die forging of steel cannot be lower than 3° and in these cases is lower or absent. The absence of draft, or of sufficient draft, causes the forging to stick in the dies, making removal impossible or difficult, requiring special forceful means for ejection from die cavities. This issue can be classified as a critical since it affects the technological feasibility of the feature.
Fillet radii provide a smooth, gradual connection rather than an abrupt angular junction. Minimum values for corner and fillet radii provide a series of advantages including a lower concentration of stress but also a less die costs, time savings and reduction of processing waste. Indeed, sharp edges cannot be obtained by forging and is required a machining operation.
Solving the design issues allowed the production of these parts and then the cost estimation analysis. In-fact in original design the parts could not be produced cause the draft angle and corner radius absence.

Regarding machining components, the design of them includes limitations about drilling operation, hole diameters, achievable and recommended surface finish and tolerances, achievable radii, ect.
For chip forming 100 rules are achieved, 70 for milling processes, 14 for turning processes and 16 related to both processes. For milling process, 9 applicable rules are critical, 52 are warning, while 9 are information. For turning, 1 rule is critical, 11 are warning and 2 are information. Considering the rules applicable for both process, 11 are warning and 5 are information. A set of rules dedicated for machining (milling and turning in particular) are reported in Appendix A. DfM/DfA rules repositories, Table 65.
In milling case study design problems are related to second and third block of feature recognition. In particular the most impacting design issue is related to the presence of sharp internal corners in the component. The use of sharp internal corners provides high concentration stress and also more machine operations, more time and an increasing of processing waste. At the same time, sharp internal edges cannot be obtained by milling, and they require more complicated and expensive technologies

such as Electrical Discharge Machining (EDM). Thanks to the elimination of sharp corner could be achieved a cost reduction of 13,25€ (approx. the 8% of total).
In turning case study, the two design problems are related to the second block of feature recognition and both are classified as warning. Their resolution allows a few reduction of manufacturing cost of the part, in-fact analyzing the breakdown of cost can be notice a decreasing in costs of "motorized lathe machine" operations (170,52 € vs. 173,76 €). The costs of the other machines remained the same of the original design.

In case of bolted/rivetted assemblies each component of assembly should be designed to reduce the number of manufacturing and assembly operations to a minimum. In this way, reducing the number of parts allows the improvement of an assembly, far overshadowing in impact any other changes in design that improve manufacturability and further other important design objectives. Other recommendations are the standardization of the parts and design, the use of modular subassemblies, avoid flexible parts and the use of easily handled parts.
In particular for bolted/rivetted assembly processes 123 rules are achieved, 18 of which are critical, 82 are warnings, while 23 are information related rules. A set of rules dedicated for assembly (bolted and rivetted in particular) are reported in Appendix A. DfM/DfA rules repositories, Table 66. It is worth noting that this is not a complete list of rules but only part of it.
In assembly case studies, as it happened in the case of forging, critical issues doesn't allow the mounting of parts. In the first case study the main problem is caused by the absence of a minimum diameter gap between screw and hole of non-threaded parts of bolted connection. This minimum gap is necessary to facilitate screw insertion and avoid possible stuck in manual assembly operations. A minimum diameter gap varies in function of screw dimensions, and it can be assessed by the difference between the hole diameter and the external screw diameter. In the second case study a first issue is related to the need to have flat surfaces for the insertion holes for screws and rivets, which cause the instability of the assembly, while a second is referred to the absence of minimum distance between the axis of two or more screw to avoid assembly problems.
For both assembly case studies, the resolution of design issues allow the mounting of the assembly, impossible in original designs.

6.2. Tool evaluation and results

To evaluate method and software two different questionnaires are developed and they were submitted to the users after extensive use (more than 6 months) of the tool. This chapter defines and explains these questionnaires: the first one wants to quantify the usability of the software (Section 6.2.1) while the second one is focused on the advantages and disadvantages in design process thanks to the software use (Section 6.2.2).

Section 6.2.3 shown the result of the submitted questionnaires to the users of two different companies.

6.2.1. Software usability

Because of the heavy impact on the design process that may be due to the implementation of the method and software, it is very important to consider its usability and user friendliness.

Among the most popular rules in literature, the Nielsen Heuristic rules (Nielsen et al. 1990) have been chosen as metric for software usability assessment. Nielsen's heuristic rules aim at evaluating the usability of the software, considering ten different abstract features. They are called "heuristics" because they are more in the nature of rules of thumb than specific usability guidelines. Heuristic evaluation is the most rapid, cheap, and effective way for identifying usability problems (Greenberg et al., 2000). Molich and Nielsen (Nielsen et al. 1990) have proposed nine usability heuristics. The heuristics are:

1. Simple and natural dialogue.
2. Speak the user's language.
3. Minimize the user memory load.
4. Be consistent.
5. Provide Feedback.
6. Provide clearly marked exits.

7. Provide shortcuts.
8. Good Error Message.
9. Prevent Errors.

These were originally developed for heuristic evaluation in collaboration with Rolf Molich in 1990 (Nielsen et al., 2000). Nielsen has refined the heuristics based on a factor analysis of 249 usability problems (Nielsen J., 1994. "Enhancing the explanatory power of usability heuristics") to derive a set of heuristics with maximum explanatory power, resulting in this revised set of heuristics (Nielsen J., 1994. "Heuristic evaluation. Usability inspection methods"). For the sake of comparison, these will be called traditional heuristics. These are shown as follows:

1. Visibility of system status: the system should always keep users informed about what is going on, through appropriate feedback within reasonable time.
2. Match between system and the real world: the system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.
3. User control and freedom: users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.
4. Consistency and standards: users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions.
5. Error prevention: even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.
6. Recognition rather than recall: minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.

7. Flexibility and efficiency of use: accelerators (unseen by the novice user) may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.

8. Aesthetic and minimalist design: dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.

9. Help users recognize, diagnose, & recover from errors: error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.

10. Help and documentation: even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.

Starting from these ten heuristics, Sivaji (Sivaji et al., 2011) develop their ones. They are summarized in Table 57.

In this table are also indicated if the heuristic is used for the evaluation questionnaire. Except "Informative Feedback", cause its inapplicability, all heuristics are used to evaluate the system.

Table 57 Heuristic used for software usability questionnaire

Heuristics	**Description**	**Used for the questionnaire**
Compatibility	The way the system looks and works should be compatible with user conventions and expectations	YES
Consistency & Standards	The way the system looks and works should be consistent at all times	YES
Error Prevention & Correction	The system should be designed to minimize the possibility of user error, with inbuilt facilities for detecting and handling; users should be able to check their	YES

	inputs and correct errors or potential error situations before the input is processed.	
Explicitness	The way the system should work is structured and should be clear to the user	YES
Flexibility & Control	The interface should be sufficiently flexible in structure, in the way information is presented and in terms of what the user can do, to suit the needs and requirements of all users, and to allow them to feel in control of the system	YES
Functionality	The system should meet the needs and requirements of users when carrying out tasks	YES
Informative Feedback	The system should always keep user informed about what is going on through appropriate feedback within reasonable time.	NO
Language & Content	The information conveyed should be understandable to the targeted users	YES
Navigation	The system navigation should be structured in a way that allows a user to access support for a specific goal as quickly as possible	YES
Privacy	The system should help the user to protect personal or private information belonging to the user or their clients	YES
User Guidance & Support	Informative, easy-to-use and relevant guidance and support should be provided to help user understand and use the system	YES
Visual Clarity Description	Information displayed on the screen should be clear, well-organized, unambiguous and easy to read	YES

Those features require to be translated into quantifiable metrics in order to obtain a quantitative mark for the usability of the platform. This mark is related to the level of the acceptance from the user perspective. It is important to state that these rules aim to test the "usability in use", thus, even if it is considered as a usability inspection method, in our case, users will be asked to give feedback after they have experienced the real use of the system/tool.

Specific questionnaires have been developed for the evaluation of the software usability according to the twelve rules identified and presented in the Table 58. These questions allow user to evaluate quantitatively some parameters of the tool under usage. Two different typologies of questions have been derived:

- General: if the question is applicable for all software.
- Specific: if the question is applicable only for DfM/DfA and cost tool software.

This approach has been chosen to obtain some general opinion and this allows the software developers to understand if globally the tools satisfy the user expectations or not.

Table 58 summarize the ranking criteria chosen for the quantification of the user's opinions.

Table 58 Ranking criteria value for DfM/DfA and cost tool software

Question	Description	Score
Yes	The tool fully satisfies the requirements given in the statement.	9
Yes, but further improvement may be useful	The tool meets the requirements given in the statement; however further improvements may be useful.	6
No	The tool does not meet the requirements given in the statement and modifications and improvements are required.	3

If "No" or "Yes, but further improvement may be useful" are chosen, the user is invited to write some feedbacks to explain the reason/reasons for the choice in the "Recommended improvements" column after explained.

Starting from the evaluation of single rules through single scores given by the user, a method to calculate the overall usability rank for each tool has been defined. In particular the approach used has been the weighted mean. The formula implemented is the following (Eq. 9):

$$Average\ overall\ usability\ rank = \frac{\sum_i weight_i * score_i}{\sum_i weight_i} \quad (9)$$

Where: $weight_i$ = weight of the i-th metric

As a first attempt each metric has been associated with a specific weight varying from a minimum of 1 to a maximum of 3.

Weights chosen to calculate our usability mark are presented in Table 59. The weights associated to the metrics allowing to evaluate the usability of the main tool functionalities have been set up to a maximum weight of 3. The weights associated to the metrics related to the interaction between the user and the tool were set up to an intermediate weight of 2. Finally, weights related to metrics dealing with language and visual aspects were set up to a minimum of 1.

Table 59 Weight

Function of metrics	**Weight**
Compatibility	2
Consistency & Standards	3
Explicitness	2
Flexibility & Control	2
Functionality	3
Language & Content	1
Navigation	2
Privacy	3
User Guidance & Support	1
Visual Clarity Description	1

Therefore, the average overall usability ranking varies from 3 to 9. As a consequence, a value obtained between 3 and 6 will be considered as a mark of insufficient satisfaction for the user. A value scoring between 6 and 8 will be considered as a mark of correct satisfaction for the user. A scoring value between 8 and 9 will be considered as showing an excellent satisfaction for the user (Table 60).

Table 60 Interpretation of usability rank value

Between 3 and 6	**Not sufficient**	Identification of problematic aspects and correction; tool improvements are required
Between 6 and 8	**Correct satisfaction**	Recommendations can be made according to the main issue identified by the user
Between 8 and 9	**Excellent satisfaction**	The tool provides an excellent satisfaction to the user. Some recommendations should be made to attain a score of 9 if the obtained score is under

In order to facilitate the questionnaire exploitations, the questions have been inserted in an Excel spreadsheet.

The excel spreadsheet is divided in 3 sheets:

- User guide.
- Questionnaire.
- Usability definitions.

In the first sheet are summarized the compilation instruction for the user, in which are described the choices, the values of each evaluation, the weight and the method used for calculating the “Average overall usability rank”. In Figure 38 are represented the first sheet of excel.

General question	General common questions for all software		
Specific question	LeanDESIGNER focused question		
Evaluation	 The tool fully satisfies the requirements given in the statement. The tool meets the requirements given in the statement, however further improvements may be useful. The tool does not meet the requirements given in the statement and modifications and improvements are required.	*3 possible choices* **Yes** **Yes, but further improvement may be useful** **No**	
Score	Function of evaluation **Yes** **Yes, but further improvement may be useful** **No**	*3 possible values* 9 6 3	
Weight	Function of metrics Compatibility Consistency & Standards Explicitness Flexibility & Control Functionality Language & Content Navigation Privacy User Guidance & Support Visual Clarity Description	*3 possible values* 2 3 2 2 3 1 2 3 1 1	The weights associated to the metrics allowing to evaluate the usability of the main tool functionalities have been set up to a maximum weight of 3. The weights associated to the metrics related to the interaction between the user and the tool were set up to an intermediate weight of 2. Finally, weights related to metrics dealing with language and visual aspects were set up to a minimum of 1.
Recommended improvements	If you choose "No" or "Yes, but further improvement may be useful", please explain the reason/reasons for your choice in the "Recommended improvements" column.		

Average overall usability rank

$$Average\ overall\ usability\ rank = \frac{\sum_i weight_i * score_i}{\sum_i weight_i}$$

Obtained value from usability ranking	**Satisfaction of the user**
Between 3 and 6	**Not sufficient** Identification of problematic aspects and correction; tool improvements are required
Between 6 and 8	**Correct satisfaction** Recommendations can be made according to the main issue identified by the user
Between 8 and 9	**Excellent satisfaction** The tool provides an excellent satisfaction to the user. Some recommendations should be made to attain a score of 9 if the obtained score is under

Figure 38 User guide sheet

The sheet questionnaire lists the questions that the user will have to answer and the formulas to calculate the evaluation.

The first raw of this sheet is composed by 7 columns:

1. Question: the column which contains all the questions of the questionnaire.
2. General question: indicate if the question is applicable for all software.
3. Specific question: indicate if the question is applicable only for DfM/DfA and cost tool software.
4. Evaluation: where the user indicates his evaluation of the tool.
5. Score: indicates the values of the previous evaluations.
6. Weight: the column which contains the weights of each question.
7. Recommended improvements: the columns where the user could indicate improvements if necessary.

The columns “general question”, specific question”, “score” and “weight” are hidden to the user and will only be used to calculate the evaluation.

In the last sheet are listed the heuristic used for the questionnaire.

In Appendix C. Questionnaire for software and method evaluation, Table 117, are represented the “software usability” questionnaire.

6.2.2. Impact on company traditional process

When an enterprise introduces a new software for the process design, it must evaluate its degree of integration with the enterprise software solutions (de Moor 2007) and the impact on the internal business processes (Häusler et al. 2009). Software assessment is a process that analyses the subjective and objective data to evaluate a tool (Bandor 2006).

First, the test had the scope of evaluating the impact of the methodology and the related software on the traditional design process of a company. Second, the test focused on evaluation of the interoperability between the new software and the design tools.

A second questionnaire was developed for these evaluations. The Likert scale (Likert 1932) is the method used in evaluation of the methodology and related system and is common scale used in software evaluation (Mitchell 1992). The original version of this scale has 5 possible answers: (i) Strongly agree, (ii) Agree, (iii) Neither agree nor disagree, (iv) Disagree and (v) Strongly disagree.

The scale is modified using only three answers possible for the users: (i)Yes, (ii) Yes, but further improvement may be useful and (iii) No.

The extreme values ('Strongly agree' and 'Strongly disagree') were removed to avoid extremist views (certain people do not accept extreme choices when there are always valid opposing views). For each question, a "Recommended improvements" section was also available to allow users to give suggestions.

The following ranking criteria (Table 61) have been chosen for the quantification of the user's opinions.

Table 61 Ranking criteria value to evaluating DfM/DfA and cost tool and its impact on company traditional process

Question	**Description**	**Score**
Yes	The tool fully satisfies the requirements given in the statement.	9
Yes, but further improvement may be useful	The tool meets the requirements given in the statement; however further improvements may be useful.	6
No	The tool does not meet the requirements given in the statement and modifications and improvements are required.	3

If "No" or "Yes, but further improvement may be useful" are choose, the user is invited to write some feedbacks to explain the reason/reasons for the choice in the "Recommended improvements" column after explained.

Starting from the evaluation of single rules through single scores given by the user, a method to calculate the overall usability rank for each tool has been defined. The formula implemented is the following:

$$Average\ overall\ usability\ rank = \sum_{i}^{n} \frac{score_i}{n} \quad (10)$$

Where:

- $score_i$ = score of the i-th question.
- n=number of questions.

The questionnaire was divided in four sections:

- Impact on the traditional design process: this section wants to highlight the differences that DfM/DfA and cost tool use has made in terms of time, process phases and competences required compared to the traditional design process.
- Data integration between traditional design and DfM/DfA and cost tool: connection between company CAD systems and DfM/DfA and cost tool.
- Training activities: this section wants to discover if the training activities have been useful and adequate.
- Personnel to involve: the section evaluates if the personnel inside the company able to use DfM/DfA and cost tool and to interpret its results.

As done previously, in order to facilitate the questionnaire exploitations, the questions have been inserted in an Excel spreadsheet. The excel spreadsheet is divided in 3 sheets:

- User guide.
- Questionnaire.
- References.

In the first sheet are summarized the compilation instruction for the user, in which are described the choices, the values of each evaluation, the weight and the method used for calculating the "Average overall usability rank". In Figure 39 are represented the first sheet of excel.

Evaluation	The tool fully satisfies the requirements given in the statement. The tool meets the requirements given in the statement, however further improvements may be useful. The tool does not meet the requirements given in the statement and modifications and improvements are required.	*3 possible choices* **Yes** **Yes, but further improvement may be useful** **No**
Score	Function of evaluation **Yes** **Yes, but further improvement may be useful** **No**	*3 possible values* 9 6 3
Recommended improvements	If you choose "No" or "Yes, but further improvement may be useful", please explain the reason/reasons for your choice in the "Recommended improvements" column.	

Average overall usability rank

$$Average\ overall\ usability\ rank = \sum_{i}^{n} \frac{score_i}{n}$$

Obtained value from usability ranking	**Satisfaction of the user**
Between 3 and 6	**Not sufficient** Identification of problematic aspects and correction; tool improvements are required
Between 6 and 8	**Correct satisfaction** Recommendations can be made according to the main issue identified by the user
Between 8 and 9	**Excellent satisfaction** The tool provides an excellent satisfaction to the user. Some recommendations should be made to attain a score of 9 if the obtained score is under

Figure 39 User guide sheet

The sheet questionnaire lists the questions that the user will have to answer and the formulas to calculate the evaluation.

The first raw of this sheet is composed by four columns:

1. Question: the column which contains all the questions of the questionnaire.
2. Evaluation: where the user indicates his evaluation of the tool.
3. Score: indicates the values of the previous evaluations.
4. Recommended improvements: the columns where the user could indicate improvements if necessary.

The column "Score" is hidden to the user and will only be used to calculate the evaluation.

In the last sheet are listed the references used for the questionnaire.

In Appendix C. Questionnaire for software and method evaluation, Table 118, are represented the questionnaire related to the impact of the tool on company traditional process.

6.2.3. Results obtained from the questionnaires

Questionnaires were submitted to the users after extensive use (more than 6 months) of the tool. The users involved in test are employed in two companies: Fabio Perini S.p.A. and Loccioni S.p.A..

Fabio Perini S.p.A. is an Italian engineering company specialized in machine design and manufacturing of industrial machinery for the paper making industry, while Loccioni S.p.A. is another Italian company specialized in many field, as measure & testing, industrial automation, ICT, robotics, software design, data science, bionics, mechatronics, nanotechnologies, etc.

6.2.3.1. Software usability evaluation

In software usability evaluation the results demonstrate the fully satisfaction of the users, since the total average score obtained by the tool in all the tests is between 8 and 9 for both the companies, but there are some difference in some question score.

Analyzing the result related to “software usability” provided by Perini tester (Table 119), could be notice that the first section “Compatibility” obtains the best results (score of 9) in 4 questions of 5 (1a, 1b, 1d and 1e), while in 1c question (Are the tool icons easily associated with their specific functions?) obtains a medium score (6). In this last question the user recommended bigger icons in tool interface. In the second section of the questionnaire (Consistency & Standards) 2 questions (2a and 2i) obtain a medium score of 6, while the other obtain the maximum results (2b, 2c, 2e, 2f, 2g and 2h). In this section the tester recommended improvements on DFA/DFM rules according to customer needs (question 2a) and an additional report easier to read (question 2i). In third section (Error Prevention & Correction) the tester recommended error messages easier to understand (question 3a and 3b). In sections 4 (Explicitness), 5 (Flexibility & Control) and 6 (Functionality) all questions obtain the best results (9). In “Language & Content” (section 7) the tool obtains the best results in questions 7b, 7c, 7d, 7e, 7f, 7h, 7i and 7j while in question 2a user recommended an easier way to understand and shown DFA/DFM rules. At the same time the tester would prefer an improvement in graphical interface to show in a more comprehensive way the default stock selected by the tool (question 7g). In section 8 (Navigation) questions 8a and 8d obtain a score of 9, while the others (8b, 8c and 8e) obtain a medium score. No recommendations are suggested in this section. Section 9 (Privacy) obtains the maximum score (9). In section 10 (User Guidance & Support) 2 questions obtain a medium score (10a and 10b) and user would prefer a manual easier to understand, for example improving video and animations. In the last section all the questions obtain a medium score (6), but the tester doesn’t suggest any recommendations.

Summarizing the results related to Fabio Perini S.p.A. could be found various request and comments, but the worst results are related to questions whit a low weight (e.g. Visual Clarity Description) helping to keep high the final score.

The worst results are related to the Visual Clarity Description, cause the information are not always well organized. Other suggestions came from the User Guidance & Support questions, in which are suggested a video or animations for a better understand, from Compatibility and Navigation (bigger icon required), from Language & Content, in which are suggested a better explanation of the rules and stock displayed and from Consistency & Standards (report must be easier to understand).

Analyzing the result related to "software usability" provided by Loccioni testers (Table 120 and Table 121), could be notice that the first section "Compatibility" obtains, for the tester 1, the best results in 3 questions (1a, 1b and 1e), while he recommended further improvements in question 1c (Icon to change material is not so easy to find) and 1d (It is not possible to change treatment after analysis has been executed). Tester 2 signed for all 5 questions the maximum score (9). Concerning the second section (Consistency & Standards), referring to tester 1, only question f (Is the default stock selected by the software correct enough?) obtains a medium score whit a suggestion related to the need of further materials and raw geometries. Other questions obtain the maximum score. Referring to tester 2, he signed for questions of section 2 the maximum score. Sections 3 (Error Prevention & Correction), 4 (Explicitness), 5 (Flexibility & Control), 7 (Language & Content), 9 (Privacy), 10 (User Guidance & Support) and 11 (Visual Clarity Description) obtains for both testers the maximum score. Section 6 (Functionality) obtains, referring to tester 1, the maximum score in question 6b, 6c, 6d and 6f, while in questions 6a and 6e obtains a medium score. Tester 1 suggests improvements in DfM/DfA rules (6a and 6e) cause the tool is used mostly for costing. In section 6 tester 2 signed a medium score at 6d question suggesting a more automatization by the tool, minimizing the choices made by the user in default stock selection. Other questions in section 6 obtain the maximum score. In section 8 (Navigation) tester 1 suggest improvements in coating and treatment changing (8b), signing the maximum score in the other questions. Tester 2 signed maximum score in all questions of this section.

Summarizing the results related to Loccioni S.p.A. can be notice that the scores are higher than 8 in all questions (average of the results of the two testers), whit only few comments (e.g. more automations required by the tool and the difficult in treatment change).

In Table 62 are summarized the results, divided by company.

Table 62 Software usability results

Questions	Weights	Fabio Perini S.p.A.		Loccioni S.p.A.	
		Score	**Notes**	**Score**	**Notes**
(1) Compatibility	2	8,4	Bigger icon required.	8,4	Bigger icon required and the possibility to change the treatment after the analysis execution.
(2) Consistency & Standards	3	8,3	Needed the addition of a report easier to read and more rules to integrate in database.	8,8	Would be needed further materials and raw geometry.
(3) Error Prevention & Correction	3	7,5	Errors messages are not always easy to understand.	9	-
(4) Explicitness	2	9	-	9	-
(5) Flexibility & Control	2	9	-	9	-
(6) Functionality	3	9	-	8,3	More useful rules needed. More automatization by the tool. It would be good the minimizations of the choices made by the user such as profiles, milled blocks.
(7) Language & Content	1	8,3	Not all the DFA/DFM rules are easy to understand cause not all the information are easy to be found. Could be improved the graphical interface for a better understanding of the default selected stock.	9	-
(8) Navigation	2	7,2	Not all the sections and icon are easily identifiable.	8,7	Difficult related to change the treatment.
(9) Privacy	3	9	-	9	-
(10) User Guidance & Support	1	7	Manual would be easier to understand improving video and animations.	9	-
(11) Visual Clarity Description	1	6	Not all the information are well organized and clear.	9	-
Total	-	*8,3*	-	*8,8*	-

6.2.3.2. Impact on company traditional process evaluation

Analyzing the result related to "Impact on company traditional process" provided by Perini tester (Table 122), could be notice that all the sections obtain the best score of 9, demonstrating the satisfaction of the tester. Same consideration could be obtained by the result provided by tester 1 of Loccioni (Table 123), while the second tester (Table 124) recommended more automation for a reduction of time dedicated in design process (question 1a). Both Loccioni testers didn't complete section 3, because they didn't attend a training session.

Summarizing, the results obtained by the tool show a fully satisfaction of the requirements given in the statement. In-fact the total average score obtained by the tool in all the tests is between 8 and 9 and this demonstrate the advantages of using the software during the design development.

In Table 63 are summarized the results, divided by company.

Table 63 Impact on company traditional process results

Questions	**Fabio Perini S.p.A.**		**Loccioni S.p.A.**	
	Score	**Notes**	**Score**	**Notes**
(1) Impact on the traditional design process	9	-	8,7	More automation would be needed for a reduction of time dedicated in design process.
(2) Data integration between traditional design and "DfM/DfA and cost tool"	-	N.A.	9	-
(3) Training activities	9	-	-	N.A.: they didn't attend a training session.
(4) Personnel to involve	9	-	9	-
Total	*9*	-	*8,6*	-

7. Conclusions and future outlook

The present research thesis investigates a CAD-integrated Design for Manufacturing and Assembly methodology and tool able to helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed. At the same time the research is also focused in showing the advantages in design process thanks to the use of the methodology and tool.

It is well known that, although the design activity costs approximately affect the 10% of the total budget for a new project, typically 80% of manufacturing costs are determined during the design stage (Ulrich et al. 2003).

During the product development process (PDP), cost plays a critical role and drives most of the technical and technological solutions (Favi et al. 2018). Cost estimation is a design task which allows to evaluate the production costs of products before their manufacturing (Mauchand et al 2008). Cost estimation activity includes a classification of cost items both for the materials and the manufacturing processes. In addition, cost estimation requires a definition of a mathematical model which integrates the cost items (Hoque et al. 2013). In literature can be found various example of manufacturing cost estimation tool, developed from late 1970s till now and the most widespread are focused in machining process. Numerous commercial cost estimation tools exist and many organizations have developed proprietary cost estimation systems.

Process planning and engineering design for mechanical products are extremely correlated processes and they require a strictly collaboration among all parties and departments to optimize the project outcomes such as cost, quality, performance, and reliability.

On the competitive global markets of today, companies have the objective to increase profits by reducing development costs and increasing quality. To guarantee the business success, must be avoided the traditional “over the wall” work, where several company departments work separated from each other. On the contrary, integrated product development process and concurrent engineering allow to create teams that work in parallel during development in multidisciplinary way.

Product design is the first step in manufacturing and is where the critical decisions are made that will affect the final form and cost of the product. Design for Manufacturing and Design for Assembly play a critical role in product design, since they are analytical processes that considers all aspects of the design, development, manufacturability, cost, assembly time, and modularity. Design for manufacture (DFM) methodology analyzes individual part geometry and process choices for impact on material, manufacturing process, and tooling costs, whereas design for assembly (DFA) is a structured methodology for analyzing product concepts or existing products for simplification of design and assembly processes. The increasing competitiveness of the markets is pushing designers to develop more and more competitive products. For this aim, designers must follow a growing number of design tips and rules, but the problem concerns in finding the set of rules to apply at the right time.

The engineering design defines the geometry, materials, and tolerances and the complete specifications of all the product's components through detailed drawings of the parts and general assembly drawings. The result of this phase is the complete and precise physical description of all the product's parts.

One of the most recurring disciplines in the engineering design contexts relates to solid modelling and drawing is CAD (Computer-Aided Design).

However, cost estimation together with DfM and DfA, are not really integrated with 3D CAD systems. DfM, DfA and cost estimation principles are currently applied at the end of the 3D CAD modelling, by following the well-known DfM and DfA guidelines available from the literature and company's know-how (internal tacit knowledge). This know-how suffers a strong dissemination among employees and technical departments and represents a critical issue.

Results and corporate knowledge tend to stay within the group instead of being documented in a way that promotes reuse. In doing so, development performance is affected by staff turnover, which occurs when projects are finished, or by the often time demanding search for the right document that contains the right information. This issue increases when considering the extensiveness of information needed during functional product development.

The mentioned practice highlights a gap in the state-of-art related to the CAD-integrated DfM and DfA methods and tools and the possibility to share manufacturing and assembly knowledge in the product design (explicit knowledge).

7.1. Positive results from the research

Consequently, the approach described in this thesis overcomes these limits through the resolution of two specific issues:

1. Making explicit the mixed manufacturing and assembly knowledge to support product designers during the product development process.
2. Integrate knowledge into the product development process and make it effective during the design process and the 3D solid modelling, estimating the cost savings of the design changes.

The first issue is solved through the use of methods which link DfM/DfA design rules with 3D CAD features developed during the engineering design process of parts or assemblies. The method is composed by three main aspects:

1. *3D CAD Model feature recognition* and organization.
2. A *Knowledge-Based (KB) System* for DfM/DfA rules classification and deposition.
3. A *Rules Validation System* to connect 3D Model feature to DfM/DfA rules contained in the database.

At the same time, from a cost estimation point of view two frameworks was developed, which can be used by designers and engineers for the analytical cost estimation of mechanical products. One framework is dedicated for manufacturing a single component, while the other one is for assembly of a group of parts.

The second issue is solved through a methodology and a software tool that helps designers during the 3D modelling activities and at the same time provide the cost of the part or assembly analysed. The methodology, starting from the 3D CAD model of the part or assembly, extracts necessary information with the aim to recognize parts features needed for cost estimation and for DfM/DfA design rules. After retrieving the information, DfM/DfA and cost analyses can be made, and the designer can then apply the changes suggested in the 3D model.

The proposed CAD-integrated DfM/DfA and cost methodology was used to perform DfM/DfA and cost analysis by using 3D CAD models of 4 parts components (2 forged parts and 2 machined parts) and 2 product (assembly).

The case studies show how the proposed methods is able to discover the design issues avoiding manufacturing/assembly technological problems and at the same time allows the costs reduction. In particular higher advantages are related to parts and assemblies affected by critical issues. Solving these design problems guarantee the production of the part and/or high cost reduction.

Methodology has been implemented in a specific software tool with a structure composed by four main modules: (i) *GUI*, (ii) *Feature recognition*, (iii) *Analysis framework* and (iv) *Database*.

To evaluate the real advantages of using the methodology and tool in design process, two questionnaires were submitted to the tool users after extensive use (more than 6 months). The first one wants to quantify the usability of the software while the second one is focused on the advantages and disadvantages of the software use in design process.

The results related to software usability demonstrate the fully satisfaction of the users, since the total average score obtained by the tool in all the tests is between 8 and 9 for both the companies involved in test. Also concerning the impact of the tool on company traditional process, the results obtained show a fully satisfaction of the requirements given in the statement. In-fact the total average score obtained by the tool in all the tests is between 8 and 9 and this demonstrate the advantages of using the software during the design development.

Another important application of the methods and tool is the possibility to use the proposed approach for teaching initiatives and to educate design students with a learning-by-doing system. Indeed, the learning curve of this new generation of engineers and designers can be boosted up by the adoption of this method.

7.2. Limitations of the research and future works

Few limitations could be observed in the proposed methodology and tool. The first one is the effort needed to update the DfM/DfA rules and cost DB which requires the analysis of many documents to catch the tacit knowledge that can be translated into explicit knowledge (the manufacturing and assembly cost models (section 3.2.4) plus Knowledge acquisition phase (section 3.3.1.1), Knowledge processing phase (section 3.3.1.2) and Knowledge representation phase (section 3.3.1.3)). Another aspect that deserves further investigation concerns the definition of geometric features. To date, researches were focused on manufacturing features related to traditional (i.e., subtractive) manufacturing processes (e.g., hole, slot, pad, pocket, etc.). Since the starting of large diffusion of new additive manufacturing technologies, future research must be also focused on evaluating the impact of these processes on manufacturing feature.

Another limitation is related to the cost estimation framework, in-fact the cost model structure does not provide a method for optimizing the cost of each operation by changing technological parameters (e.g., machine, equipment, consumables) and respecting constraints. For example, the best machine may not be the cheapest one but the one that guarantees the minimum manufacturing cost.

Moreover, the cost routing structure does not provide a method for sorting operations within a manufacturing process. Only validity and priority rules are managed. The operations order may depend on the process; thus, specific rules should be defined.

Then future works could be summarized in five main points:

1. Cost routings and cost models should include rules for optimizing the manufacturing cost of a single operation as well as of the whole process.

2. Cost routing should manage rules required for sorting manufacturing operations. Indeed, the operations instantiated by the proposed approach may not follow the correct production order.

3. Cost routing should also include rules for managing process yield, which may strongly influence the production cost for very innovative processes.

4. Enlargement of DfM rules collection and cost estimation models definition for new technologies with different challenges, as emerging technologies (i.e. additive manufacturing) or auxiliary manufacturing processes (i.e. coating, thermal treatments).
   The first obstacle is the research of DfM rules and cost estimation models for these technologies which will be therefore retrieved and classified based on the described methodology. Furthermore, feature recognition for additive manufacturing processes will be a challenging task due to the nature of this process. In traditional manufacturing processes there are multiple and different operations (e.g., forging, milling, drilling), which are connected to relative manufacturing features (e.g., hole, pocket, slot). A 3D printing process cannot be split down in multiple manufacturing features. This situation implies the need to devise a new feature concept applicable to these additive manufacturing technologies.

5. Extension of the methodology and tool in other design aspects, as sustainability or disassembly. Using new analytical models could be calculate other design requirements (e.g., environmental indicators, de-manufacturing time) and then is possible to consider multiple design targets (e.g., Design for Environment, Design for Manufacturing Planning, Design for Disassembly). Feature of the parts and their properties could relate to dedicated indices (i.e., environmental impact indices as CO2 emissions), calculated through analytical models. Thus, new embedded CAD environments can be developed (CAD-integrated Design for X systems), providing a complete overview of the project requirements and life cycle performances.

8. References

[1] Ahlmann H., 1998. ABB Industrial Manual, Lunds Tekniska Högskola

[2] Anderson D.M., 2014. Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low-Cost, High-Quality Products for Lean Production. CRC Press. https://doi.org/10.1201/b16501

[3] Arundacahawat P., Roy R., Al-Ashaab A., 2013. An analogy-based estimation framework for design rework efforts. Journal of Intelligent Manufacturing 24(3): 625-639. https://doi.org/10.1007/s10845-011-0605-6

[4] Ashby M.F., 2010. Materials Selection in Mechanical Design. 4th Edition. Butterworth-Heinemann. ISBN: 978-9380931722

[5] ASM International Handbook Committee, 1989. Asm Handbook Volume 16 Machining. ISBN: ISBN: 978-0-87170-022-3

[6] ASM International Handbook Committee, 2005. Asm Handbook Volume 14A Metalworking: Bulk Forming. ISBN: 978-0-87170-708-6

[7] Ball M., Fleischer M.A., Church D.G., 2000. A product design system for optimization-based tradeoff analysis. 2000 ASME Design Engineering Technical Conference.

[8] Bandor, M.S., 2006. Quantitative Methods for Software Selection and Evaluation. Pittsburgh: Carnegie Mellon University. CMU/SEI-2006-TN-026. https://doi.org/10.1184/R1/6582749.v1

[9] Barbosa G.F., Carvalho J., 2013. Guideline tool based on design for manufacturing and assembly (DFMA) methodology for application on design and manufacturing of aircrafts. Journal of the Brazilian Society of Mechanical

Sciences and Engineering 36: 605-614. https://doi.org/10.1007/s40430-013-0103-1

[10] Barg S., Flager F., Fischer M., 2018. An analytical method to estimate the total installed cost of structural steel building frames during early design. Journal of Building Engineering 15: 41-50. https://doi.org/10.1016/j.jobe.2017.10.010

[11] Bateman R.J., Cheng K., 2006. Extending the product portfolio with ‘devolved manufacturing’: methodology and case studies. International Journal of Production Research 44(16): 3325-3343. https://doi.org/10.1080/00207540500536947

[12] Benabdellah A.b., Bouhaddou A., Benghabrit A., Benghabrit O., 2019. A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives. International Journal of Advanced Manufacturing Technology 102: 3473-3502. https://doi.org/10.1007/s00170-019-03418-6

[13] Ben-Arieh D., Li Q., 2001. Remote Cost Estimation of Machined Parts. IFAC Proceedings Volumes 34(10): 97-102. https://doi.org/10.1016/S1474-6670(17)34178-2

[14] Benkamoun N., El Maraghy W., Huyet A.L., Kouiss K., 2014. Architecture framework for manufacturing system design. Procedia CIRP 17: 88-93. https://doi.org/10.1016/j.procir.2014.01.101

[15] Berlioz M., Marin P., Tichkiewitch S., 1999. A Fast and Reliable Cost-Estimation Tool for Hot-Forged Parts. Integrated Design and Manufacturing in Mechanical Engineering ’98: 595-602. https://doi.org/10.1007/978-94-015-9198-0_73

[16] Boothroyd G., 1994. Product design for manufacture and assembly. Computer-Aided Design 26(7): 505-520. https://doi.org/10.1016/0010-4485(94)90082-5

[17] Boothroyd G., Dewhurst P., Knight W. A., 2011. Product Design for Manufacture and Assembly 3rd Edition. CRC Press. ISBN: 978-1420089271

[18] Boothroyd G., Knight W.,1993. Design for assembly. IEEE Spectrum 30(9): 53-55. https://doi.org/10.1109/6.275164

[19] Boothroyd G., Radovanovic P., 1989. Estimating the Cost of Machined Components During the Conceptual Design of a Product. CIRP Annals 38(1): 157-160. https://doi.org/10.1016/S0007-8506(07)62674-2

[20] Bouaziz Z., Ben Younes J., Zghal A., 2006. Cost estimation system of dies manufacturing based on the complex machining features. International Journal of Advanced Manufacturing Technology 28: 262-271. https://doi.org/10.1007/s00170-004-2179-3

[21] Bralla J., 1998. Design for Manufacturability Handbook. McGraw-Hill Professional. ISBN: 978-0070071391

[22] Budiono H.D.S., Kiswanto G., Soemardi T.P., 2014. Method and Model Development for Manufacturing Cost Estimation during the early design phase related to the complexity of the machining processes. International Journal of Technology 5(2): 183-192. https://doi.org/10.14716/ijtech.v5i2.402

[23] Bukchin J., Masin M., 2004. Multi-objective design of team oriented assembly systems. European Journal of Operational Research 156(2): 326-352. https://doi.org/10.1016/S0377-2217(03)00054-7

[24] Campi F., Favi C., Mandolini M., Germani M., 2019. Using design geometrical features to develop an analytical cost estimation method for axisymmetric components in open-die forging. Procedia 84: 656-661. https://doi.org/10.1016/j.procir.2019.04.324

[25] Campi F., Mandolini M., Favi C., Checcacci E., Germani M., 2020. An analytical cost estimation model for the design of axisymmetric components with open-die forging technology. The International Journal of Advanced Manufacturing Technology 110: 869-1892. https://link.springer.com/article/10.1007/s00170-020-05948-w

[26] Chang K.H., 2016. e-Design Computer-Aided Engineering Design, 1st Edition. Academic Press. https://doi.org/10.1016/C2009-0-63076-2

[27] Chang P.C., Lin J.J, Dzan W.Y, 2012. Forecasting of manufacturing cost in mobile phone products by case-based reasoning and artificial neural network models. International Journal of Intelligent Manufacturing 23(3): 517-531. https://doi.org/10.1007/s10845-010-0390-7

[28] Chen W.L., Xie S.Q., Zeng F.F., Li B.M., 2011. A new process knowledge representation approach using parameter flow chart. Computers in Industry 62(1): 9-22. https://doi.org/10.1016/j.compind.2010.05.016

[29] Chiadamrong N., 2003. The development of an economic quality cost model. Total Quality Management & Business Excellence 14(9): 999-1014. https://doi.org/10.1080/1478336032000090914.

[30] Choi S.H., Dean T.A., 1984. Computer aids to data preparation for cost estimation. International Journal of Machine Tool Design and Research 24(2): 105-119. https://doi.org/10.1016/0020-7357(84)90036-2

[31] Chougule R.G., Ravi B., 2006. Casting Cost Estimation in an Integrated Product and Process Design Environment. International Journal of Computer Integrated Manufacturing 19(7): 676-688. https://doi.org/10.1080/09511920500324605

[32] Ciambrone D. 2007. Effective Transition from Design to Production, Auerbach Publications. ISBN: 9781420046861

[33] Cicconi P., Germani M., Mandolini M., 2010. How to Support Mechanical Product Cost Estimation in the Embodiment Design Phase. In P. Jerzy, F. Shuichi, & J. Salwìnski (Eds.), New world situation: new directions in concurrent engineering 1: 465-477. http://doi.org/10.1007/978-0-85729-024-3_45

[34] Cicconi P., Germani M., Mandolini M., Marconi M., 2013. Tool for Life Cycle Costing of Electric Motors during the Early Design Phases. Proceedings of the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013). https://doi.org/10.1007/978-3-319-02054-9_73

[35] D'Urso G., Quarto M., Ravasio C., 2017. A model to predict manufacturing cost for micro-EDM drilling. International Journal of Advanced Manufacturing Technology 91: 2843-2853. https://doi.org/10.1007/s00170-016-9950-0

[36] Darai D.S., Singh S., Biswas S., 2010. Knowledge Engineering-an overview. International Journal of Computer Science and Information Technologies 1(4): 230-234. https://doi.org/ijcsit2010010406

[37] Darken R., Darken C.J., 1996. VR + AI = intelligent environments: A synergistic approach to engineering design support. Stereoscopic Displays and Virtual Reality Systems III 2653: 292-300. https://doi.org/10.1117/12.237450

[38] De Fazio T.L., Rhee S.J., Whitney D.E., 1999. Design-specific approach to design-for-assembly (DFA) for complex mechanical assemblies. IEEE Transactions on Robotics and Automation 15(5): 869-881. https://doi.org/10.1109/70.795792

[39] De Moor A., 2007. The Pragmatic Evaluation of Tool System Interoperability. Proceedings. of the 2nd ICCS Conceptual Structures Tool Interoperability Workshop (CS-TIW 2007). Research Press International, Bristol, UK: 1-19.

[40] De Toni A, Meneghetti A., 2000. Traditional and innovative paths towards timebased competition. International Journal of Products Economics 66(3):255-268. https://doi.org/10.1016/S0925-5273(99)00140-1

[41] Deneux D. 1999. Introduction to assembly features: an illustrated synthesis methodology. Journal of Intelligent Manufacturing 10 (1): 29-39. https://doi.org/10.1023/A:1008912429442

[42] Desai A., Mital A., 2010. Facilitating Design For Assembly Through The Adoption Of A Comprehensive Design Methodology. International Journal of Industrial Engineering, 17(2): 92-102.

[43] Dewhurst P., Boothroyd G., 1988. Early cost estimating in product design. Journal of Manufacturing Systems 7(3): 183-191. https://doi.org/10.1016/0278-6125(88)90003-9

[44] Dewhurst P., Blum C., 1989. Supporting analyses for the economic assessment of diecasting in product design. CIRP Annals 38(1):161-164. https://doi.org/10.1016/S0007-8506(07)62675-4

[45] Dimache A., Dimache L., Zoldi E., Roche T., 2007. Life Cycle Cost Estimation Tool for Decision-Making in the Early Phases of the Design Process.

Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses: 455-459. https://doi.org/10.1007/978-1-84628-935-4_79

[46] Dixon J., Cunningham J. 1988. Design with features: the origin of features. Proceedings ASME computer in engineering conference, San Francisco.

[47] Doan N.W., Bloor M.I.G., Wilson M.J.,1993. A Strategy for the Automated Design of Mechanical Parts," 2nd ACM Solid Modeling Conference: 15-21. https://doi.org/10.1145/164360.164370

[48] Durairaj S.K. Ong S.K., Nee A.Y.C., Tan R.B.H., 2002. Evaluation of Life-Cycle Cost analysis methodologies. Corporate Environmental Strategy 9(1): 30-39. https://doi.org/10.1016/S1066-7938(01)00141-5

[49] Duverlie P., Castelain J.M., 1999. Cost estimation during design step: parametric method versus case based reasoning method. International Journal of Advanced Manufacturing Technology 15(12): 895-906. https://doi.org/10.1007/s001700050147

[50] El Wakil S.D. 2019. Processes and Design for Manufacturing, 3rd Edition, CRC Press. ISBN: 9781138581081

[51] Everhart T.E., Thornley R.F.M. (1960) Wide-band detector for micro-microampere low-energy electron currents. Journal of Scientific Instruments 37(7): 246-248. https://doi.org/10.1088/0950-7671/37/7/307

[52] Fagade A., Kazmer D., 2000. Early cost estimation of injection molded components. Journal of Injection Molding Technology 4(3): 97-106.

[53] Fan Y., Zhao D., Zhang L., Huang S., Liu B., 2003. Manufacturing grid: needs, concept, and architecture. International conference on grid and cooperative computing: 653-656. https://doi.org/10.1007/978-3-540-24679-4_115

[54] Farineau T., Rabenasolo B., Castelain J.M., Meyer Y., Duverlie P., 2001. Use of parametric models in an economic evaluation step during the design phase. International Journal of Advanced Manufacturing Technology 17(2): 79-86. https://doi.org/10.1007/s001700170195

[55] Favi C., Campi F., 2020. CAD-based design for welding (DFW) method. International Journal on Interactive Design and Manufacturing (IJIDeM). https://doi.org/10.1007/s12008-020-00727-z

[56] Favi C., Garziera R., Campi F., 2021. A Rule-Based System to Promote Design for Manufacturing and Assembly in the Development of Welded Structure: Method and Tool Proposition. Applied Sciences 11(5): 2326. https://doi.org/10.3390/app11052326

[57] Favi C., Germani M., Mandolini M., 2016. Design for Manufacturing and Assembly vs. Design to Cost: Toward a Multi-objective Approach for Decision-making Strategies during Conceptual Design of Complex Products. Procedia CIRP 50: 275-280. https://doi.org/10.1016/j.procir.2016.04.190

[58] Favi C., Germani M., Mandolini M., 2017. Analytical Cost Estimation Model in High Pressure Die Casting. Procedia Manufacturing 11: 526-535. https://doi.org/10.1016/j.promfg.2017.07.146

[59] Favi C., Germani M., Mandolini M., 2018. Development of complex products and production strategies using a multi-objective conceptual design approach. International Journal of Advanced Manufacturing Technology 95(1-4): 1281-1291. https://doi.org/10.1007/s00170-017-1321-y

[60] Favi C., Germani M., Mandolini M., Marconi M., 2018. Implementation of a software platform to support an eco-design methodology within a

manufacturing firm, International Journal of Sustainable Engineering 11(2): 79-96. https://doi.org/10.1080/19397038.2018.1439121

[61] Feng C., Kusiak A., Huang C., 1996. Cost evaluation in design with form features. Computer Aided Design 28(11): 875-885. https://doi.org/10.1016/0010-4485(96)00009-7

[62] Feyen, R., Liu, Y., Chaffin, D., Jimmerson, G., Joseph, B., 2000. Computer-aided ergonomics: a case study of incorporating ergonomics analyses into workplace design, Applied Ergonomics 31 (3): 291-300. https://doi.org/10.1016/S0003-6870(99)00053-8

[63] Gao J.X., Manson B.M., Kyratsis P., 2000. Implementation of concurrent engineering in the suppliers to the automotive industry. Journal of Materials Processing Technology 107(1-3): 201-208. https://doi.org/10.1016/S0924-0136(00)00669-5

[64] Garcia-Crespo A., Ruiz-Mezcua B., Lopez-Cuadrado J.L., Gomez-Berbis J.M., 2010. Conceptual model for semantic representation of industrial manufacturing processes. Computers in Industry 61(7): 595-612. https://doi.org/10.1016/j.compind.2010.01.004

[65] García-Crespo Á., Ruiz-Mezcua B., López-Cuadrado J.L., González-Carrasco I., 2011. A review of conventional and knowledge based systems for machining price quotation. Journal of Intelligent Manufacturing 22(6): 823-841. https://doi.org/10.1007/s10845-009-0335-1

[66] Gonçalves-Coelho A.M., Mourao A.J., 2007. Axiomatic design as support for decision-making in a design for manufacturing context: a case study. International Journal of Products Economics 109(1–2): 81-89. https://doi.org/10.1016/j.ijpe.2006.11.002

[67] Grabowik C., Knosala R., 2003. The method of knowledge representation of a CAPP system. Journal of Material Process Technology 133(1-2): 90-98. https://doi.org/10.1016/S0924-0136(02)00249-2

[68] Greenberg G., Fitzpatrick G., Gutwin C., Kaplan S., 2000. Adapting the locales framework for heuristic evaluation of groupware. Australian Journal of Information Systems 7: 102-108. http://dx.doi.org/10.11575/PRISM/30631

[69] Gröger, C., Schwarz, H., Mitschang, B., 2014. The Manufacturing Knowledge Repository. Consolidating Knowledge to Enable Holistic Process Knowledge Management in Manufacturing. In: Proceedings of the 16th International Conference on Enterprise Information Systems (ICEIS), pp. 39-51.

[70] Groover M. 2007. Automation, production systems, and computer-integrated manufacturing. Prentice Hall Press.

[71] H'mida F., Martin P., Vernadat F., 2006. Cost estimation in mechanical production: The Cost Entity approach applied to integrated product engineering. International Journal of Production Economics 103(1): 17-35. https://doi.org/10.1016/j.ijpe.2005.02.016.

[72] Haddad C.J., 1992. Concurrent Engineering in the Automotive Industry: Prospects for Worker Participation IFAC Proceedings Volumes 25 (27): 75-81. https://doi.org/10.1016/S1474-6670(17)49561-9

[73] Han J, Pratt M., Regli W.C., 2000. Manufacturing Feature Recognition from Solid Models: A Status Report, IEEE Transactions on Robotics and Automation, Vol. 16, No 6, pp. 782-796

[74] Haque B, Pawar K.S., Barson R.J., 2000. Analysing organisational issues in concurrent new product development. International Journal of Production Economics 67(2):169-182. https://doi.org/10.1016/S0925-5273(00)00017-7

[75] Hausler S., Buschermohle, Koppe R., Hahn A., 2009. Towards Process Change Impact Analysis in Industrial Engineering. Industrial Engineering and Engineering Management, IEEM 2009. https://doi.org/10.1109/IEEM.2009.5373075

[76] Herder P.M., Weijnen M.P.C., 2000. A concurrent engineering approach to chemical process design. International Journal of Production Economics 64(1-3): 311-318. https://doi.org/10.1016/S0925-5273(99)00068-7

[77] Holt R., Barnes C., 2010. Towards an integrated approach to "Design for X": an agenda for decision-based DFX research. Research in Engineering Design 21(2): 123-136. https://doi.org/10.1007/s00163-009-0081-6

[78] Holzner P., Rauch E., Spena P.R., Matt D.T., 2015. Systematic design of SME manufacturing and assembly systems based on axiomatic design. Procedia CIRP 34:81-86. https://doi.org/10.1016/j.procir.2015.07.010

[79] Hooshmand Y, Köhler P, Korff-Krumm A., 2016. Cost Estimation in Engineer-to-Order Manufacturing. Open Engineering 1:22-34. https://doi.org/10.1515/eng-2016-0002

[80] Hoque A.S.M., Halder P.K., Parvez M.S., Szecsi T., 2013. Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment. Computers & Industrial Engineering 66: 988-1003. https://doi.org/10.1016/j.cie.2013.08.016

[81] https://dfmpro.com/

[82] https://galorath.com/seer-for-manufacturing/

[83] https://quotecam.com/

[84] https://schouenc.home.xs4all.nl/

[85] https://sourceforge.net/projects/imcycletimeest/

[86] https://www.almacam.com/products/almaquote/

[87] https://www.apriori.com/

[88] https://www.avix.eu/process-mapping-tools/avix-dfx

[89] https://www.cnccookbook.com/g-wizard-cnc-speeds-and-feeds-calculator/

[90] https://www.custompartnet.com/

[91] https://www.dfma.com/

[92] https://www.jetcam.com/quickcost.php

[93] https://www.metalix.net/solutions/quoting-cost-estimation/

[94] https://www.microest.com/index.html

[95] https://www.mtisystems.com/index.html

[96] https://rapidmanufacturing.com/erapid/

[97] https://www.solidworks.com/it

[98] https://www.ufab.io/

[99] https://www.ulprospector.com/costmate

[100] Huang G.Q., Mak K.L., 1998. The DFX shell: a generic framework for developing design for X tools. Robotics and Computer-Integrated Manufacturing 13(3): 271-280. https://doi.org/10.1016/S0736-5845(97)00006-9

[101] IDA Report R-338. Alexandria. USA: Institute for Defense Analyses (IDA); 1986.

[102] Ishii K, 1993. Modeling of concurrent engineering design. in Andrew Kusiak, editor, Concurrent Engineering: Automation, Tools and Techniques, pages 19-39. John Wiley & Sons, Inc.

[103] Jiang Y., Peng G., Liu W., 2010. Research on ontology-based integration of product knowledge for collaborative manufacturing. The International Journal of Advanced Manufacturing Technology 49:1209-1221. https://doi.org/10.1007/s00170-009-2463-3

[104] Jung J.Y., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. Journal of Intelligent Manufacturing 13(4): 227–238. https://doi.org/10.1023/A:1016092808320

[105] Kalpakjian S, Schmid S, 2017. Manufacturing Processes for Engineering Materials, 6th Edition, Pearson. ISBN: 978-0132272711

[106] Kaluza A., Kleemann S., Fröhlich T., Herrmann C., Vietorbc T., 2017. Concurrent Design & Life Cycle Engineering in Automotive Lightweight Component Development. Procedia CIRP Volume 66: 16-21. https://doi.org/10.1016/j.procir.2017.03.293

[107] Kamrani A.K., Nasr E. A., 2010. Engineering Design and Rapid Prototyping. Springer Science+Business Media, LLC. https://doi.org/10.1007/978-0-387-95863-7

[108] Kayis B., Arndt G., Zhou M, Amornsawadwatana S., 2007. A Risk Mitigation Methodology for New Product and Process Design in Concurrent Engineering Projects. CIRP Annals 56(1): 167-170. https://doi.org/10.1016/j.cirp.2007.05.040

[109] Kayis B., Arndt G., Zhou M., Savci S., Khoo Y.B., Rispler A., 2006. Risk Quantification for New Product Design and Development in a Concurrent

Engineering Environment. CIRP Annals 55(1): 147-150. https://doi.org/10.1016/S0007-8506(07)60386-2

[110] Khan R.A, Mustafa K., Ahson S.I., 2007. An empirical validation of object oriented design quality metrics. Journal of King Saud University - Computer and Information Sciences 19:1-16. https://doi.org/10.1016/S1319-1578(07)80001-2

[111] Kim J.S., Kim C.G., Hong C.H., Hahn H.T., 2000. Development of concurrent engineering system for design of composite structures. Composite Structures 50(3): 297-309. https://doi.org/10.1016/S0263-8223(00)00120-3

[112] Kimura F. 2001 Geometric Modelling: Theoretical and Computational Basis towards Advanced CAD Applications. Springer. https://doi.org/10.1007/978-0-387-35490-3

[113] Kingsman B.G., de Souza A.A., 1997. A knowledge-based decision support system for cost estimation and pricing decisions in versatile manufacturing. International Journal of Production Economics 53: 119-139. https://doi.org/10.1016/S0925-5273(97)00116-3

[114] Knight, W.A., 1992. Simplified Early Cost Estimating for Hot-Forged Parts. International Journal of Advanced Manufacturing Technology 7(3): 159-167. https://doi.org/10.1007/BF02601619

[115] Komoto, H., Tomiyama, T., 2012. A framework for computer-aided conceptual design and its application to system architecting of mechatronics products. Computer-Aided Design 44 (10): 931-946. https://doi.org/10.1016/j.cad.2012.02.004

[116] Koonce D, Judd R., Keyser T., 2000. A Cost Estimation Tool Integrated into FIPER. International Working Conference on the Design of Information Infrastructure Systems for Manufacturing DIISM 2000: Global Engineering,

Manufacturing and Enterprise Networks: 396-402. https://doi.org/10.1007/978-0-387-35412-5_46

[117] Koonce D., Judd R., Sormaz D., Masel D.T., 2003. A hierarchical cost estimation tool. Computers in Industry 50(3): 293-302. https://doi.org/10.1016/S0166-3615(03)00016-2

[118] Kulon J., Broomhead P., Mynors D.J., 2006. Applying knowledge based engineering to traditional manufacturing design. The International Journal of Advanced Manufacturing Technology 30: 945-951. https://doi.org/10.1007/s00170-005-0067-0

[119] Kuo T., Huang S. and Zhang H., 2001. Design for manufacture and design for X_ concepts- applications and perspectives. Computers and Industrial Engineering, 41 (3): 241-260.

[120] Leaney P.G., Wittenberg G., 1992. Design For Assembling: The Evaluation Methods Of Hitachi, Boothroyd And Lucas. Assembly Automation, 12 (2): 8-17. https://doi.org/10.1108/eb004359

[121] Lee, H.S., Chang, S.L., 2003. Development of a CAD/CAE/CAM system for a robot manipulator, Journal of Materials Processing Technology, 140 (1-3): 100-104. https://doi.org/10.1016/S0924-0136(03)00695-2

[122] Lehmhus D., Wuest T., Wellsandt S., Bosse S., Kaihara T., Thoben K.D., Busse M., 2015. Cloud-based automated design and additive manufacturing: a usage data-enabled paradigm shift. Sensors 15(12): 32079-32122. https://doi.org/10.3390/s151229905

[123] Li C., 2014. An analytical method for cost analysis in multi-stage supply chains: A stochastic network model approach. Applied Mathematical Modelling 38(11-12): 2819-2836. https://doi.org/10.1016/j.apm.2013.10.056

[124] Li L., Zheng Y., Yange M., Leng J., Cheng Z., Xie Y., Jiang P., Ma Y. 2020. A survey of feature modeling methods: Historical evolution and new development. Robotics and Computer Integrated Manufacturing 61: 101851. https://doi.org/10.1016/j.rcim.2019.101851

[125] Likert R., 1932. A Technique for the Measurement of Attitudes. New York, NY: Woodworth.

[126] Liu D.Z., Liu M., Zhong P.S., 2004. Method of Product Development Process Analysis and Reengineering for Concurrent Engineering. Materials Science Forum 471-472:770-774. https://doi.org/10.4028/www.scientific.net/MSF.471-472.770

[127] Logistics Management Institute (LMI). 1965. Life cycle costing in equipment procurement. Report no. LMI task 4C-5, Washington, D.C.

[128] Luong, L., Spedding, T., 1995. An integrated system for process planning and cost Estimation in hole making. International Journal of Advanced Manufacturing Technology 10(6): 411-415. https://doi.org/10.1007/BF01179405

[129] Maciol A., 2017. Knowledge-based methods for cost estimation of metal casts. The International Journal of Advanced Manufacturing Technology 91: 641-656. https://doi.org/10.1007/s00170-016-9704-z

[130] Mahadik A., Masel D.T., 2018. Implementation of Additive Manufacturing Cost Estimation Tool (AMCET) Using Break-down Approach. 28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018). https://doi.org/10.1016/j.promfg.2018.10.014

[131] Mandolini M, Campi F., Favi C., Germani M., Raffaeli R., 2020. A framework for analytical cost estimation of mechanical components based on manufacturing knowledge representation. The International Journal of Advanced

Manufacturing Technology 107:1131-1151. https://doi.org/10.1007/s00170-020-05068-5

[132] Mantyla M., Dana N., Jami S. 1996. Challenges in features-based manufacturing research. Communications of the ACM 39 (2):77-85. https://doi.org/10.1145/230798.230808

[133] Mao Y., Zhang J., Letaief K.B., 2015. A Lyapunov optimization approach for green cellular networks with hybrid energy supplies. IEEE Journal on Selected Areas in Communications 33(12): 2463-2477. https://doi.org/10.1109/JSAC.2015.2481209

[134] Marconi, M., Germani, M., Favi, C., Raffaeli, R., 2018. CAD feature recognition as a means to prevent ergonomics issues during manual assembly tasks. Computer-Aided Design and Applications 15 (5), 734-736. https://doi.org/10.1080/16864360.2018.1441240

[135] Martinelli I., Campi F., Checcacci E., Lo Presti G.M., Pumo A., Germani M., 2019. Cost Estimation Method for Gas Turbine in Conceptual Design Phase. Procedia CIRP 84: 650-655. https://doi.org/10.1016/j.procir.2019.04.311

[136] Matt D.T., Rauch E., 2017. Designing assembly lines for mass customization production systems. Mass customized manufacturing: theoretical concepts and practical approaches, 1st edn Routledge, New York, pp 15-36.

[137] Mauchand M., Siadat A., Bernard A., Perry N., 2008. Proposal for Tool-based Method of Product Cost Estimation during Conceptual Design. Journal of Engineering Design 19 (2): 159-170. https://doi.org/10.1080/09544820701802857

[138] Maulana M.I.I.M., Flisiak J.W., Alashaab A., Araci Z.C., Lasisz P.W., Beg N., Rehman A., 2016. The Application of Set-Based Concurrent Engineering to

Enhance the Design Performance of Surface Jet Pump. WSEAS Transactions on Business and Economics 13: 634-643.

[139] March S. T., Smith G. F., 1995. Design and natural science research on information technology. Decision Support Systems, 15(4): 251-266, https://doi.org/10.1016/0167-9236(94)00041-2

[140] Minis I., Herrmann J.W., Lam G., Lin E., 1999. A Generative Approach for Concurrent Manufacturability Evaluation and Subcontractor Selection. Journal of Manufacturing Systems 18(6): 383-395. https://doi.org/10.1016/S0278-6125(00)87641-4

[141] Mital A., Desai A., Subramanian A., Mital A., 2015. Product Development A Structured Approach to Consumer Product Development, Design, and Manufacture, Second Edition. Elsevier.

[142] Mitchell N.B., 1992. A Simple Method for Hardware and Software Evaluation. Applied Ergonomics 23(4): 277-280. https://doi.org/10.1016/0003-6870(92)90156-P.

[143] Molloy O., Warman E., Tilley S., 1998. Design for Manufacturing and Assembly: Concepts, architectures and implementation, Chapman & Hall. ISBN: 9780412781902

[144] Morbidoni A., Favi C., Germani, M., 2011. CAD-Integrated LCA Tool: Comparison with dedicated LCA Software and Guidelines for the Improvement. Glocalized Solutions for Sustainability in Manufacturing: 569-574. https://doi.org/10.1007/978-3-642-19692-8_99

[145] Moultrie J., Maier A.M., 2014. A simplified approach to design for assembly. Journal of Engineering Design, 25(1-3): 44-63. https://doi.org/10.1080/09544828.2014.887059

[146] Nagahanumaiah, Ravi B., Mukherjee N.P., 2005. An integrated framework for die and mold cost estimation using design features and tooling parameters. The International Journal of Advanced Manufacturing Technology 26: 1138-1149. https://doi.org/10.1007/s00170-004-2084-9

[147] Nagahanumaiah, Subburaj K., Ravi B., 2008. Computer aided rapid tooling process selection and manufacturability evaluation for injection mold development. Computers in Industry 59: 262-276. https://doi.org/10.1016/j.compind.2007.06.021

[148] Nahm Y.E., Ishikawa H.A., 2006. new 3D-CAD system for set-based parametric design. The International Journal of Advanced Manufacturing Technology: 29:137-150. https://doi.org/10.1007/s00170-004-2213-5

[149] Naranje V., Kumar S., Hussein H.M.A., 2014. A Knowledge Based System for Cost Estimation of Deep Drawn Parts. Procedia Engineering 97: 2313-2322. https://doi.org/10.1016/j.proeng.2014.12.476

[150] Nasr E.A., Kamrani A.K., 2006. Computer Based Design and Manufacturing. Springer US. ISBN: 978-0-387-23324-6

[151] Niazi A., Dai J.S., Balabani S., Seneviratne L., 2005. Product Cost Estimation: Technique Classification and Methodology Review. Journal of Manufacturing Science and Engineering 128(2): 563-575. https://doi.org/10.1115/1.2137750

[152] Nielsen J., 1994. Enhancing the explanatory power of usability heuristics. CHI'94: Proceedings of the SIGCHI Conference on Human Factors in Computing: 152-158. https://doi.org/10.1145/191666.191729

[153] Nielsen J., Mack R.L., 1994. Usability inspection methods. John Wiley & Sons, New York, NY. ISBN: 978-0471018773.

[154] Nielsen J., Molich R., 1990. Heuristic evaluation of user interfaces. In Proceedings of ACM CHI 90: 249-256. https://doi.org/10.1145/97243.97281

[155] Nielsen J., Norman D., 2000. Web-site usability: Usability on the web isn't a luxury. Information Week. http://www.informationweek.com/773/web2.htm

[156] O'Grady P., Young R.E., Greef A., Smith L., 1991. An advice system for concurrent engineering. International Journal of Computer Integrated Manufacturing 4(2): 63-70. https://doi.org/10.1080/09511929108944481

[157] Orady E.A., Newcombe R.W., Yellowley I., 1979. Computer AIDED Estimation of the Manufacturing Time for Turned Components. Proceedings of the Nineteenth International Machine Tool Design and Research Conference: 295-303. https://doi.org/10.1007/978-1-349-81412-1_36

[158] Ou-Yang C., Lin T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. International Journal of Advanced Manufacturing Technology 13: 618-629. https://doi.org/10.1007/BF01350820

[159] Ozbayraka M., Akgunb M., Turker A.K., 2004. Activity-based cost estimation in a push/pull advanced manufacturing system. International Journal of Production Economics 87: 49-65. https://doi.org/10.1016/S0925-5273(03)00067-7

[160] Pahl G., Beitz W., Feldhusen J., Grote K.H., 2007. Engineering Design: A Systematic Approach (3rd edition). Springer-Verlag London. https://doi.org/10.1007/978-1-84628-319-2

[161] Pech J.C., Bonneau G., Fallot J., 1973. Purification partielle et proprietes des amylases de la poire. Phytochemistry 12(2): 299-305

[162] Poli C. 2001. Design for manufacturing: a structured approach, Elsevier. ISBN: 9780750673419

[163] Prat N., Comyn-Wattiau I., Akoka J., 2014. Artifact evaluation in Information systems design science research – a holistic view. PACIS 2014 Proceedings. 23, http://aisel.aisnet.org/pacis2014/23.

[164] Pratt M.J., Wilson P.R. 1985. Requirements for support of form features in a solid modeling system. Final report, CAM-I Report R-85-ASPP.-01.

[165] Putnik G.D., Putnik Z., 2019. Defining Sequential Engineering (SeqE), Simultaneous Engineering (SE), Concurrent Engineering (CE) and Collaborative Engineering (ColE): On similarities and differences. Procedia CIRP 84: 68-75. https://doi.org/10.1016/j.procir.2019.07.005

[166] Ramnath B.V., Elanchezhian C., Naveen E., Rekha G., Vidhyarajan M., Manivannan M., Dhanush J., 2018. Implementation of Concurrent Redesign & Manufacture procedure for an automotive component. Materials Today: Proceedings 5(1 Part 1): 1418-1424. https://doi.org/10.1016/j.matpr.2017.11.228

[167] Rush C., Roy R., 2001. Expert judgement in cost estimating: modelling the reasoning process. Concurrent Engineering 9(4): 271-284. https://doi.org/10.1177/1063293X0100900404

[168] Ryan, W. J., 1968. Procurement views of life cycle costing. Proceedings of the Annual Symposium on Reliability 164–168.

[169] Sajadfar N., Ma Y., 2015. A hybrid cost estimation framework based on feature-oriented data mining approach. Advanced Engineering Informatics 29(3): 633-647. https://doi.org/10.1016/j.aei.2015.06.001

[170] Sajid M., Wasim A., Hussain S., Jahanzaib M., 2018. Manufacturing feature-based cost estimation of cast parts. China Foundry 15(6): 464-469. https://doi.org/10.1007/s41230-018-8084-4

[171] Salonitis K., 2014. Modular design for increasing assembly automation. CIRP Annals 63(1): 189-192. https://doi.org/10.1016/j.cirp.2014.03.100

[172] Sanfilippo E.M., Borgo S. 2016. What are features? An ontology-based review of the literature. Computer-Aided Design 80: 9-18. http://dx.doi.org/10.1016/j.cad.2016.07.001

[173] Sapuan S.M., Mansor M.R., 2014. Concurrent engineering approach in the development of composite products: A review Materials & Design 58: 161-167 https://doi.org/10.1016/j.matdes.2014.01.059

[174] Shah J.J., Mäntylä M. 1995. Parametric and feature-based CAD/CAM. Concepts, techniques, applications. John Wiley and Sons.

[175] Shahrokhi M., Bernard A., Shidpour H., 2011. A hybrid method to select best process and suppliers, in the concurrent engineering environment. IFAC Proceedings Volumes 44(1): 6402-6406. https://doi.org/10.3182/20110828-6-IT-1002.00904

[176] Shehab E.M, Abdalla H.S., 2002. An Intelligent Knowledge-Based System for Product Cost Modeling. International Journal of Advanced Manufacturing Technology 191(1): 49-65. https://doi.org/10.1007/PL00003967

[177] Siadat A., Dantan J.Y., Mauchand M., Martin P., 2007. A Cost Estimation System For Manufacturing Product Using Ontology And Exepert System. IFAC Proceedings Volumes 40(18): 37-42. https://doi.org/10.3182/20070927-4-RO-3905.00008

[178] Sivaji A., Abdullah A., Downe A.G., 2011. Usability Testing Methodology: Effectiveness of Heuristic Evaluation in E- Government Website Development. Proceedings of 2011 Fifth Asia Modelling, AMS 2011 Conference: 68-72. https://doi.org/10.1109/AMS.2011.24

[179] Soundar P., Bao H.P., 1994. Concurrent design of products for manufacturing system performance," Proceedings of the IEEE 1994 International Engineering Management Conference: 233-240. https://doi.org/10.1109/IEMC.1994.379925

[180] Sreevalsan P.C., Shah J.J. 1992. Unification of form feature definition methods. Intelligent Computer Aided Design, Browns DC, Waldron M, Yoshikawa H eds: 83-106.

[181] Stone R.B., McAdams D. A., Kayyalethekkel V.J., 2004. A product architecture-based conceptual DFA technique. Design Studies 25 (3): 301-325. https://doi.org/10.1016/j.destud.2003.09.001

[182] Streppel A.H., Weustink I.F., Brinke E., Kals H.J.J., 2003. A generic framework for cost estimation and cost control in product design. Journal of Materials Processing Technology 103 (1): 141-148. https://doi.org/10.1016/S0924-0136(00)00405-2

[183] Suh N.P., 1990. The Principles of Design. Oxford University Press, New York. ISBN: 978-0195043457

[184] Syan C., Menon U., 1992. Concurrent Engineering Concepts, implementation and practice. Springer Netherlands. https://doi.org/10.1007/978-94-011-1298-7

[185] Tao, J., Li, L., Yu, S., 2018. An innovative eco-design approach based on integration of LCA, CAD\CAE and optimization tools, and its implementation

perspectives. Journal of Cleaner Production, 187: 839-851. https://doi.org/10.1016/j.jclepro.2018.03.213

[186] Thompson M.K., Jespersen I.K.J., Kjærgaard T., 2018. Design for manufacturing and assembly key performance indicators to support high-speed product development. Procedia CIRP 70:114-119. https://doi.org/10.1016/j.procir.2018.02.005

[187] Ulrich K.T., Eppinger S.D., 2003. Product Design and Development, 3rd ed. USA, McGraw-Hill Inc.

[188] Unglert J., Hoekstra S., Jauregui-Becker J., van Houten F., 2016. Towards decision-support for reconfigurable manufacturing systems based on computational design synthesis. Procedia CIRP 41: 153-158. https://doi.org/10.1016/j.procir.2015.12.053

[189] Urbanic R.J., Saqib S.M., 2019. A manufacturing cost analysis framework to evaluate machining and fused filament fabrication additive manufacturing approaches. The International Journal of Advanced Manufacturing Technology 102:3091-3108. https://doi.org/10.1007/s00170-019-03394-x

[190] VDI-Richtlinie 2221: Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte. Düsseldorf: VDI-Verlag 1993.

[191] VDI-Richtlinie 2222 Blatt 1: Konzipieren technischer Produkte: Düsseldorf: VDI-Verlag (Entwurf) 1973, überarbeitete Fassung: 1977. Methodisches Entwickeln von Lösungsprinzipien. Düsseldorf: VDI-EKV 1996.

[192] VDI-Richtlinie 2222 Blatt 2: Erstellung und Anwendung von Konstruktionskatalogen. Düsseldorf: VDI-Verlag 1982.

[193] Verlinden B., Duflou J.R., Collin P., Cattrysse D., 2008. Cost estimation for sheet metal parts using multiple regression and artificial neural networks: A case study. International Journal of Production Economics 111(2): 484-492. https://doi.org/10.1016/j.ijpe.2007.02.004

[194] Wang H., Zhou X.H., Ruan, X.Y., 2002. Research on injection mould intelligent cost estimation system and key technologies. International Journal of Advanced Manufacturing Technology 21(3): 215-222.

[195] Wang, H.S., 2007. Application of BPN with feature-based models on cost estimation of plastic injection products. Computers & Industrial Engineering 53(1): 79-94. https://doi.org/10.1016/j.cie.2007.04.005.

[196] Weber N.O., 1994. Aircraft design takes off with DFMA. Assembly-Radnor 37(8):26-29.

[197] Wei Y., Egbelu P.J., 2000. A framework for estimating manufacturing cost from geometric design data. International Journal of Computer Integrated Manufacturing 13(1): 50-63. https://doi.org/10.1080/095119200130054

[198] Wilson P., Pratt M. 1988. A taxonomy of features for solid modeling. In: McLaughlin HW, Encarnacao JL, editors. Geometric modeling for CAD applications. North-Holland: 125-136.

[199] Wingård L. 1991. Introducing form features in product models: a step towards CAD/CAM with engineering terminology (Ph.D. thesis), Stockholm: Department of Manufacturing Systems, Royal Institute of Technology.

[200] Winner R.I., Pennell J.P., Bertrand H.E., Slusarzuk M.M.G., 1988. The Role of Concurrent Engineering in Weapon Systems Acquisition. Institute of Defense Analyses Report R-338, Alexandria.

[201] Woo T.G., Hayes C.C., Shaw M., 1996. An Intelligent-Agent Framework for Concurrent Product Design and Planning. IEEE Transactions on Engineering Management 43 (3): 297-306. https://doi.org/10.1109/17.511840

[202] Woo T.G., Hayes C.C., Shaw M., 1997. Concurrent product design. IEEE Potentials 16(2): 9-12. https://doi.org/10.1109/MP.1997.581375

[203] Woodward D. G., 1997. Life Cycle Costing-theory, information acquisition and application, International Journal of Project Management 15(6): 335-344. https://doi.org/10.1016/S0263-7863(96)00089-0

[204] Xiao T., Qi X., 2008. Price competition, cost and demand disruptions and coordination of a supply chain with one manufacturer and two competing retailers. Omega 36(5): 741-753. https://doi.org/10.1016/j.omega.2006.02.008

[205] Xu Y., Elgh F., Erkoyuncu J. A., Bankole O., Goh Y., Cheung W. M., Baguley P., Wang Q., Arundachawat P., Shehab E., Newnes L., Roy R., 2012. Cost Engineering for manufacturing: Current and future research. International Journal of Computer Integrated Manufacturing 25 (4-5):300-314. https://doi.org/10.1080/0951192X.2010.542183.

[206] Yamaguchi K., Nakamoto T., Mizuno T., Daido S., 1993. The Development of Free Machining Sintered Metals Including Nonmetallic. Materials Journal of Engineering for Industry 115(3): 278-283. https://doi.org/10.1115/1.2901661

[207] Zenger D., Dewhurst P., 1988. Early assessment of tooling costs in the design of sheet metal parts. Report 29. Dep. Industrial & Manufacturing Engineering, University of Rhode Island, USA.

[208] Zhao X., Verhagen W.J.C., Curran R., 2015. Estimation of aircraft component production cost using knowledge-based engineering techniques.

Advanced Engineering Informatics 29(3): 616-632. https://doi.org/10.1016/j.aei.2015.05.004

[209] Ziemke M.C., Spann M.S., 1991. Warning: Don’t be half-hearted in your efforts to employ concurrent engineering. Industrial Engineering 23(2): 45-49.

Appendix A. DfM/DfA rules repositories

A.1. DfM repository for closed-die forging

Table 64 Example of DfM rules repository for closed-die forging (precision type in particular)

Rule #	Rule type	Manufacturing Technology			Material		CAD features and algorithms			Guideline
		Class	Type – Level 1	Type – Level 2	Class	Type	CAD features to recognize	PMI to recognize	Dimensions and rules to verify	
1	Critical	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Shape: -Type: Round (R), Bar (B), Section open (S), Tube (T), Flat (F), Sperical (Sp); -Spatial complexity: Uniform cross section (0), Change at end (1), Change at centre (2), Spatial curvature (3); Closed one end (4); Closed both end (5) Transverse element (6), Irregular (complex) (7).	N.A.	Shape = R; B; S; T1, 2, 4, 6, 7; Sp	Avoid component shape not compatible with closed-die forging

2	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Weight (W)	N.A.	0,01 kg < W < 100 kg	Avoid components with a weight less than 0,01 kg and higher than 100 kg in closed-die forging
3	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Section thickness (t)	N.A.	$t \geq 3$ mm	Avoid section thickness less than 3 mm in closed-die forging process
4	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Production volume (P)	N.A.	P > 100	Avoid low production volume in closed-die forging
5	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Hole diameter (d)	N.A.	$d \geq 10$	Avoid hole diameter less than 10 mm in closed-die forging process
6	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Parting line angle (αp)	N.A.	$\alpha p \leq 75°$	Avoid, in case of broken parting line, a parting line angle over 75°

										in closed-die forging
7	Critical	Metal forming	Closed-die forging	Precision	Metals	Steel	Outside draft angle (αdo)	N.A.	αdo ≥3°	Guarantee an outside draft angle higher than 3° in precision closed-die forging of steel
8	Critical	Metal forming	Closed-die forging	Precision	Metals	Steel	Inside draft angle (αdi)	N.A.	αdi ≥1°	Guarantee an inside draft angle higher than 5° in precision closed-die forging of steel
9	Warning	Metal forming	Closed-die forging	Precision	Metals	Steel	Outside draft angle (αdo)	Outside draft angle tolerance (tαdo)	tαdo = +2°; -0°; ±1/2°	Respect the outside draft angle tolerance values (+2°; -0°; +-1/2°) in precision closed-die forging of steel
10	Warning	Metal forming	Closed-die forging	Precision	Metals	Steel	Inside draft angle (αdi)	Inside draft angle tolerance (tαdi)	tαdi = +2°; -0°; ±1°	Respect the inside draft angle tolerance values (+2°; -0°; +-1°) in

										precision closed-die forging of steel
11	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Central Rib between two webs	N.A.	N.A.	Thickening the web to avoid the formation of a void in the web directly below in closed-die forging
12	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib	N.A.	N.A.	Avoid metal push-through at the base of the rib in closed-die forging
13	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib and fillet radius	N.A.	N.A.	Enlarge the fillet at rib base to avoid lap in closed-die forging
14	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Ribs height (hr) Ribs distance (dr)	N.A.	$dr \geq hr$	Guarantee a distance between parallel ribs (dr) equal or greater then their heights

										(hr) in closed-die forging
15	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib width (wr)	N.A.	Wr = constant	Guarantee a constant widht (wr) for each rib in closed-die forging
16	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib draft angle (αr)	N.A.	αr = constant	Guarantee a constant draft angle (αr) for each rib in closed-die forging
17	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib corner radius (rcr)	N.A.	rcr = constant	Guarantee a constant corner radius (rcr) for each rib in closed-die forging
18	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib fillet radius (rfr)	N.A.	rfr = constant	Guarantee a constant fillet radius (rfr) for each rib in closed-die forging
19	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib width (wr) Rib height (hr)	N.A.	wr/hr ≤ 6	Avoid a rib height (hr) higher 6 times than the rib

										width (wr) in closed die forging
20	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Rib width (wr) Rib height (hr)	N.A.	wr/hr ≤ 4	It's recommended a rib height (hr) lower than 4 times rib width (wr) in closed-die forging
21	Critical	Metal forming	Closed-die forging	N.A.	Metals	Steel	Corner radius (r)	N.A.	r ≥ 1,5mm	Guarantee a minimum corner radius of 1,5 mm in closed-die forging of steels
22	Critical	Metal forming	Closed-die forging	N.A.	Metals	Steel	Fillet radius (R)	N.A.	R ≥ 1,5mm	Guarantee a minimum fillet radius of 1,5 mm in closed-die forging of steels
23	Critical	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Web thickness (tw) Rib widht (wr)	N.A.	tw ≥ wr	Avoid a web thickness (tw) lower than rib widht (wr) above it for

										closed-die forging
24	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Punched hole distance (dp) Web thickness (tw) Hole height (hh)	N.A.	dp ≥ 2tw	Guarantee a distance (dp) between two punched hole greater or equal than two web thickness (tw) in closed-die forging
25	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Punched slot fillet radius (R)	N.A.	R ≥ 6,4mm	Guarantee a fillet radius (R) in punched slot greater or equal than 6,4mm for closed-die forging
26	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Punched hole	N.A.	N.A.	It's recommended positioning a punched hole in the centre of a web in closed-die forging

28	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Punched hole	N.A.	N.A.	Avoid a huge number of punched holes closed-die forging
29	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Draft angle (α)	N.A.	α = constant trought parting line	Use a constant draft all over the periphery of the part in closed-die forging
30	Information	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Recess	N.A.	N.A.	Avoid recesses perpendicular to the direction of metal flow in closed-die forging
31	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Lenght (l) Widht (w) Height (h)	Finish allowance (δf)	δf = f (l, w, h)	Guarantee the recommended finish allowance for machining (δf) in closed-die forging
32	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Lenght (l) Widht (w)	Lenght tolerance (δlw)	δl = f (l, w)	Avoid closer lenght tolerance (δl) than recommended

										values in closed-die forging
33	Warning	Metal forming	Closed-die forging	N.A.	Metals	Carbon and low-alloy steels	Flash lenght (fl) Plan area (Ap)	Flash-extension tolerance (δfl)	δfl = f (Ap)	Avoid closer flash-extension tolerance (δfl) than recommended values in closed-die forging of carbon and low-alloy steels
34	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Lenght (l) Widht (w) Height (h)	Straightness tolerance (δs)	δs = +0,003mm/mm	Avoid closer straightness tolerance (δs) than +0,003mm/mm in closed-die forging
35	Warning	Metal forming	Closed-die forging	N.A.	Metals	N.A.	Lenght (l) Widht (w) Height (h)	Flatness tolerance (δf)	δf = +0,006mm/mm	Avoid closer flatness tolerance (δf) than +0,003mm/mm in closed-die forging

A.2. DfM rules repository for machining

Table 65 Example of DfM rules repository for machining (milling and turning in particular)

Rule #	Rule type	Manufacturing Technology			Material		CAD features and algorithms			Guideline
		Class	Type – Level 1	Type – Level 2	Class	Type	CAD features to recognize	PMI to recognize	Dimensions and rules to verify	
1	Warning	Machining	Milling	N.A.	All materials	N.A.	Initial volume of the part (Vi) Final volume of the part (Vf)	N.A.	S = Vi / Vf S > 3	Keep limited the ratio between the volume of the raw material (Vi) and the volume of the finished part (Vf) in machining processes
2	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole diameter (D) Hole length (L)	Hole roughness (Ra)	Ra ≤ 0,8 µm L/D ≥ 5	Avoid tight roughnesses (Ra ≤ 0.8 µm) for deep holes (L/D ≥ 5) in machining operations

3	Critical	Machining	Milling	N.A.	All materials	N.A.	Radius of the pocket/contours edge (r)	N.A.	r = 0	Avoid sharp internal corners in milling operations
4	Warning	Machining	Milling	N.A.	All materials	N.A.	Radius of the pocket/contours edge (r) Pocket/contours thickness (s)	N.A.	r <= s/6	Avoid sharp internal corners in milling operations
5	Information	Machining	Milling	N.A.	All materials	N.A.	Radius of the pocket/contours edge (r) Pocket/contours thickness (s)	N.A.	r <= s/4	Avoid sharp internal corners in milling operations
6	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole cylinder area (A) Hole radius (R) Hole height (H)	N.A.	A ≥ 2π * R* H * 0,8	Avoid partial holes which do not involve at least 80% of the area of the material to be processed in drilling operations
7	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole circular surface (A1) Hole circular	N.A.	A1 ≠ A2 ≠ π R^2	Avoid starting hole from the non-flat surface

							surface (A2) Hole radius (R)			in drilling operations
8	Warning	Machining	Milling	N.A.	All materials	N.A.	Pocket height (H) Pocket width (W)	N.A.	W ≤ 3 mm H/W ≥ 10	Avoid pocket widths less than 3 mm and with H/W ratio less than 10 in milling operations
9	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole edge (H) Pocket edge (P) Slot edge (S) Surrounding edges (E) Distances among edges (D)	N.A.	D ≤ 3 mm	Avoid holes and slot too close to the edge of the component (less than 3 mm)
10	Warning	Machining	Milling	Threading	All materials	N.A.	Hole height (H) Thread height (Ht)	N.A.	Ht ≤ 1,25 H	Guarantee that hole depth is higher than thread depth in blind threaded holes
11	Information	Machining	Milling	Drilling	All materials	N.A.	Hole diameter (D)	N.A.	D ≤ 3 mm	Avoid holes with a diameter less than 3mm
12	Information	Machining	Milling	N.A.	All materials	N.A.	Radius of pad edges (R)	N.A.	R = 0	Avoid sharp external corners

13	Warning	Machining	Turning	N.A.	All materials	N.A.	Part length (L) Part minimum diameter (d)	N.A.	$L/d \leq 8$	Avoid a ratio between part length (L) and part minimum diameter (d) higher than 8 in turning process
14	Warning	Machining	Turning	N.A.	All materials	N.A.	Fillet radius (r)	N.A.	$r \leq 3$ mm	Avoid internal fillet radius (r) lower than 3 mm in turning process
15	Warning	Machining	Turning	N.A.	All materials	N.A.	Angle of sidewall (αs)	N.A.	$\alpha s \geq 90°$	Avoid grooves with parallel or steep sidewalls in turning process
16	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole diameter (D)	N.A.	$D \neq$ standard dimensions	Guarantee standard hole diameter (D) in drilling operations
17	Warning	Machining	Milling	Drilling	All materials	N.A.	Angle between hole wall and hole base (αwb)	N.A.	$\alpha wb > 90°$	Avoid hole with flat bottom in drilling operations

18	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole height (h) Hole diameter (D)	N.A.	h/D > 5	Avoid a ratio between hole height (h) and hole diameter (D) higher than 5 in drilling operations
19	Warning	Machining	Milling	N.A.	All materials	N.A.	Angle between pocket wall and pocket base (αwb)	N.A.	αwb ≠ 90°	Avoid angle between pocket wall and pocket base (αwb) different from 90° in milling process
20	Warning	Machining	Milling	N.A.	All materials	N.A.	Pocket area (A) Pocket height (h)	N.A.	A/h < 0,8 mm	Avoid deep pocket with a ratio between area (A) and height (h) less than 8 mm in milling process
21	Warning	Machining	Turning	N.A.	All materials	N.A.	Surface diameter (d) Surface length (l)	N.A.	l/h > 3	Avoid a ratio between surface length (l) and surface diameter (d) higher than 3 in turning operation for

										cantilever mounted components
22	Warning	Machining	Milling	Drilling	All materials	N.A.	Angle between hole axis and drilled surface (αa)	N.A.	αa ≠ 90°	Avoid an angle between hole axis and drilled surface (αa) different from 90° in drilling operations
23	Warning	Machining	Milling	Threading	All materials	N.A.	Diameter of the first hole (D) Diameter of the second hole (d) Distance between two threaded holes (L)	N.A.	L < 1,2D + 1,2d	Avoid a short distance between two holes in threading operations
24	Warning	Machining	Milling	Threading	All materials	N.A.	Threaded section (ht)	N.A.	ht < 3mm	Avoid a treaded section less than 3 mm in threading operations
25	Warning	Machining	Milling	Threading	Plastics	N.A.	Threaded hole	N.A.	N.A:	Avoid treaded holes in plastic components

26	Warning	Machining	Milling	Drilling	All materials	N.A.	Hole angle (α)	N.A.	$\alpha \neq 90°$	Avoid conical holes in drilling process
27	Warning	Machining	Milling	Drilling	Plastics	N.A.	Hole height (h) Hole diameter (D)	N.A.	$h / D < 2$	Avoid a ratio between hole height (h) and hole diameter (D) higher than 2 in plastic components
28	Information	Machining	N.A.	N.A.	All materials	N.A.	Hole length (lh) Part dimensions (dp)	N.A.	lh, dp ≠ standard dimensions	Guarantee standard dimensions in milling process
29	Warning	Machining	N.A.	N.A.	All materials	N.A.	N.A.	Roughness (Ra)	$Ra \leq 0{,}8$ µm	Avoid tight roughness ($Ra \leq 0.8$ µm) in machining process
30	Warning	Machining	N.A.	N.A.	All materials	N.A.	N.A.	Dimensional tolerance (δd)	$\delta d < IT6$	Avoid tight dimensional tolerance ($\delta d < IT6$) in machining process

31	Information	Machining	N.A.	N.A.	All materials	N.A.	Chamfer	N.A.	N.A.	Avoid chamfer where not required in machining process
32	Information	Machining	N.A.	N.A.	All materials	N.A.	Counterbore hole diameter (D) Counterbore hole height (h)	N.A.	D, h ≠ standard dimensions	Guarantee standard dimensions of counterbore holes in milling process
33	Information	Machining	N.A.	N.A.	All materials	N.A.	Countersink hole diameter (D) Countersink hole height (h) Countersink hole angle (α)	N.A.	D, h, α ≠ standard dimensions	Guarantee standard dimensions of countersink holes in milling process
34	Warning	Machining	N.A.	N.A.	All materials	N.A.	Slot wall distance (ds) Slot height (hs)	N.A.	ds ≥ hs	Avoid slot wall distance (ds) lower than slot height (hs) in machining process

A.3. DfA repository for assembly

Table 66 Example of DfA repository for assembly (bolted/rivetted in particular)

Rule #	**Rule type**	**Assembly Technology**			**Material**		**CAD features and algorithms**			**Guideline**
		Class	**Type – Level 1**	**Type – Level 2**	**Class**	**Type**	**CAD features to recognize**	**PMI to recognize**	**Dimensions and rules to verify**	
1	Critical	Manual assembly	Bolted	N.A.	All materials	N.A.	Threaded axis direction (A) Plane perpendicular to the threaded axis lean on the head of a threaded element (P)	N.A.	No obstruction along A direction (+ and -) No obstruction on P plane (≤ 90°)	Guarantee tool entrance for threaded elements (screws, bolts, nuts) in the manual assembly process of bolted components
2	Critical	Manual assembly	Bolted	N.A.	All materials	N.A.	Hole axis Ah (Ah) Screw axis (As) Hole diameter (Dh) Screw diameter (Ds) Diameter gap (G = Dh - Ds)	N.A.	G ≥ f(Ds) Ah = As	Guarantee minimum diameter gap between screw and hole of non-threaded parts in the manual assembly process of bolted components
3	Critical	Manual assembly	Bolted	Screwing	All materials	N.A.	Hole axis Ah (Ah) Screw axis (As)	N.A.	As = An = Ah = At	Keep aligned screw, nut and hole axis in

							Nut axis (An) Threaded hole axis (At)			the manual assembly process of bolted components
4	Warnin g	Manual assembly	Bolted	Screwing	All materials	N.A.	Threaded hole The chamfer on the threaded hole Hole chamfer Screw chamfer	N.A.	Chamfer < 1 x 45°	Guarantee chamfered/countersu nk insertion holes and chamfered screw ends in the manual assembly process of bolted components
5	Warnin g	Manual assembly	Bolted	N.A.	All materials	N.A.	Hole area (Ah) Threaded hole area (At)	N.A.	Ah ∩ other circular areas At ∩ other circular areas	Delete non-useful holes and threaded holes in the assembly in the manual assembly process of bolted components
6	Warnin g	Manual assembly	Bolted	N.A.	All materials	N.A.	Screw Washer Nut	N.A.	N.A.	Prefer the use of combined fasteners in the manual assembly process of bolted components
7	Critical	Manual assembly	Bolted	N.A.	All materials	N.A.	Angle between hole axis and surface (α)	N.A.	α = 90°	Guarantee flat surfaces for the insertion holes for screws in the manual

										assembly process of bolted components
8	Critical	Manual assembly	Bolted	N.A.	All materials	N.A.	Diameter of first screw (Ds) Diameter of second screw (ds) Distance between the screw axis (La)	N.A.	La > 1,2Ds + 1,2ds	Guarantee minimum distance between the axis of two or more screw in the manual assembly process of bolted components
9	Warnin g	Manual assembly	Bolted	N.A.	All materials	N.A.	Screw type (hex head, cylindrical head, etc.) Diameter of screw (Ds) Required space volume for clamping tool (V)	N.A.	V ≥ f(Ds)	Guarantee access of the clamping tool in the case of threaded elements in the manual assembly process of bolted components
10	Critical	Manual assembly	Bolted	N.A.	All materials	N.A.	Lead screw length (Ll) Screw length (Ls)	N.A.	Ll > Ls	Guarantee that the threaded length of the lead screw is greater than the length of the screw in order to ensure complete tightening of the screw in the manual assembly process of bolted components

11	Informa tion	All type of assemblie s	N.A.	N.A.	All materials	N.A.	Assembly length (L) Assembly width (W) Assembly height (H)	N.A.	L ≤ 13,60 m W ≤ 2,40 m H ≤ 2,35 m	Avoid an assembly larger than limits of a standard articulated unit in case of transport by road
12	Informa tion	All type of assemblie s	N.A.	N.A.	All materials	N.A.	Assembly length (L) Assembly width (W) Assembly height (H)	N.A.	L ≤ 12,00 m W ≤ 2,30 m H ≤ 2,30 m	Avoid an assembly larger than limits of a standard container (high cube) in case of transport by ship
13	Informa tion	All type of assemblie s	N.A.	N.A.	All materials	N.A.	Assembly length (L) Assembly width (W) Assembly height (H)	N.A.	L ≤ 6,05 m W ≤ 2,44 m H ≤ 2,20 m	Avoid an assembly larger than limits of a standard pallet unit in case of transport by plane
14	Warnin g	Manual assembly	Bolted	N.A.	All materials	N.A.	Screws Nuts Bolts Snap rings Dowel pins Grease nipples Nails Rivets Tabs Keys	N.A.	N.A.	Guarantee the accessibility of the connections and elements of an assembly (screws, nuts, bolts, snap rings, dowel pins, grease nipples, nails, rivets, tabs, keys etc) for assembly and disassembly operations in manual bolted assembly

15	Warnin g	Manual/a utomated /robotize d assembly	Bolted	N.A.	All materials	N.A.	Pin hole	Pin hole tolerance (δ)	δ = H7	Guarantee an H7 tolerance for pin holes in bolted assembly
16	Warnin g	Manual/a utomated /robotize d assembly	Bolted	N.A.	All materials	N.A.	Surface 1 Surface 2	Surface 1 roughness (μ1) Surface 2 roughness (μ2)	μ1 = μ2	Guarantee the same surface roughness of contact surfaces in in bolted assembly
17	Warnin g	Manual/a utomated /robotize d assembly	Rivetted	N.A.	All materials	N.A.	Plate thickness (t) Distance between rivet axis and plate edge (Lre)	N.A.	1,5t < Lre < 8t	Maintain the correct distance between a rivet and an edge of the plate between in rivetted assembly
18	Warnin g	Manual/a utomated /robotize d assembly	Rivetted	N.A.	All materials	N.A.	Rivet hole diameter (Dh) Rivet diameter (Dr) Radial clearance (Dh – Dr = δr)	N.A.	0,05 Dr < δr < 0,07 Dr	Maintain the correct radial clearance for the rivet hole in rivetted assembly
19	Warnin g	Manual/a utomated /robotize d assembly	Rivetted	N.A.	All materials	N.A.	Solid rivet diameter (Dsr) Semi-tubolar rivet diameter (Dstr) Tubolar rivet	N.A.	Lr < 2 * Dsr 0,5 Dstr < Lr < 0,7 Dstr Lr < Dtr	Guarantee the correct rivet length in rivetted assembly

							diameter (Dtr) Rivet length (Lr)			
20	Informa tion	Manual/a utomated /robotize d assembly	N.A.	N.A.	All materials	N.A.	Hole	N.A.	N.A.	Avoid holes in a component if they are not used for assembly and/or operation
21	Informa tion	Manual/a utomated /robotize d assembly	Bolted	N.A.	All materials	N.A.	Screw Bolt Nut	N.A.	N.A.	Avoid using a large variety of different screws/bolts unless necessary in manual bolted assembly
22	Informa tion	Manual assembly	Bolted/Ri vetted	N.A.	All materials	N.A.	Components material (Mp)	N.A.	Mc = fragile and/or flexible	Avoid fragile and flexible parts in manual bolted/rivetted assembly
23	Informa tion	Manual assembly	N.A.	N.A.	All materials	N.A.	Components length (Lc) Components width (Wc) Components height (Hc)	N.A.	Lc > 5 mm Wc > 5 mm Hc > 5 mm	Avoid too small parts in manual assembly
24	Informa tion	Manual assembly	N.A.	N.A.	All materials	N.A.	Components weight (Wec)	N.A.	Wec > 5 gr	Avoid too light part in manual assembly
25	Warnin g	Manual/a utomated	Bolted/ri vetted	N.A.	All materials	N.A.	Diameter of screw (Ds) Distance between	N.A.	Le > 1,2Ds	Guarantee the minimum distance between screw hole

		/robotized assembly					the screw axis and component edge (Le)			and component edge in bolted/rivetted assembly
26	Information	Manual assembly	N.A.	N.A.	All materials	N.A.	Spring housing	N.A.	N.A.	Guarantee the housing for the springs in manual assembly
27	Information	Manual assembly	Bolted	N.A.	All materials	N.A.	Threaded hole diameter (Dt)	N.A.	Dt > M3	Avoid the use of threaded hole whit a diameter less than M3 in manual bolted assembly
28	Information	Manual/automated /robotized assembly	N.A.	N.A.	All materials	N.A.	Bearing type (Tb)	Bearing geometric tolerance shaft side (δgs) Bearing geometric tolerance housing side (δgh) Bearing dimensional tolerance shaft side (δds) Bearing dimensiona	δgs = f(Tb) δgh = f(Tb) δds = f(Tb) δds = f(Tb)	Respect dimensional and geometric tolerances for bearing in assembly

								l tolerance housing side (δgh)		
29	Information	Manual/automated/robotized assembly	N.A.	N.A.	All materials	N.A.	Bearing type (Tb)	Bearing roughness (μb)	μb = f(Tb)	Respect roughness of bearing in assembly
30	Information	Manual/automated/robotized assembly	N.A.	N.A.	All materials	N.A.	Bearing type (Tb)	N.A.	N.A.	Respect the correct mounting of bearings in assembly
31	Information	Manual/automated/robotized assembly	N.A.	N.A.	All materials	N.A.	Bushing material type (Mb) Bushing housing material type (Mh)	Bushing geometric tolerance shaft side (δgs) Bushing geometric tolerance housing side (δgh) Bushing dimensional tolerance shaft side (δds)	δgs = f(Mb; Mh) δgh = f(Mb; Mh) δds = f(Mb; Mh) δds = f(Mb; Mh)	Respect dimensional and geometric tolerances for bushings in assembly

								Bushing dimensional tolerance housing side (δgh)		
32	Information	Manual/automated/robotized assembly	N.A.	N.A.	All materials	N.A.	Bushing material type (Mb) Bushing housing material type (Mh)	Bushing roughness (μb)	$\mu b = f(Mb; Mh)$	Respect roughness of bushings in assembly

Appendix B. Features of components analysed in case studies

B.1. Forging

Table 67 Features of 1° block (part 1 – pin original design)

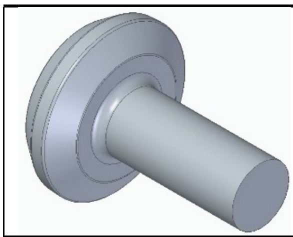
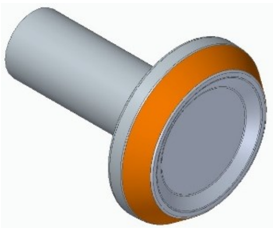
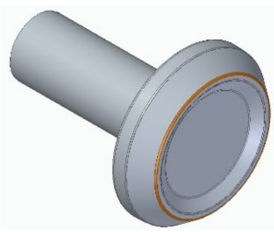
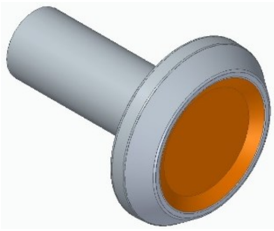
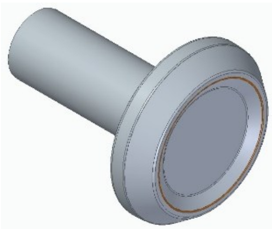
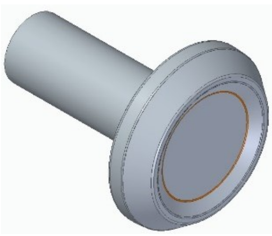
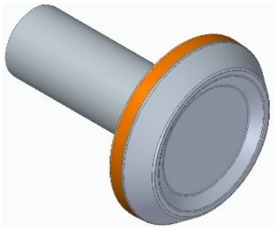
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 265423,76 [mm^3] → Area: 29707,09 [mm^2] → Dimensions: 119*95,78*95,78 [mm]

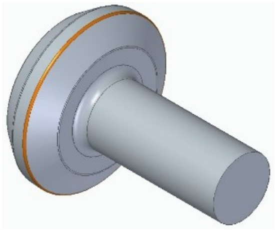
Table 68 Features of 2° block (part 1 – pin original design)

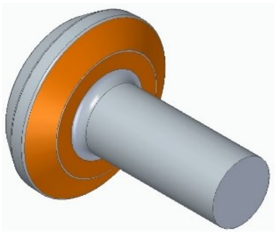
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_1 - TRUNCATED CONE_1**
	→ Coordinates of the feature in reference with origin: [00;00;00]
	→ Properties of the feature:
	  → Large diameter: 95 [mm]
	  → Small diameter: 77,66 [mm]
	  → Height: 12,16 [mm]
	  → Draft angle: 35,51 [°]
	→ Volume of the feature: 71417,49 [mm^3]
	→ Area of the feature: 15875,41 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01
	  → Circular_face_01.02
	  → Conical_face_01.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

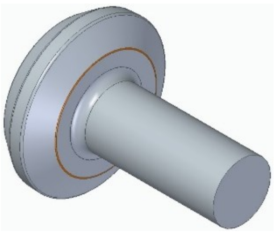
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_2 - FILLET_1**
	→ Coordinates of the feature in reference with origin: [00;00;12,16]
	→ Properties of the feature:
	  → Diameter: 77,66 [mm]
	  → Radius: 1,5 [mm]
	→ Volume of the feature: - [mm^3]
	→ Area of the feature: 347,05 [mm^2]
	→ Faces of the feature:
	  → Toroidal_face_02.01
	→ PMI:

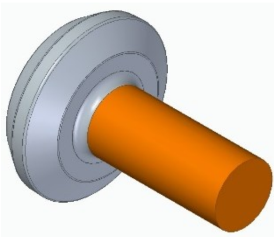
	→ Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_3 - TRUNCATED CONE_SLOT** → Coordinates of the feature in reference with origin: [00;00;12,16] → Properties of the feature: → Large diameter: 70,81 [mm] → Small diameter: 57,17 [mm] → Height: 4 [mm] → Draft angle: 59,62 [°] → Volume of the feature: 12912,65 [mm^3] → Area of the feature: 8094,48 [mm^2] → Faces of the feature: → Circular_face_03.01 → Circular_face_03.02 → Conical_face_03.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_4 - FILLET_2** → Coordinates of the feature in reference with origin: [00;00;12,16] → Properties of the feature: → Diameter: 70,81 [mm] → Radius: 1,5 [mm] → Volume of the feature: - [mm^3] → Area of the feature: 177,02 [mm^2] → Faces of the feature: → Toroidal_face_04.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_5 - FILLET_3** → Coordinates of the feature in reference with origin: [00;00;8,16] → Properties of the feature: → Diameter: 57,17 [mm] → Radius: 1,5 [mm] → Volume of the feature: - [mm^3] → Area of the feature: 142,74 [mm^2] → Faces of the feature: → Toroidal_face_05.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_6 - TRUNCATED CONE_2**
	→ Coordinates of the feature in reference with origin: [00;00;-8,32]
	→ Properties of the feature:
	  → Large diameter: 95,87 [mm]
	  → Small diameter: 95 [mm]
	  → Height: 8,32 [mm]
	  → Draft angle: 3 [°]
	→ Volume of the feature: 59515,70 [mm^3]
	→ Area of the feature: 16804,75 [mm^2]
	→ Faces of the feature:
	  → Circular_face_06.01
	  → Circular_face_06.02
	  → Conical_face_06.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_7 - FILLET_4**
	→ Coordinates of the feature in reference with origin: [00;00;-8,32]
	→ Properties of the feature:
	  → Diameter: 95,87 [mm]
	  → Radius: 1,5 [mm]
	→ Volume of the feature: - [mm^3]
	→ Area of the feature: 490,79 [mm^2]
	→ Faces of the feature:
	  → Toroidal_face_07.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_8 - TRUNCATED CONE_2**
	→ Coordinates of the feature in reference with origin: [00;00;-8,32]
	→ Properties of the feature:
	  → Large diameter: 95,87 [mm]
	  → Small diameter: 66,79 [mm]
	  → Height: 8,53 [mm]
	  → Draft angle: 59,62 [°]
	→ Volume of the feature: 44786,06 [mm^3]
	→ Area of the feature: 15029,39 [mm^2]
	→ Faces of the feature:
	  → Circular_face_08.01
	  → Circular_face_08.02
	  → Conical_face_08.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_9 - FILLET_5**
	→ Coordinates of the feature in reference with origin: [00;00;-16,85]
	→ Properties of the feature:
	    → Diameter: 66,79 [mm]
	    → Radius: 1,5 [mm]
	→ Volume of the feature: - [mm^3]
	→ Area of the feature: 166,77 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_09.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_10 - CYLINDER**
	→ Coordinates of the feature in reference with origin: [00;00;-16,85]
	→ Properties of the feature:
	    → Diameter: 38 [mm]
	    → Height: 90 [mm]
	→ Volume of the feature: 102070,34 [mm^3]
	→ Area of the feature: 13012,48 [mm^2]
	→ Faces of the feature:
	    → Circular_face_10.01
	    → Circular_face_10.02
	    → Cylindrical_face_10.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

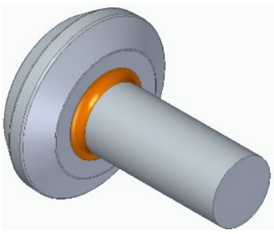
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_11 - FILLET_6**
	→ Coordinates of the feature in reference with origin: [00;00;-16,85]
	→ Properties of the feature:
	    → Diameter: 38 [mm]
	    → Radius: 5 [mm]
	→ Volume of the feature: - [mm^3]
	→ Area of the feature: 1027,27 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_11.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

Table 69 Physical and material features of the model (Features of 1° block) (part 1 – pin updated design) (prior to machining)

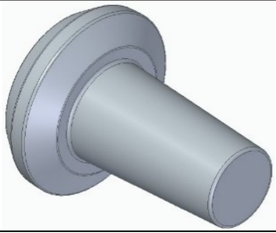
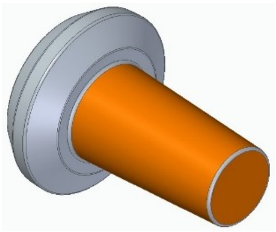
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 265423,76 [mm^3] → Area: 29707,09 [mm^2] → Dimensions: 119*95,78*95,78 [mm]

Table 70 Manufacturing and material features of the updated model (isolated) (Features of 2° block) (part 1 – pin updated design) (prior to machining)

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_12 – TRUNCATED_CONE_NEW**
	→ Coordinates of the feature in reference with origin: [00;00;-16,85]
	→ Properties of the feature:
	    → Large diameter: 51,43 [mm]
	    → Small diameter: 42 [mm]
	    → Height: 90 [mm]
	    → Draft angle 3 [°]
	→ Volume of the feature: 154780,89 [mm^3]
	→ Area of the feature: 16689,32 [mm^2]
	→ Faces of the feature:
	    → Circular_face_12.01
	    → Circular_face_12.02
	    → Conical_face_12.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

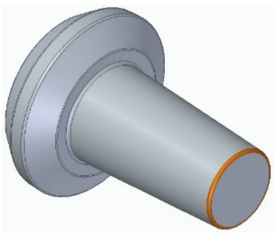
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_13 - FILLET_NEW**
	→ Coordinates of the feature in reference with origin: [00;00;119]
	→ Properties of the feature:
	    → Diameter: 42 [mm]
	    → Radius: 1,5 [mm]
	→ Volume of the feature: 55,53 [mm^3]
	→ Area of the feature: 293,56 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_13.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

Table 71 Features of 1° block (part 2 – planet carrier original design)

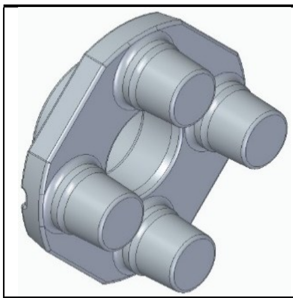
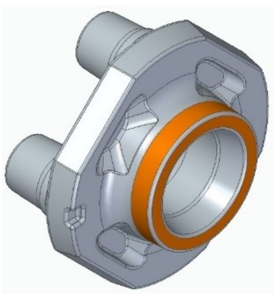
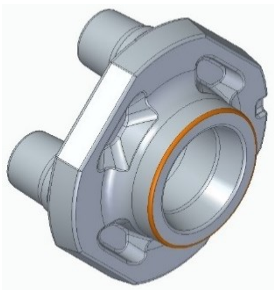
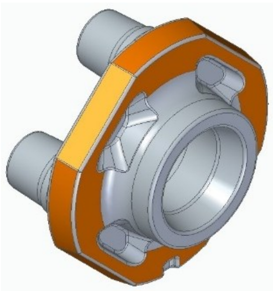
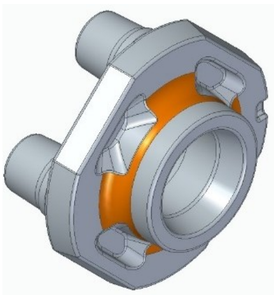
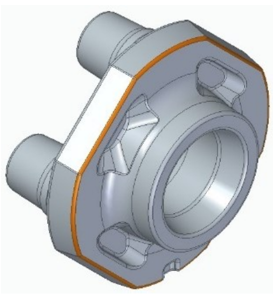
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 2237280,61 [mm^3] → Area: 181899,32 [mm^2] → Dimensions: 256,5*236,85*134,5 [mm]

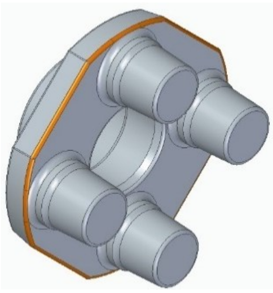
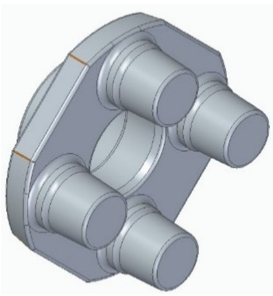
Table 72 Features of 2° block (part 2 – planet carrier original design)

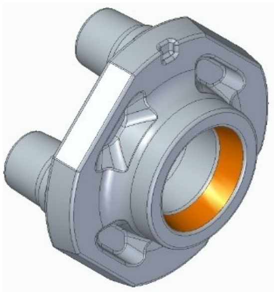
	→ Material: C40 Carbon Steel → Type of feature: **Feature_1 - TRUNCATED CONE_1** → Coordinates of the feature in reference with origin: [00;00;42] → Properties of the feature: → Large diameter: 140 [mm] → Small diameter: 137,07 [mm] → Height: 42 [mm] → Draft angle: 2 [°] → Volume of the feature: 633103,01 [mm^3] → Area of the feature: 48440,39 [mm^2] → Faces of the feature: → Circular_face_01.01 → Circular_face_01.02 → Conical_face_01.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_2 - FILLET_1** → Coordinates of the feature in reference with origin: [00;00;00] → Properties of the feature: → Diameter: 137,07 [mm] → Radius: 3 [mm] → Volume of the feature: 759,40 [mm^3] → Area of the feature: 1954,80 [mm^2] → Faces of the feature: → Toroidal_face_02.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

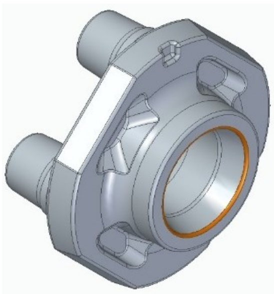
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_3 - TRUNCATED CONE_OCTAGON**
	→ Coordinates of the feature in reference with origin: [00;00;72]
	→ Properties of the feature:
	    → Large diameter: 256,5 [mm]
	    → Small diameter: 247,00 [mm]
	    → Height: 30 [mm]
	    → Draft angle: 9 [°]
	→ Volume of the feature: 1413036,39 [mm^3]
	→ Area of the feature: 117955,75 [mm^2]
	→ Faces of the feature:
	    → Octagonal_face_03.01
	    → Octagonal _face_03.02
	    → Rectangular_face_03.01
	    → Rectangular_face_03.02
	    → Rectangular_face_03.03
	    → Rectangular_face_03.04
	    → Conical_face_03.01
	    → Conical_face_03.02
	    → Conical_face_03.03
	    → Conical_face_03.04
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

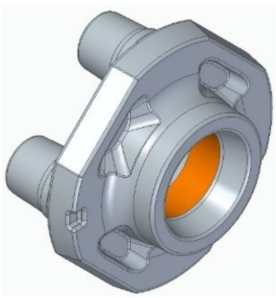
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_4 - FILLET_2**
	→ Coordinates of the feature in reference with origin: [00;00;42]
	→ Properties of the feature:
	    → Diameter: 140 [mm]
	    → Radius: 20 [mm]
	→ Volume of the feature: 36847,67 [mm^3]
	→ Area of the feature: 14812,50 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_04.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_5 - FILLET_3**
	→ Coordinates of the feature in reference with origin: [00;00;42]
	→ Properties of the feature:
	    → Diameter: 247 [mm]
	    → Radius: 3 [mm]
	→ Volume of the feature: 962,98 [mm^3]
	→ Area of the feature: 3175,92 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_05.01
	    → Toroidal_face_05.02
	    → Toroidal_face_05.03
	    → Toroidal_face_05.04
	    → Toroidal_face_05.05
	    → Toroidal_face_05.06
	    → Toroidal_face_05.07

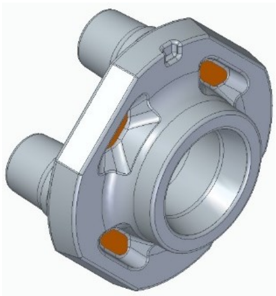
	→ Toroidal_face_05.08 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_6 - FILLET_4** → Coordinates of the feature in reference with origin: [00;00;72] → Properties of the feature: → Diameter: 256,5 [mm] → Radius: 3 [mm] → Volume of the feature: 2152,13 [mm^3] → Area of the feature: 3978,44 [mm^2] → Faces of the feature: → Toroidal_face_06.01 → Toroidal_face_06.02 → Toroidal_face_06.03 → Toroidal_face_06.04 → Toroidal_face_06.05 → Toroidal_face_06.06 → Toroidal_face_06.07 → Toroidal_face_06.08 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_7 - FILLET_OCTAGONAL_PATTERN** → Coordinates of the feature in reference with origin: → For first fillet: [118,55;48,93;72]; [115,02;44,98;42] → For large octagonal base: [00;00;72] → For small octagonal base: [00;00;42] → Properties of the feature: → For fillet: → Radius: 3 [mm] → For octagonal pattern: → Large octagonal base diameter: 256,5 [mm] → Small octagonal base diameter: 247 [mm] → Volume of the feature: 0,86*8 [mm^3] → Area of the feature: 36,81*8 [mm^2] → Faces of the feature: → Toroidal_face_07.01 → Toroidal_face_07.02 → Toroidal_face_07.03 → Toroidal_face_07.04 → Toroidal_face_07.05 → Toroidal_face_07.06 → Toroidal_face_07.07 → Toroidal_face_07.08 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

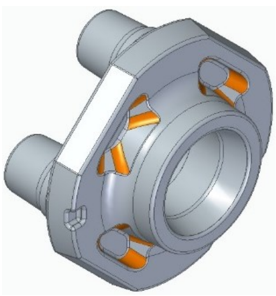
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_8 - TRUNCATED CONE_2**
	→ Coordinates of the feature in reference with origin: [00;00;00]
	→ Properties of the feature:
	  → Large diameter: 104 [mm]
	  → Small diameter: 88 [mm]
	  → Height: 29,86 [mm]
	  → Draft angle: 15 [°]
	→ Volume of the feature: 216633,84 [mm^3]
	→ Area of the feature: 23900,16 [mm^2]
	→ Faces of the feature:
	  → Circular_face_08.01
	  → Circular_face_08.02
	  → Conical_face_08.03
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

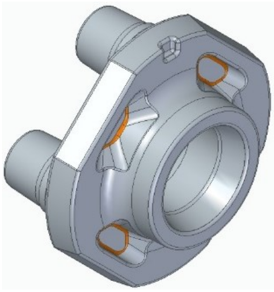
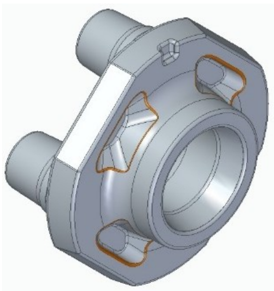
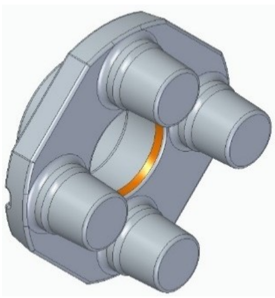
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_9 - FILLET_5**
	→ Coordinates of the feature in reference with origin: [00;00;00]
	→ Properties of the feature:
	  → Diameter: 104 [mm]
	  → Radius: 3 [mm]
	→ Volume of the feature: 334,12 [mm^3]
	→ Area of the feature: 1297,93 [mm^2]
	→ Faces of the feature:
	  → Toroidal_face_09.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

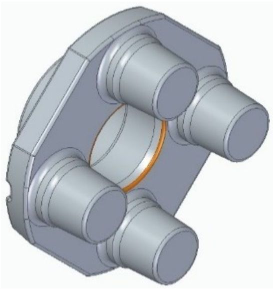
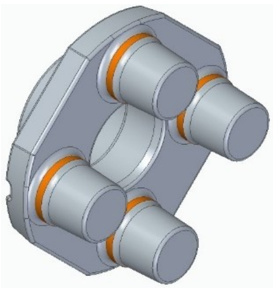
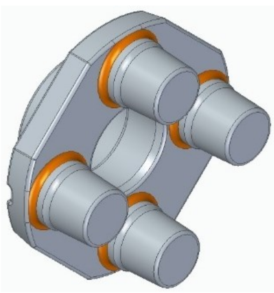
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_10 - CYLINDER**
	→ Coordinates of the feature in reference with origin: [00;00;29,86]
	→ Properties of the feature:
	  → Diameter: 88 [mm]
	  → Height: 32,81 [mm]
	→ Volume of the feature: 199554,47[mm^3]
	→ Area of the feature: 15152,78 [mm^2]
	→ Faces of the feature:
	  → Circular_face_10.01
	  → Circular_face_10.02
	  → Cylindrical_face_10.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

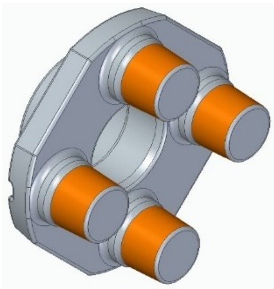
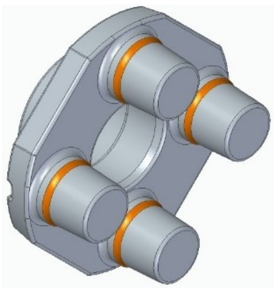
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_11 - FILLET_6**
	→ Coordinates of the feature in reference with origin: [00;00;29,86]
	→ Properties of the feature:
	  → Diameter: 88 [mm]
	  → Radius: 3 [mm]
	→ Volume of the feature: 238,26 [mm^3]
	→ Area of the feature: 923,65 [mm^2]
	→ Faces of the feature:
	  → Toroidal_face_11.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

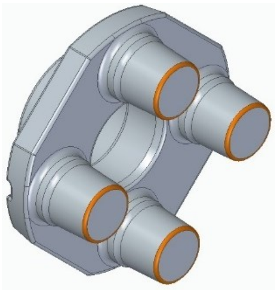
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_12 – SLOTS**
	→ Coordinates of the feature in reference with origin:
	  → For first slot large base: [106,53;31,72;42]; [31,72;106,53;42]; [64,83;31,72;42]; [31,72;64,83;42]
	  → For first slot small base: [93,04;43,72;54]; [43,72;93,04;54]; [58,74;43,72;54]; [43,72;58,74;54]
	→ Properties of the feature:
	  → Height: 12 [mm]
	→ Volume of the feature: 19075,12*4 [mm^3]
	→ Area of the feature: 5977,05*4 [mm^2]
	→ Faces of the feature (for one slot):
	  → Trapezoidal_face_12.01
	  → Trapezoidal_face_12.02
	  → Trapezoidal_face_12.03
	  → Trapezoidal_face_12.04
	  → Trapezoidal_face_12.05
	  → Conical_face_12.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_13 - FILLET_SLOT_INTERNAL**
	→ Coordinates of the feature in reference with origin:
	  → For first fillet of first slot: [93,04;43,72;54]; [106,53;31,72;42];
	  → For second fillet of first slot: [43,72;93,04;54]; [31,72;106,53;42]
	  → For third fillet of first slot: [58,74;43,72;54]; [64,83;31,72;42]
	  → For fourth fillet of first slot: [43,72;58,74;54]; [31,72;64,83;42]
	→ Properties of the feature:
	  → Radius: 10 [mm]
	→ Volume of the feature: 2764,06*4 [mm^3]
	→ Area of the feature: 1264,73*4 [mm^2]
	→ Faces of the feature (for one slot):
	  → Toroidal_face_13.01
	  → Toroidal_face_13.02
	  → Toroidal_face_13.03
	  → Toroidal_face_13.04
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO

	→ Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_14 - SLOT_SMALL BASE** → Coordinates of the feature in reference with origin: → For first fillet of first slot: [93,04;43,72;54]; [43,72;93,04;54] → For second fillet of first slot: [43,72;93,04;54]; [58,74;43,72;54] → For third fillet of first slot: [58,74;43,72;54]; [43,72;58,74;54] → For fourth fillet of first slot: [43,72;58,74;54]; [93,04;43,72;54] → Properties of the feature: → Radius: 3 [mm] → Volume of the feature: 159,27*4 [mm^3] → Area of the feature: 563,36*4 [mm^2] → Faces of the feature (for one slot): → Toroidal_face_14.01 → Toroidal_face_14.02 → Toroidal_face_14.03 → Toroidal_face_14.04 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_15 - SLOT_LARGE BASE** → Coordinates of the feature in reference with origin: → For first fillet of first slot: [106,53;31,72;42]; [31,72;106,53;42] → For second fillet of first slot: [31,72;106,53;42]; [64,83;31,72;42] → For third fillet of first slot: [64,83;31,72;42]; [31,72;64,83;42] → For fourth fillet of first slot: [31,72;64,83;42]; [106,53;31,72;42] → Properties of the feature: → Radius: 3 [mm] → Volume of the feature: 248,56*4 [mm^3] → Area of the feature: 856,68*4 [mm^2] → Faces of the feature (for one slot): → Toroidal_face_15.01 → Toroidal_face_15.02 → Toroidal_face_15.03 → Toroidal_face_15.04 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_16 - TRUNCATED CONE_3** → Coordinates of the feature in reference with origin: [00;00;72] → Properties of the feature: → Large diameter: 93 [mm] → Small diameter: 88 [mm] → Height: 9,33 [mm] → Draft angle: 15 [°] → Volume of the feature: 60031,49 [mm^3] → Area of the feature: 15621,26 [mm^2] → Faces of the feature: → Circular_face_16.01 → Circular_face_16.02 → Conical_face_16.01

	→ PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_17 - FILLET_7** → Coordinates of the feature in reference with origin: [00;00;72] → Properties of the feature: → Diameter: 93 [mm] → Radius: 3 [mm] → Volume of the feature: 299,03 [mm^3] → Area of the feature: 1162,23 [mm^2] → Faces of the feature: → Toroidal_face_17.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_18 – CYLINDER_CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern: [00;00;72] → For first cylinder: [89;00;72] → Properties of the feature: → For circular pattern: → Diameter: 178 [mm] → For cylinders: → Diameter:65 [mm] → Height: 13,5 [mm] → Volume of the feature: 44797,15*4 [mm^3] → Area of the feature: 6075,05*4 [mm^2] → Faces of the feature (for first cylinder): → Circular_face_18.01 → Circular_face_18.02 → Cylindrical_face_18.03 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_19 – FILLET_CIRCULAR PATTERN_1** → Coordinates of the feature in reference with origin: → For circular pattern: [00;00;72] → For first fillet: [89;00;72] → Properties of the feature: → For circular pattern: → Diameter: 178 [mm] → For fillets: → Diameter:65 [mm] → Radius: 6 [mm] → Volume of the feature: 1642,66*4 [mm^3] → Area of the feature: 2053,68*4 [mm^2] → Faces of the feature (for first cylinder): → Toroidal_face_19.01

	→ PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_20 – TRUNCATED CONE_CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern: [00;00;85,5] → For first truncated cone: [89;00;85,5] → Properties of the feature: → For circular pattern: → Diameter: 178 [mm] → For truncated cones: → Large diameter:61 [mm] → Small diameter:55,86 [mm] → Height: 49 [mm] → Draft angle: 3 [°] → Volume of the feature: 131473,34*4 [mm^3] → Area of the feature: 14380,14*4 [mm^2] → Faces of the feature (for first cylinder): → Circular_face_20.01 → Circular_face_20.02 → Conical_face_20.03 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_21 – FILLET_CIRCULAR PATTERN_2** → Coordinates of the feature in reference with origin: → For circular pattern: [00;00;85,5] → For first fillet: [89;00;85,5] → Properties of the feature: → For circular pattern: → Diameter: 178 [mm] → For fillets: → Diameter:61 [mm] → Radius: 6 [mm] → Volume of the feature: 514,52*4 [mm^3] → Area of the feature: 984,65*4 [mm^2] → Faces of the feature (for first cylinder): → Toroidal_face_21.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_22 – FILLET_CIRCULAR PATTERN_3**
	→ Coordinates of the feature in reference with origin:
	    → For circular pattern: [00;00;134,5]
	    → For first fillet: [89;00;134,5]
	→ Properties of the feature:
	    → For circular pattern:
	        → Diameter: 178 [mm]
	    → For fillets:
	        → Diameter:55,86 [mm]
	        → Radius: 3 [mm]
	→ Volume of the feature: 293,29*4 [mm^3]
	→ Area of the feature: 771,57*4 [mm^2]
	→ Faces of the feature (for first cylinder):
	    → Toroidal_face_22.01
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_23 – SLOT**
	→ Coordinates of the feature in reference with origin: [8;123,24;42]; [8;110;42]; [-8;110;42]; [-8;123,24;42]
	→ Properties of the feature:
	    → Height: 7 [mm]
	→ Volume of the feature: 1564,43 [mm^3]
	→ Area of the feature: 881,87 [mm^2]
	→ Faces of the feature:
	    → Rectangular_face_23.01
	    → Rectangular_face_23.02
	    → Rectangular_face_23.03
	    → Rectangular_face_23.04
	    → Rectangular_face_23.05
	    → Rectangular_face_23.06
	→ PMI:
	    → Specific roughness: NO
	    → Specific tolerance: NO
	    → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_24 - FILLET_SLOT_EXTERNAL_CONTOUR**
	→ Coordinates of the feature in reference with origin: [8;123,24;42]; [8;110;42]; [-8;110;42]; [-8;123,24;42]; [-8;124,35;49]; [8;124,35;49]
	→ Properties of the feature:
	    → Radius: 3 [mm]
	→ Volume of the feature: 140,13 [mm^3]
	→ Area of the feature: 357,47 [mm^2]
	→ Faces of the feature:
	    → Toroidal_face_24.01
	    → Toroidal_face_24.02
	    → Toroidal_face_24.03
	    → Toroidal_face_24.04
	    → Toroidal_face_24.05
	    → Toroidal_face_24.06
	→ PMI:

	→ Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_25 – FILLET_SLOT_ INTERNAL_CONTOUR** → Coordinates of the feature in reference with origin: [8;110;49]; [-8;110;49]; [-8;124,35;49]; [8;124,35;49] → Properties of the feature: → Radius: 3 [mm] → Volume of the feature: 80,91 [mm^3] → Area of the feature: 189,06 [mm^2] → Faces of the feature: → Toroidal_face_25.01 → Toroidal_face_25.02 → Toroidal_face_25.03 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

Table 73 Features of 1° block (part 2 – planet carrier updated design)

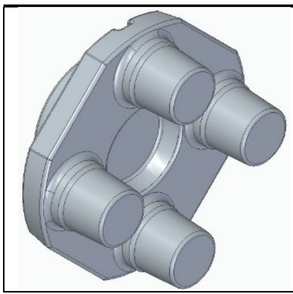
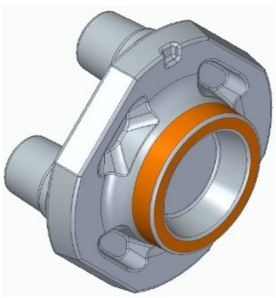
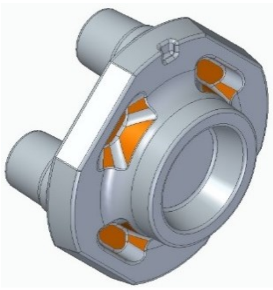
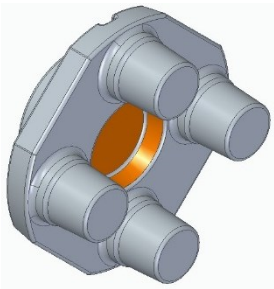
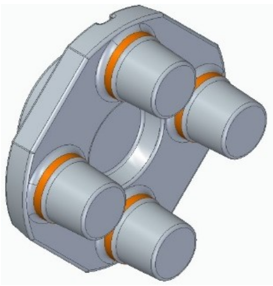
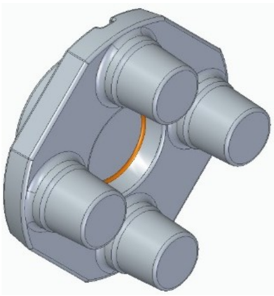
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 2372381,52 [mm^3] → Area: 186342,95 [mm^2] → Dimensions: 256,5*236,85*134,5 [mm]

Table 74 Features of 2° block (part 2 – planet carrier updated design)

	→ Material: C40 Carbon Steel → Type of feature: **Feature_1 - TRUNCATED CONE_1_MOD** → Coordinates of the feature in reference with origin: [00;00;42] → Properties of the feature: → Large diameter: 140 [mm] → Small diameter: 135,60 [mm] → Height: 42 [mm] → Draft angle: 3 [°] → Volume of the feature: 626432,82 [mm^3] → Area of the feature: 48042,41 [mm^2] → Faces of the feature: → Circular_face_01.01 → Circular_face_01.02

	→ Conical_face_01.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_12 – SLOTS_MOD** → Coordinates of the feature in reference with origin: → For first slot large base: [105,93;31,72;42]; [31,72;105,93;42]; [64,83;31,72;42]; [31,72;64,83;42] → For first slot small base: [93,04;43,72;54]; [43,72;93,04;54]; [58,74;43,72;54]; [43,72;58,74;54] → Properties of the feature: → Height: 12 [mm] → Volume of the feature: 18.838,98*4 [mm^3] → Area of the feature:5.914,96*4 [mm^2] → Faces of the feature (for one slot): → Trapezoidal_face_12.01 → Trapezoidal_face_12.02 → Trapezoidal_face_12.03 → Trapezoidal_face_12.04 → Trapezoidal_face_12.05 → Conical_face_12.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_16 - TRUNCATED CONE_3_MOD** → Coordinates of the feature in reference with origin: [00;00;72] → Properties of the feature: → Large diameter: 93 [mm] → Small diameter: 82,28 [mm] → Height: 20 [mm] → Draft angle: 15 [°] → Volume of the feature: 120799,67 [mm^3] → Area of the feature: 17810,96 [mm^2] → Faces of the feature: → Circular_face_16.01 → Circular_face_16.02 → Conical_face_16.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_18 – TRUNCATED_CONE_CIRCULAR PATTERN_NEW**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern: [00;00;72]
	  → For first cylinder: [89;00;72]
	→ Properties of the feature:
	  → For circular pattern:
	    → Diameter: 178 [mm]
	  → For truncated cones:
	    → Large diameter: 66,42 [mm]
	    → Small diameter: 65 [mm]
	    → Height: 13,5 [mm]
	    → Draft angle: 3 [°]
	→ Volume of the feature: 45782,92*4 [mm^3]
	→ Area of the feature: 9573,89*4 [mm^2]
	→ Faces of the feature (for first cone):
	  → Circular_face_18.01
	  → Circular_face_18.02
	  → Conical_face_18.03
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_26 - FILLET_NEW**
	→ Coordinates of the feature in reference with origin: [00;00;52]
	→ Properties of the feature:
	  → Diameter: 82,28 [mm]
	  → Radius: 3 [mm]
	→ Volume of the feature: 260,14 [mm^3]
	→ Area of the feature: 1000,20 [mm^2]
	→ Faces of the feature:
	  → Toroidal_face_26.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

B.2. Machining

Table 75 Features of 1° block (part 1 – plate original design)

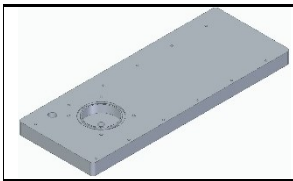
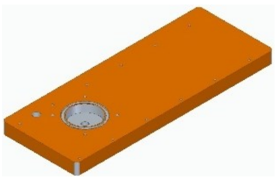
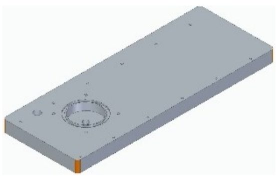
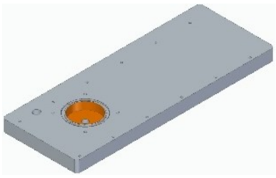
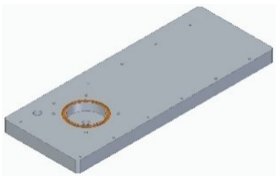
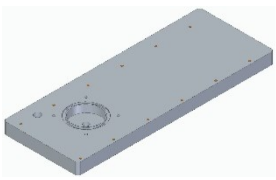
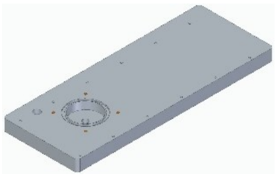
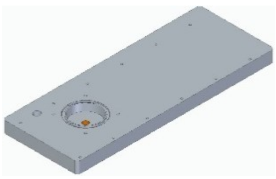
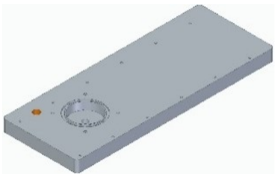
	→ Material: Aluminium - AC 100 → Shape: Prismatic → Volume: 744047,36 [mm^3] → Area: 136459,51 [mm^2] → Dimensions: 131,00*345,00*20,00 [mm]

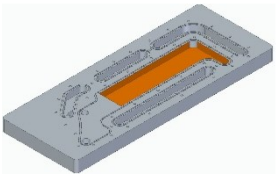
Table 76 Features of 2° block (part 1 – plate original design)

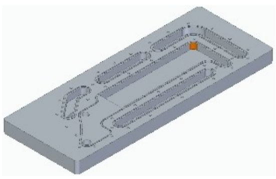
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_1 – PAD_1** → Coordinates of the feature in reference with origin: [65,50;80,00;00,00]; [65,50;265,00;00,00]; [-65,50;265,00;00,00]; [-65,50;-80,00;00,00] → Properties of the feature: → Height: 20 [mm] → Volume of the feature: 903.900,00 [mm^3] → Area of the feature: 128.470,00 [mm^2] → Faces of the feature: → Rectangular_face_01.01 → Rectangular_face_01.02 → Rectangular_face_01.03 → Rectangular_face_01.04 → Rectangular_face_01.05 → Rectangular_face_01.06 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Rectangular_face_01.01 → Rectangular_face_01.02 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_2 - FILLET_1** → Coordinates of the feature in reference with origin: [65,50;80,00;00,00]; [65,50;265,00;00,00]; [-65,50;265,00;00,00]; [-65,50;-80,00;00,00] → Properties of the feature: → Height: 20,00 [mm] → Radius: 5 [mm] → Volume of the feature: 107,30*4 [mm^3] → Area of the feature: 157,08*4 [mm^2] → Faces of the feature (for one fillet): → Cylindrical_face_02.01 → PMI:

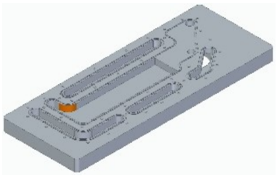
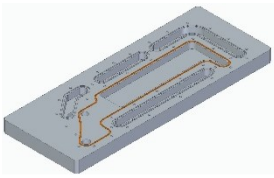
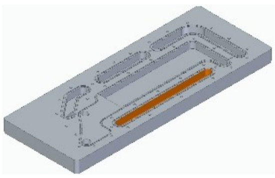
	→ Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_3 – CYLINDRICAL_SLOT_1** → Coordinates of the feature in reference with origin: [00,00;00,00;20,00] → Properties of the feature: → Diameter: 49,50 [mm] → Height: 13,00 [mm] → Volume of the feature: 25017,48 [mm^3] → Area of the feature: 3946,04[mm^2] → Faces of the feature: → Circular_face_03.01 → Circular_face_03.02 → Cylindrical_face_03.01 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Circular_face_03.02 → Cylindrical_face_03.01 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_4 – CYLINDRICAL_SLOT_2** → Coordinates of the feature in reference with origin: [00,00;00,00;20,00] → Properties of the feature: → Diameter external: 60,50[mm] → Diameter internal: 52,50 [mm] → Height: 2,40 [mm] → Volume of the feature: 1704,00 [mm^3] → Area of the feature: 2272,00 [mm^2] → Faces of the feature: → Circular_face_04.01 → Circular_face_04.02 → Cylindrical_face_04.01 → Cylindrical_face_04.02 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Circular_face_04.02 → Cylindrical_face_04.01 → Cylindrical_face_04.02 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_5 – THREADED_HOLES_PATTERN_1** → Coordinates of the feature in reference with origin: [-44,41;-62,92;20,00]; [-44,41;-12,20;20,00]; [-44,41;47,68;20,00]; [-44,41;107,63;20,00]; [-44,41;167,43;20,00]; [-44,41;227,27;20,00]; [60,45;-62,92;20,00]; [60,45;-12,20;20,00]; [60,45;47,68;20,00]; [60,45;107,63;20,00]; [60,45;167,43;20,00]; [60,45;227,27;20,00] → Properties of the feature (for one hole): → Hole number: 12 [ad.] → Hole height: 7 [mm] → Thread type: M4 (ISO metric coarse thread)

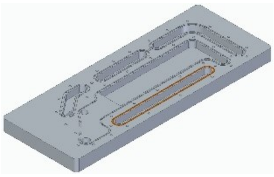
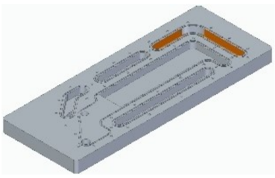
	→ Thread lenght: 5 [mm] → Volume of the feature: 59,87*12 [mm^3] → Area of the feature: 81,12*12 [mm^2] → Faces of the feature: → Circular_face_05.01 → Circular_face_05.02 → Cylindrical_face_05.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_6 – THREADED_HOLES_PATTERN_2** → Coordinates of the feature in reference with origin: [-28,35;-28,38;20,00]; [-28,35;28,38;20,00]; [28,35;--28,38;20,00]; [28,35;28,38;20,00] → Properties of the feature: → Hole number: 4 [ad.] → Hole height: 10 [mm] → Thread: M5 (ISO metric coarse thread) → Thread length: 8 → Volume of the feature: 138,54*4 [mm^3] → Area of the feature: 145,80*4 [mm^2] → Faces of the feature (for one hole): → Circular_face_06.01 → Circular_face_06.02 → Cylindrical_face_06.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_7 - HOLE_1** → Coordinates of the feature in reference with origin: [00,00;00,00;00,00] → Properties of the feature: → Diameter: 10 [mm] → Height: 7 [mm] → Volume of the feature: 549,78 [mm^3] → Area of the feature: 298,45 [mm^2] → Faces of the feature: → Circular_face_07.01 → Circular_face_07.02 → Cylindrical_face_07.01 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Cylindrical_face_07.01 → Specific tolerance: NO → Coating: NO

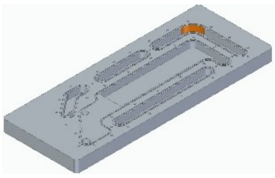
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_8 – THREADED_HOLE_2**
	→ Coordinates of the feature in reference with origin: [-43,86;-41,42;20,00]
	→ Properties of the feature:
	  → Height: 20 [mm]
	  → Thread type: M14 (ISO metric coarse thread)
	  → Thread lenght: 20 [mm]
	→ Volume of the feature: 2187,18 [mm^3]
	→ Area of the feature: 850,77 [mm^2]
	→ Faces of the feature:
	  → Circular_face_08.01
	  → Circular_face_08.02
	  → Cylindrical_face_08.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

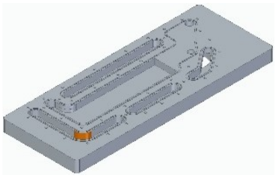
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_9 - SLOT_1**
	→ Coordinates of the feature in reference with origin: [16,57;41,41;00,00]; [16,57;205,50;00,00]; [-43,84;205,50;00,00]; [-43,86;193,70;00,00]; [-21,83;193,70;00,00]; [-21,83; 41,41;00,00]
	→ Properties of the feature:
	  → Height: 10,00 [mm]
	  → Radius: 5,90 [mm]
	→ Volume of the feature: 66.086,40 [mm^3]
	→ Area of the feature: 4556,90 [mm^2]
	→ Faces of the feature:
	  → Poligonal_face_09.01
	  → Poligonal_face_09.02
	  → Rectangular_face_09.01
	  → Rectangular_face_09.02
	  → Rectangular_face_09.03
	  → Rectangular_face_09.04
	  → Rectangular_face_09.05
	  → Semicircular_face_09.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

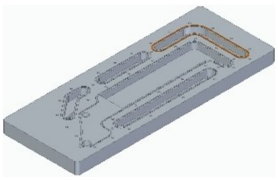
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_10 – FILLET_2**
	→ Coordinates of the feature in reference with origin: [16,57;205,50;00,00]
	→ Properties of the feature:
	  → Radius: 7 [mm]
	  → Height: 10 [mm]
	→ Volume of the feature: 105,05 [mm^3]
	→ Area of the feature: 109,92 [mm^2]
	→ Faces of the feature:
	  → Cylindrical_face_10.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO

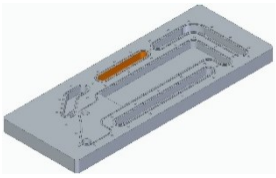
	→ Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_11 – FILLET_3** → Coordinates of the feature in reference with origin: [-21,83;193,70;00,00] → Properties of the feature: → Radius: 13,55 [mm] → Height: 10 [mm] → Volume of the feature: 378,45 [mm^3] → Area of the feature: 243,03 [mm^2] → Faces of the feature: → Cylindrical_face_11.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_12 – GASKET_SLOT_1** → Coordinates of the feature in reference with origin: [20,27;41,41;00,00]; [20,20;198,50;00,00]; [9,50;209,20;00,00]; [-43,84;209,20;00,00]; [-43,86;190,00;00,00]; [-36,83;190,00;00,00]; [-25,53;178,70;00,00]; [-25,53;9,48;00,00]; [-36,83;-1,82;00,00]; [-43,86;-1,82;00,00]; [-53,46;--11,42;00,00]; [-36,83;-1,82;00,00]; [-53,46;-41,42;00,00]; [-36,24;-47,26;00,00]; [4,41;-7,92;00,00]; [8,89;0,78;00,00]; [8,89;25,36;00,00]; [13,10;31,30;00,00] → Properties of the feature: → Widht: 2,20 [mm] → Height: 1,30 [mm] → Volume of the feature: 1865,41 [mm^3] → Area of the feature: 4565,67 [mm^2] → Faces of the feature: → Polygonal_face_12.01 → Polygonal_face_12.02 → Polygonal_face_12.03 → Polygonal_face_12.04 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Polygonal_face_12.02 → Polygonal_face_12.03 → Polygonal_face_12.04 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_13 - SLOT_2** → Coordinates of the feature in reference with origin: [-37,96;16,83;00,00]; [-37,96;171,50;00,00]; [-49,76;16,83;00,00]; [-49,76;171,50;00,00] → Properties of the feature: → Height: 10,00 [mm] → Radius: 5,90 [mm] → Volume of the feature: 19344,20 [mm^3] → Area of the feature: 3.810,4 [mm^2] → Faces of the feature: → Poligonal_face_13.01

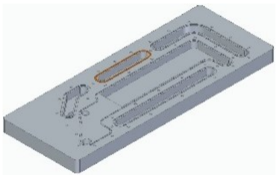
	→ Poligonal_face_13.02 → Rectangular_face_13.01 → Rectangular_face_13.02 → Semicircular_face_13.01 → Semicircular_face_13.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_14 – GASKET_SLOT_2** → Coordinates of the feature in reference with origin: [-34,26;16,83;00,00]; [-34,26;171,50;00,00]; [-53,46;16,83;00,00]; [-53,46;171,50;00,00] → Properties of the feature: → Widht: 2,20 [mm] → Height: 1,30 [mm] → Volume of the feature: 1037,44 [mm^3] → Area of the feature: 2539,18[mm^2] → Faces of the feature: → Polygonal_face_14.01 → Polygonal_face_14.02 → Polygonal_face_14.03 → Polygonal_face_14.04 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Polygonal_face_14.02 → Polygonal_face_14.03 → Polygonal_face_14.04 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_15 - SLOT_3** → Coordinates of the feature in reference with origin: [-43,86;233,30;00,00]; [44,29;233,30;00,00]; [44,29;165,13;00,00]; [32,49;165,13;00,00]; [32,49;221,50;00,00]; [-43,86;221,50;00,00] → Properties of the feature: → Height: 10,00 [mm] → Radius: 5,90 [mm] → Volume of the feature: 18147,60 [mm^3] → Area of the feature: 6890,72 [mm^2] → Faces of the feature: → Poligonal_face_15.01 → Poligonal_face_15.02 → Rectangular_face_15.01 → Rectangular_face_15.02 → Rectangular_face_15.03 → Rectangular_face_15.04 → Semicircular_face_15.01 → Semicircular_face_15.02 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

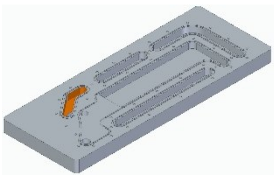
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_16 – FILLET_4**
	→ Coordinates of the feature in reference with origin: [44,29;233,30;00,00]
	→ Properties of the feature:
	  → Radius: 20 [mm]
	  → Height: 10 [mm]
	→ Volume of the feature: 819,131 [mm^3]
	→ Area of the feature: 314,16 [mm^2]
	→ Faces of the feature:
	  → Cylindrical_face_16.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

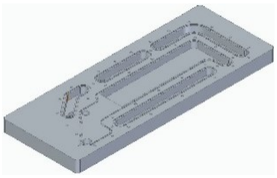
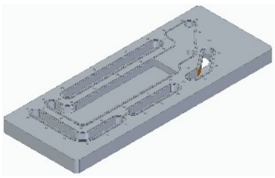
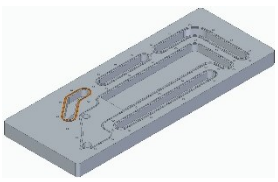
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_17 – FILLET_5**
	→ Coordinates of the feature in reference with origin: [34,49;221,50;00,00]
	→ Properties of the feature:
	  → Radius: 13,55 [mm]
	  → Height: 10 [mm]
	→ Volume of the feature: 378,65 [mm^3]
	→ Area of the feature: 243,02 [mm^2]
	→ Faces of the feature:
	  → Cylindrical_face_17.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_18 – GASKET_SLOT_3**
	→ Coordinates of the feature in reference with origin: [-43,86;237,00;00,00]; [24,29;237,00;00,00]; [47,99;213,30;00,00]; [47,99;165,13;00,00]; [28,79;165,13;00,00]; [28,79;206,50;00,00]; [17,49;217,80;00,00]; [-43,86;217,80;00,00];
	→ Properties of the feature:
	  → Widht: 2,20 [mm]
	  → Height: 1,30 [mm]
	→ Volume of the feature: 938,59 [mm^3]
	→ Area of the feature: 2297,23 [mm^2]
	→ Faces of the feature:
	  → Polygonal_face_18.01
	  → Polygonal_face_18.02
	  → Polygonal_face_18.03
	  → Polygonal_face_18.04
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Polygonal_face_18.02
	      → Polygonal_face_18.03
	      → Polygonal_face_18.04
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_19 - SLOT_4**
	→ Coordinates of the feature in reference with origin: [44,31;139,26;00,00]; [44,31;67,75;00,00]; [32,51;67,75;00,00]; [32,51;139,26;00,00]
	→ Properties of the feature:
	  → Height: 10,00 [mm]
	  → Radius: 5,90 [mm]
	→ Volume of the feature: 9532,00 [mm^3]
	→ Area of the feature: 3707,3 [mm^2]
	→ Faces of the feature:
	  → Poligonal_face_19.01
	  → Poligonal_face_19.02
	  → Rectangular_face_19.01
	  → Rectangular_face_19.02
	  → Semicircular_face_19.01
	  → Semicircular_face_19.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_20 – GASKET_SLOT_4**
	→ Coordinates of the feature in reference with origin: [48,01;139,26;00,00]; [48,01;67,75;00,00]; [28,81;67,75;00,00]; [28,81;139,26;00,00]
	→ Properties of the feature:
	  → Widht: 2,20 [mm]
	  → Height: 1,30 [mm]
	→ Volume of the feature: 561,79 [mm^3]
	→ Area of the feature: 1375,02 [mm^2]
	→ Faces of the feature:
	  → Polygonal_face_20.01
	  → Polygonal_face_20.02
	  → Polygonal_face_20.03
	  → Polygonal_face_20.04
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Polygonal_face_20.02
	      → Polygonal_face_20.03
	      → Polygonal_face_20.04
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_21 - SLOT_5**
	→ Coordinates of the feature in reference with origin: [44,27;34,51;00,00]; [44,27;12,15;00,00]; [18,82;-19,91;00,00]; [9,58;-12,57;00,00]; [34,72;16,27;00,00]
	→ Properties of the feature:
	  → Height: 10,00 [mm]
	  → Radius: 5,90 [mm]
	→ Volume of the feature: 8076,60 [mm^3]
	→ Area of the feature: 3169,62 [mm^2]
	→ Faces of the feature:

	→ Poligonal_face_21.01 → Poligonal_face_21.02 → Rectangular_face_21.01 → Rectangular_face_21.02 → Rectangular_face_21.03 → Rectangular_face_21.04 → Semicircular_face_21.01 → Semicircular_face_21.02 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_22 – FILLET_6** → Coordinates of the feature in reference with origin: [44,27;12,15;00,00] → Properties of the feature: → Radius: 5,9 [mm] → Height: 10 [mm] → Volume of the feature: 4,59 [mm^3] → Area of the feature: 39,59 [mm^2] → Faces of the feature: → Cylindrical_face_22.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_23 – FILLET_7** → Coordinates of the feature in reference with origin: [32,47;16,27;00,00] → Properties of the feature: → Radius: 12,50 [mm] → Height: 10 [mm] → Volume of the feature: 20,59 [mm^3] → Area of the feature: 83,87 [mm^2] → Faces of the feature: → Cylindrical_face_23.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_24 – GASKET_SLOT_5** → Coordinates of the feature in reference with origin: [47,97;34,51;00,00]; [44,97;14,21;00,00]; [45,89;8,24;00,00]; [21,72;-22,21;00,00]; [6,68;-10,27;00,00]; [26,86;15,15;00,00]; [28,77;20,63;00,00]; [28,77;34,51;00,00] → Properties of the feature: → Widht: 2,20 [mm] → Height: 1,30 [mm] → Volume of the feature: 489,85 [mm^3] → Area of the feature: 1198,95 [mm^2] → Faces of the feature: → Polygonal_face_24.01 → Polygonal_face_24.02 → Polygonal_face_24.03

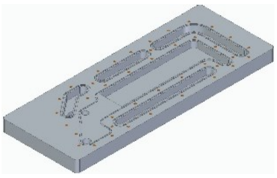
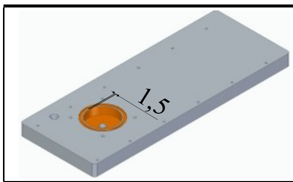
	→ Polygonal_face_24.04 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Polygonal_face_24.02 → Polygonal_face_24.03 → Polygonal_face_24.04 → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_25 – THREADED_HOLES_PATTERN_3** → Coordinates of the feature in reference with origin: [-44,13;-54,83;00,00]; [-56,83;-41,26;00,00]; [-23,63;-39,80;00,00]; [-2,07;-35,13;00,00]; [24,97;-24,79;00,00]; [-57,45;-10,88;00,00]; [43,33;-1,79;00,00]; [-43,79;2,72;00,00]; [-29,68;17,13;00,00]; [-58,19;16,83;00,00]; [20,71;24,77;00,00]; [52,45;27,18;00,00]; [-58,19;55,38;00,00]; [-26,98;57,52;00,00]; [24,50;59,43;00,00]; [52,22;74,24;00,00]; [-29,68;97,90;00,00]; [-58,19;110,82;00,00]; [24,48;99,81;00,00]; [52,22;102,95;00,00]; [52,22;131,67;00,00]; [24,47;140,20;00,00]; [-29,68;138,29;00,00]; [-58,19;166,26;00,00]; [38,21;152,30;00,00]; [52,19;165,13;00,00]; [24,45;180,58;00,00]; [52,19;197,16;00,00]; [19,13;210,13;00,00]; [-13,63;213,38;00,00]; [-43,48;213,40;00,00]; [-57,61;199,36;00,00]; [-43,86;185,80;00,00]; [-29,68;178,67;00,00]; [-58,19;166,26;00,00]; [47,79;228,34;00,00]; [20,20;241,20;00,00]; [-11,83;241,20;00,00]; [-43,86;241,20;00,00]; [-57,66;227,40;00,00] → Properties of the feature: → Hole number: 40 [ad.] → Height: 10 [mm] → Thread: M4 (ISO metric coarse thread) → Thread length: 8 → Volume of the feature: 85,53*40 [mm^3] → Area of the feature: 103.67*40 [mm^2] → Faces of the feature (for one hole): → Circular_face_25.01 → Circular_face_25.02 → Cylindrical_face_25.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

Table 77 Features of 3° block (part 1 – plate original design)

	→ Material: Aluminium - AC 100 → Type of feature vs. type/s of feature/s: **Feature_3 – CYLINDRICAL_SLOT_1 vs. Feature_3 – CYLINDRICAL_SLOT_2** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;20,00] vs. [00,00;00,00;20,00] → Properties of the feature vs. properties of the feature:

	→ Diameter of Feature_3 – CYLINDRICAL_SLOT_1 vs. External diameter of Feature_3 – CYLINDRICAL_SLOT_2: 49,50 [mm] vs. 52,50 [mm] → Minimum distance: 1,5 [mm] → Volume of the feature vs. volume of the feature/s: 25017,48 [mm^3] vs. 1704,00 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 852,00 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_03.01 vs. Cylindrical_face_04.02 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_03_01 vs. Cylindrical_face_04.02 → Specific tolerance: NO → Coating: NO

Table 78 Features of 1° block (part 1 – plate updated design)

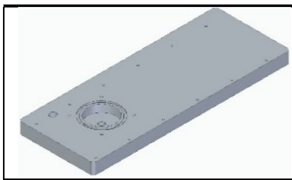
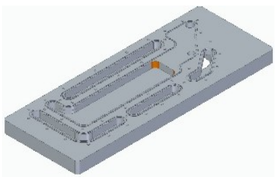
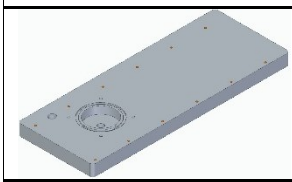
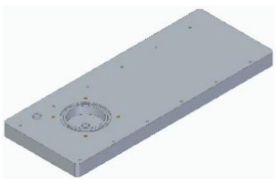
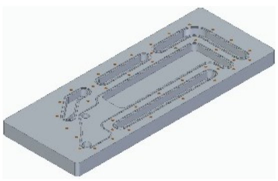
	→ Material: Aluminium - AC 100 → Shape: Prismatic → Volume: 743996,99[mm^3] → Area: 136527,98 [mm^2] → Dimensions: 131,00*345,00*20,00 [mm]

Table 79 Features of 2° block (part 1 – plate updated design)

	→ Material: Aluminium - AC 100 → Type of feature: **Feature_26 – FILLET_8** → Coordinates of the feature in reference with origin: [16,57;41,41;00,00]; [-21,83;41,41;00,00] → Properties of the feature: → Radius: 7,00 [mm] → Height: 10 [mm] → Volume of the feature: 105,21*2 [mm^3] → Area of the feature: 109,99*2 [mm^2] → Faces of the feature (for one fillet): → Cylindrical_face_26.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_5 – THREADED_HOLES_PATTERN_1_MOD** → Coordinates of the feature in reference with origin: [-44,41;-62,92;20,00]; [-44,41;-12,20;20,00]; [-44,41;47,68;20,00]; [-44,41;107,63;20,00]; [-44,41;167,43;20,00]; [-44,41;227,27;20,00];

	[60,45;-62,92;20,00]; [60,45;-12,20;20,00]; [60,45;47,68;20,00]; [60,45;107,63;20,00]; [60,45;167,43;20,00]; [60,45;227,27;20,00] → Properties of the feature: → Hole number: 12 [ad.] → Hole height: 7 [mm] → Thread type: M4 (ISO metric coarse thread) → Thread lenght: 5 [mm] → Volume of the feature: 62,70*12 [mm^3] → Area of the feature: 82,55*12 [mm^2] → Faces of the feature (for one hole): → Circular_face_05.01 → Circular_face_05.02 → Cylindrical_face_05.01 → Conical_face_05.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_6 - THREADED_HOLES_PATTERN_2_MOD** → Coordinates of the feature in reference with origin: [-28,35;-28,38;20,00]; [-28,35;28,38;20,00]; [28,35;--28,38;20,00]; [28,35;28,38;20,00] → Properties of the feature: → Hole number: 4 [ad.] → Hole height: 10 [mm] → Thread: M5 (ISO metric coarse thread) → Thread length: 8 → Volume of the feature: 138,54*4 [mm^3] → Area of the feature: 148,11*4 [mm^2] → Faces of the feature (for one hole): → Circular_face_06.01 → Circular_face_06.02 → Cylindrical_face_06.01 → Conical_face_06.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: Aluminium - AC 100 → Type of feature: **Feature_25 – THREADED_HOLES_PATTERN_3_MOD** → Coordinates of the feature in reference with origin: [-44,13;-54,83;00,00]; [-56,83;-41,26;00,00]; [-23,63;-39,80;00,00]; [-2,07;-35,13;00,00]; [24,97;-24,79;00,00]; [-57,45;-10,88;00,00]; [43,33;-1,79;00,00]; [-43,79;2,72;00,00]; [-29,68;17,13;00,00]; [-58,19;16,83;00,00]; [20,71;24,77;00,00]; [52,45;27,18;00,00]; [-58,19;55,38;00,00]; [-26,98;57,52;00,00]; [24,50;59,43;00,00]; [52,22;74,24;00,00]; [-29,68;97,90;00,00]; [-58,19;110,82;00,00]; [24,48;99,81;00,00]; [52,22;102,95;00,00]; [52,22;131,67;00,00]; [24,47;140,20;00,00]; [-29,68;138,29;00,00]; [-58,19;166,26;00,00]; [38,21;152,30;00,00]; [52,19;165,13;00,00]; [24,45;180,58;00,00]; [52,19;197,16;00,00]; [19,13;210,13;00,00]; [-13,63;213,38;00,00]; [-43,48;213,40;00,00]; [-57,61;199,36;00,00]; [-43,86;185,80;00,00]; [-

	29,68;178,67;00,00]; [-58,19;166,26;00,00]; [47,79;228,34;00,00]; [20,20;241,20;00,00]; [-11,83;241,20;00,00]; [-43,86;241,20;00,00]; [-57,66;227,40;00,00]
	→ Properties of the feature:
	  → Hole number: 40 [ad.]
	  → Height: 10 [mm]
	  → Thread: M4 (ISO metric coarse thread)
	  → Thread length: 8
	→ Volume of the feature: 85,53*40 [mm^3]
	→ Area of the feature: 113.65*40 [mm^2]
	→ Faces of the feature (for one hole):
	  → Circular_face_25.01
	  → Circular_face_25.02
	  → Cylindrical_face_25.01
	  → Conical_face_25.01
	→ PMI:
	  → Specific roughness:NO
	  → Specific tolerance: NO
	  → Coating: NO

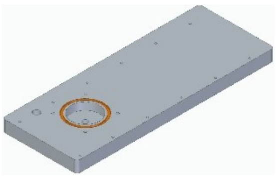
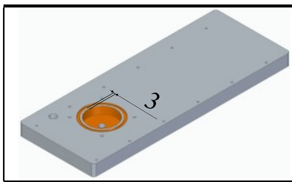
	→ Material: Aluminium - AC 100
	→ Type of feature: **Feature_4 – CYLINDRICAL_SLOT_2_MOD**
	→ Coordinates of the feature in reference with origin: [00,00;00,00;20,00]
	→ Properties of the feature:
	  → Diameter external: 63,50[mm]
	  → Diameter internal: 55,50 [mm]
	  → Height: 2,40 [mm]
	→ Volume of the feature: 1794,48 [mm^3]
	→ Area of the feature: 2392,64 [mm^2]
	→ Faces of the feature:
	  → Circular_face_04.01
	  → Circular_face_04.02
	  → Cylindrical_face_04.01
	  → Cylindrical_face_04.02
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Circular_face_04.02
	      → Cylindrical_face_04.01
	      → Cylindrical_face_04.02
	  → Specific tolerance: NO
	  → Coating: NO

Table 80 Features of 3° block (part 1 – plate updated design)

 	→ Material: Aluminium - AC 100 → Type of feature vs. type/s of feature/s: **Feature_3 – CYLINDRICAL_SLOT_1 vs. Feature_4 – CYLINDRICAL_SLOT_2_MOD** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;20,00] vs. [00,00;00,00;20,00] → Properties of the feature vs. properties of the feature:

	→ Diameter of Feature_3 – CYLINDRICAL_SLOT_1 vs. External diameter of Feature_4 – CYLINDRICAL_SLOT_2: 49,50 [mm] vs. 55,50 [mm] → Minimum distance: 3,00 [mm] → Volume of the feature vs. volume of the feature/s: 25017,48 [mm^3] vs. 1794,48 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 2392,64 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_03.01 vs. Cylindrical_face_04.02 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_03_01 vs. Cylindrical_face_04.02 → Specific tolerance: NO → Coating: NO

Table 81 Features of 1° block (part 2 – shaft original design)

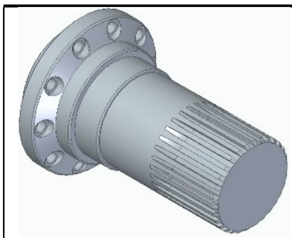
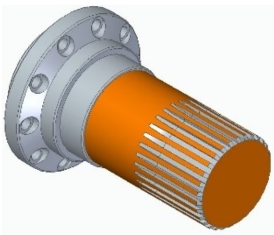
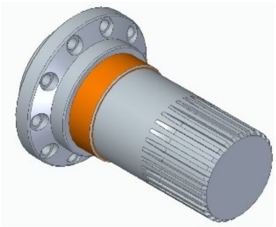
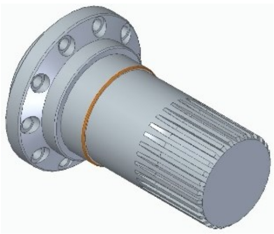
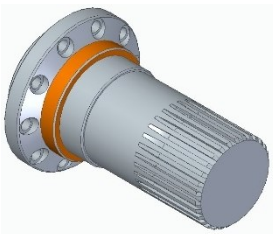
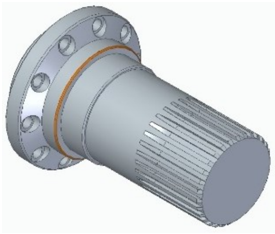
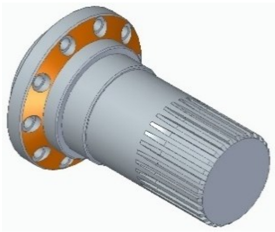
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 4905816,33 [mm^3] → Area: 275650,91 [mm^2] → Dimensions: 220*220*330 [mm]

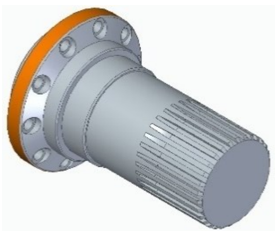
Table 82 Features of 2° block (part 2 – shaft original design)

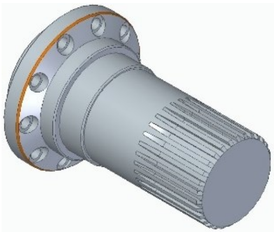
	→ Material: C40 Carbon Steel → Type of feature: **Feature_1 - CYLINDER_1** → Coordinates of the feature in reference with origin: [00;00;00] → Properties of the feature: → Diameter: 131,8 [mm] → Height: 205 [mm] → Volume of the feature: 2796884,70 [mm^3] → Area of the feature: 112169,37 [mm^2] → Faces of the feature: → Circular_face_01.01 → Circular_face_01.02 → Cylindrical_face_01.01 → PMI: → Specific roughness: → Ra 0,4 [µm] on: → Cylindrical_face_01.01 → Specific tolerance: → h7 on: → Cylindrical_face_01.01

	→ Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_2 - CYLINDER_2** → Coordinates of the feature in reference with origin: [00;00;-40] → Properties of the feature: → Diameter: 140 [mm] → Height: 40 [mm] → Volume of the feature: 615752,16 [mm^3] → Area of the feature: 32986,72 [mm^2] → Faces of the feature: → Circular_face_02.01 → Circular_face_02.02 → Cylindrical_face_02.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_3 - CHAMFER_1** → Coordinates of the feature in reference with origin: [00;00;00] → Properties of the feature: → Diameter: 140 [mm] → Height: 2 [mm] → Angle: 45 [°] → Volume of the feature: 871,27 [mm^3] → Area of the feature: 1226,24 [mm^2] → Faces of the feature: → Conical_face_03.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_4 - CYLINDER_3** → Coordinates of the feature in reference with origin: [00;00;-64,08] → Properties of the feature: → Diameter: 160 [mm] → Height: 24,08 [mm] → Volume of the feature: 484157,13 [mm^3] → Area of the feature: 32210,12 [mm^2] → Faces of the feature: → Circular_face_04.01 → Circular_face_04.02 → Cylindrical_face_04.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO

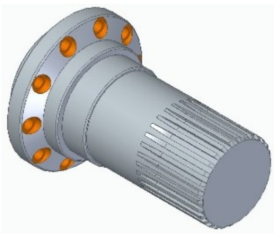
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_5 - CHAMFER_2**
	→ Coordinates of the feature in reference with origin: [00;00;-40]
	→ Properties of the feature:
	  → Diameter: 160 [mm]
	  → Height: 2 [mm]
	  → Angle: 45 [°]
	→ Volume of the feature: 996,93 [mm^3]
	→ Area of the feature: 1403,95 [mm^2]
	→ Faces of the feature:
	  → Conical_face_05.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

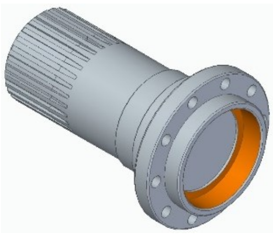
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_6 - TRUNCATED CONE_1**
	→ Coordinates of the feature in reference with origin: [00;00;-75]
	→ Properties of the feature:
	  → Large diameter: 220 [mm]
	  → Small diameter: 160 [mm]
	  → Height: 10,92 [mm]
	  → Draft angle: 70 [°]
	→ Volume of the feature: 312186,34 [mm^3]
	→ Area of the feature: 77175,96 [mm^2]
	→ Faces of the feature:
	  → Circular_face_06.01
	  → Circular_face_06.02
	  → Conical_face_06.03
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

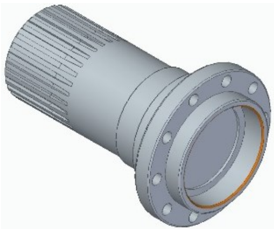
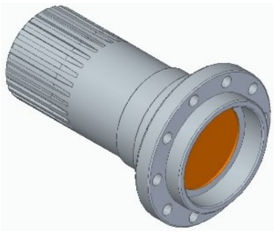
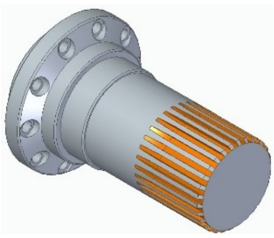
	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_7 - CYLINDER_4**
	→ Coordinates of the feature in reference with origin: [00;00;-100]
	→ Properties of the feature:
	  → Diameter: 220 [mm]
	  → Height: 25 [mm]
	→ Volume of the feature: 950331,78 [mm^3]
	→ Area of the feature: 55292,03 [mm^2]
	→ Faces of the feature:
	  → Circular_face_07.01
	  → Circular_face_07.02
	  → Cylindrical_face_07.01
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Circular_face_07.01
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_8 - CHAMFER_3**
	→ Coordinates of the feature in reference with origin: [00;00;-75]
	→ Properties of the feature:
	  → Diameter: 220 [mm]
	  → Height: 2 [mm]
	  → Angle: 45 [°]
	→ Volume of the feature: 1291,54 [mm^3]
	→ Area of the feature: 2245,28 [mm^2]
	→ Faces of the feature:
	  → Conical_face_08.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_9 - CHAMFER_4**
	→ Coordinates of the feature in reference with origin: [00;00;-100]
	→ Properties of the feature:
	  → Diameter: 220 [mm]
	  → Height: 2 [mm]
	  → Angle: 45 [°]
	→ Volume of the feature: 1373,92 [mm^3]
	→ Area of the feature: 1937,10 [mm^2]
	→ Faces of the feature:
	  → Conical_face_09.01
	→ PMI:
	  → Specific roughness: NO
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: C40 Carbon Steel
	→ Type of feature: **Feature_10 - HOLE CIRCULAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern [00;00;-100]
	  → For first hole [90,35;00;-100]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 17,5 [mm]
	    → Length: 25 [mm]
	    → Number: 10 [ad.]
	  → For spotfaces:
	    → Diameter: 26 [mm]
	    → Length: 10,92 [mm]
	    → Number: 10 [ad.]
	→ Volume of the feature: 6013,20*10 + 2855,63*10 [mm^3]
	→ Area of the feature: 1614,97*10 + 1528,65*10 [mm^2]
	→ Faces of the feature:
	  → Circular_face_10.01*10
	  → Circular_face_10.02*10
	  → Circular_face_10.03*10
	  → Cilindrical_face_10.01*10
	  → Cilindrical_face_10.02*10
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:

	→ Circular_face_10.02*10 → Cilindrical_face_10.01*10 → Cilindrical_face_10.02*10 → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_11 - CYLINDER_5** → Coordinates of the feature in reference with origin: [00;00;-125] → Properties of the feature: → Diameter: 160 [mm] → Height: 25 [mm] → Volume of the feature: 502654,82 [mm^3] → Area of the feature: 32672,56 [mm^2] → Faces of the feature: → Circular_face_11.01 → Circular_face_11.02 → Cylindrical_face_11.01 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Circular_face_11.01 → Cylindrical_face_11.01 → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_12 - CHAMFER_5** → Coordinates of the feature in reference with origin: [00;00;-125] → Properties of the feature: → Diameter: 160 [mm] → Height: 2 [mm] → Angle: 45 [°] → Volume of the feature: 996,93 [mm^3] → Area of the feature: 1403,95 [mm^2] → Faces of the feature: → Conical_face_12.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_13 - SLOT_1** → Coordinates of the feature in reference with origin: [00;00;-125] → Properties of the feature: → Diameter: 140 [mm] → Height: 32,2 [mm] → Volume of the feature: 495680,49 [mm^3] → Area of the feature: 29556,10 [mm^2] → Faces of the feature: → Circular_face_13.01 → Circular_face_13.02 → Cylindrical_face_13.01 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Circular_face_13.02

	→ Cylindrical_face_13.01 → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_14 - CHAMFER_6** → Coordinates of the feature in reference with origin: [00;00;-125] → Properties of the feature: → Diameter: 140 [mm] → Height: 2 [mm] → Angle: 45 [°] → Volume of the feature: 888,02 [mm^3] → Area of the feature: 1261,78 [mm^2] → Faces of the feature: → Conical_face_14.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_15 - SLOT_2** → Coordinates of the feature in reference with origin: [00;00;-92,8] → Properties of the feature: → Diameter: 120 [mm] → Height: 3,8 [mm] → Volume of the feature: 42976,99 [mm^3] → Area of the feature: 12742,30 [mm^2] → Faces of the feature: → Circular_face_15.01 → Circular_face_15.02 → Cylindrical_face_15.01 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Circular_face_15.02 → Cylindrical_face_15.01 → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_16 – SPLINED PROFILE** → Coordinates of the feature in reference with origin: [00;00;205] → Properties of the feature: → Length: 115,55 [mm] → Widht: 7,58 [mm] → Height: 5 [mm] → Volume of the feature: 3790,13*10 [mm^3] → Area of the feature: 1865,54*10 [mm^2] → Faces of the feature: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30

	→ Trapezoidal_face_16.02*30 → PMI: → Specific roughness: → Ra 0,4 [µm] on: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30 → Specific tolerance: → h7 on: → Rectangular_face_16.01*30 → Rectangular_face_16.02*30 → Rectangular_face_16.03*30 → Rectangular_face_16.04*30 → Rectangular_face_16.05*30 → Triangular_face_16.01*30 → Triangular_face_16.02*30 → Trapezoidal_face_16.01*30 → Trapezoidal_face_16.02*30 → Coating: NO

Table 83 Features of 1° block (part 2 – shaft updated design)

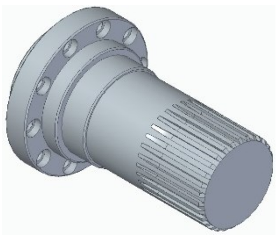
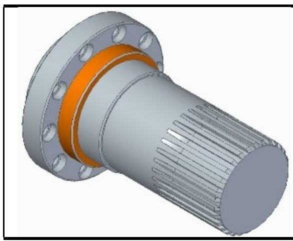
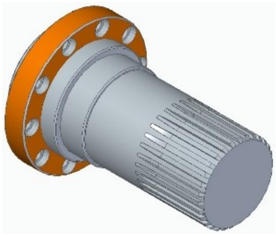
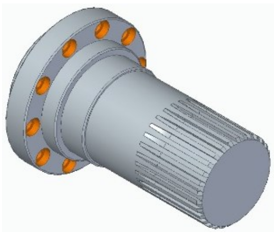
	→ Material: C40 Carbon Steel → Shape: Axysimmetrical → Volume: 4967652,19 [mm^3] → Area: 285749,69 [mm^2] → Dimensions: 220*220*330 [mm]

Table 84 Features of 2° block (part 2 – shaft updated design)

	→ Material: C40 Carbon Steel → Type of feature: **Feature_4 - CYLINDER_3_MOD** → Coordinates of the feature in reference with origin: [00;00;-64,08] → Properties of the feature: → Diameter: 160 [mm] → Height: 25 [mm] → Volume of the feature: 502654,82 [mm^3] → Area of the feature: 32672,56 [mm^2] → Faces of the feature:

	→ Circular_face_04.01 → Circular_face_04.02 → Cylindrical_face_04.01 → PMI: → Specific roughness: NO → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_7 - CYLINDER_4_MOD** → Coordinates of the feature in reference with origin: [00;00;-100] → Properties of the feature: → Diameter: 220 [mm] → Height: 35 [mm] → Volume of the feature: 1330464,49 [mm^3] → Area of the feature: 62203,53 [mm^2] → Faces of the feature: → Circular_face_07.01 → Circular_face_07.02 → Cylindrical_face_07.01 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Circular_face_07.01 → Specific tolerance: NO → Coating: NO
	→ Material: C40 Carbon Steel → Type of feature: **Feature_10 - HOLE CIRCULAR PATTERN_MOD** → Coordinates of the feature in reference with origin: → For circular pattern [00;00;-100] → For first hole [90,35;00;-100] → Properties of the feature: → For holes: → Diameter: 17,5 [mm] → Length: 25 [mm] → Number: 10 [ad.] → For spotfaces: → Diameter: 26 [mm] → Length: 10 [mm] → Number: 10 [ad.] → Volume of the feature: 6013,20*10 + 5309,29*10 [mm^3] → Area of the feature: 1614,97*10 + 1347,74*10 [mm^2] → Faces of the feature: → Circular_face_10.01*10 → Circular_face_10.02*10 → Circular_face_10.03*10 → Cilindrical_face_10.01*10 → Cilindrical_face_10.02*10 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Circular_face_10.02*10 → Cilindrical_face_10.01*10 → Cilindrical_face_10.02*10 → Specific tolerance: NO

	→ Coating: NO

B.3. Assembly

Table 85 Features of 1° block (assembly 1 part 5 – coupling original design)

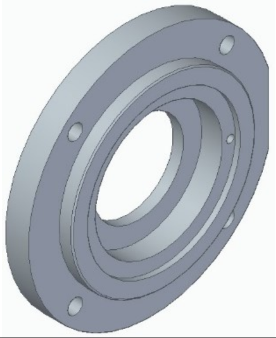
	→ Material: Aisi 316 → Shape: Axysimmetric → Volume: 58477,11 [mm^3] → Area: 19021,97 [mm^2] → Dimensions: 14,00*96,00*94,00 [mm]

Table 86 Features of 2° block (assembly 1 part 16 – bearing cover original design)

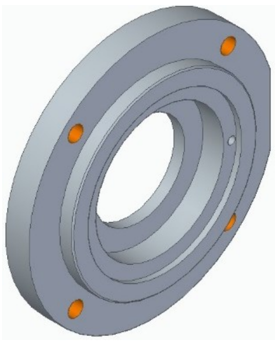
	→ Material: Aisi 316 → Type of feature: **Feature_1 - HOLE CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [00;00;00] → For first hole [00;29,7;29,7] → Properties of the feature: → For holes: → Diameter: 6 [mm] → Length: 9 [mm] → Number: 4 [ad.] → For circular pattern: → Diameter: 84 [mm] → Volume of the feature: 254,47*4 [mm^3] → Area of the feature: 197,92*4 [mm^2] → Faces of the feature: → Circular_face_01.01*4 → Circular_face_01.02*4 → Cilindrical_face_01.01*4 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01*4 → Specific tolerance: NO → Coating: NO

Table 87 Features of 1° block (assembly 1 part 2 – casing original design)

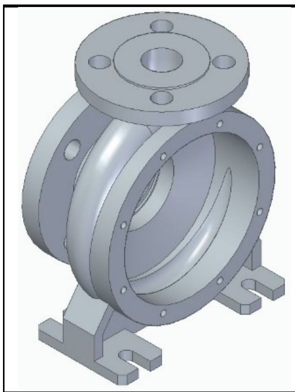
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 1185824,19 [mm^3] → Area: 271949,61 [mm^2] → Dimensions: 130,00*190,00*250,00 [mm]

Table 88 Features of 2° block (assembly 1 part 2 – casing original design)

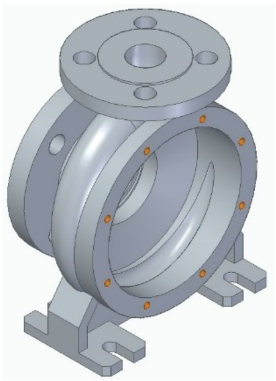
	→ Material: Grey cast iron → Type of feature: **Feature_1 – THREADED HOLE CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [34;00;00] → For first hole [34,00;32,15;77,61] → Properties of the feature: → For holes: → Type: M8 [mm] → Length: 14 [mm] → Number: 8 [ad.] → For circular pattern: → Diameter: 168 [mm] → Volume of the feature: 508,43*8 [mm^3] → Area of the feature: 377,77*8 [mm^2] → Faces of the feature: → Circular_face_01.01*8 → Circular_face_01.02*8 → Cilindrical_face_01.01*8 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Cilindrical_face_01.01*8 → Specific tolerance: NO → Coating: NO

Table 89 Features of 1° block (assembly 1 part 20 – house bearing original design)

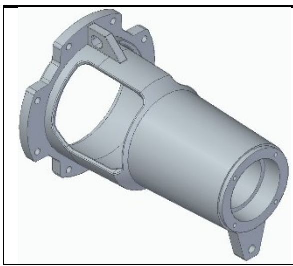
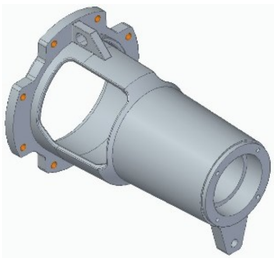
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 1013622,54 [mm^3] → Area: 181931,04 [mm^2] → Dimensions: 255,00*185,00*185,00 [mm]

Table 90 Features of 2° block (assembly 1 part 20 – house bearing original design)

	→ Material: Grey cast iron
	→ Type of feature: **Feature_1 - HOLE BASE**
	  → Coordinates of the feature in reference with origin: [235;00;-77]
	→ Properties of the feature:
	    → Diameter: 10 [mm]
	    → Length: 15 [mm]
	→ Volume of the feature: 1178,10 [mm^3]
	→ Area of the feature: 628,31 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01
	  → Circular_face_01.02
	  → Cilindrical_face_01.01
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Cilindrical_face_01.01
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Grey cast iron
	→ Type of feature: **Feature_2 - HOLE CIRCULAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern [05;00;00]
	  → For first hole [05;32,15;77,61]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 8 [mm]
	    → Length: 11,5 [mm]
	    → Number: 8 [ad.]
	  → For circular pattern:
	    → Diameter: 168 [mm]
	→ Volume of the feature: 578,05*8 [mm^3]
	→ Area of the feature: 389,56*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_02.01*8
	  → Circular_face_02.02*8
	  → Cilindrical_face_02.01*8
	→ PMI:

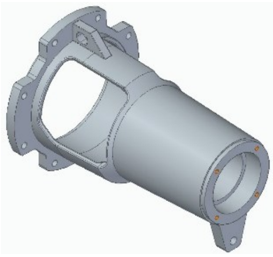
	→ Specific roughness: → Ra 1,6 [μm] on: → Cilindrical_face_02.01*8 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_3 – THREADED HOLE CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [255;00;00] and [119;00;00] → For first hole [255;29,7;29,7] and [119;29,7;29,7] → Properties of the feature: → For holes: → Diameter: M6 [mm] → Length: 24 [mm] → Number: 4 (for each pattern) [ad.] → For circular pattern: → Diameter: 84 [mm] → Volume of the feature: 471,24*4 [mm^3] → Area of the feature: 409,72*4 [mm^2] → Faces of the feature: → Circular_face_03.01*4 → Conical_face_03.02*4 → Cilindrical_face_03.01*4 → PMI: → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Cilindrical_face_03.01*8 → Specific tolerance: NO → Coating: NO

Table 91 Features of 1° block (assembly 1 part 5 – coupling original design)

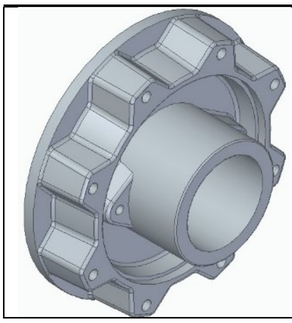
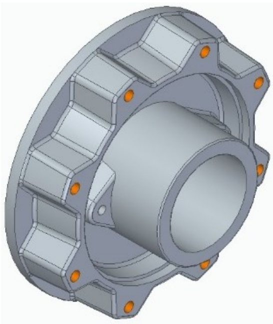
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 686316,35 [mm^3] → Area: 137072,39 [mm^2] → Dimensions: 85,00*190,00*190,00 [mm]

Table 92 Features of 2° block (assembly 1 part 5 – coupling original design)

	→ Material: Grey cast iron
	→ Type of feature: **Feature_1 - HOLE CIRCULAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern [08;00;00]
	  → For first hole [08;32,15;77,61]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 8 [mm]
	    → Length: 42 [mm]
	    → Number: 8 [ad.]
	  → For circular pattern:
	    → Diameter: 168 [mm]
	→ Volume of the feature: 2111,15*8 [mm^3]
	→ Area of the feature: 1156,11*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*8
	  → Circular_face_01.02*8
	  → Cilindrical_face_01.01*8
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Cilindrical_face_01.01*8
	  → Specific tolerance: NO
	  → Coating: NO

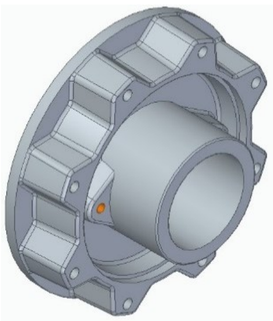
	→ Material: Grey cast iron
	→ Type of feature: **Feature_2 – THREADED HOLE LINEAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For linear pattern [45;50;00]
	  → For first hole [45;50;00]
	→ Properties of the feature:
	  → For holes:
	    → Type: M8 [mm]
	    → Length: 18 [mm]
	    → Number: 2 [ad.]
	  → For linear pattern:
	    → Distance between hole centre: 100 [mm]
	→ Volume of the feature: 653,70*2 [mm^3]
	→ Area of the feature: 445,06*2 [mm^2]
	→ Faces of the feature:
	  → Circular_face_02.01*2
	  → Conical_face_02.02*2
	  → Cilindrical_face_02.01*2
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Cilindrical_face_02.01*2
	  → Specific tolerance: NO
	  → Coating: NO

Table 93 Features of 1° block (assembly 1 part 9 – packing gland original design)

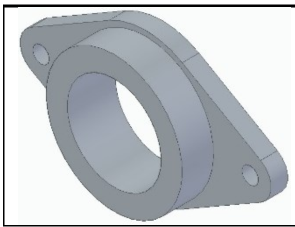
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 55505,41 [mm^3] → Area: 16420,72 [mm^2] → Dimensions: 23,00*120,00*70,00 [mm]

Table 94 Features of 2° block (assembly 1 part 9 – packing gland original design)

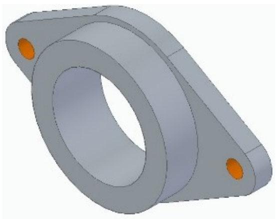
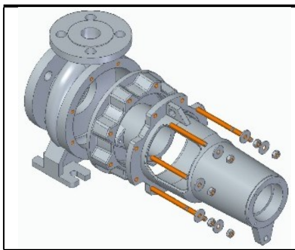
	→ Material: Grey cast iron → Type of feature: **Feature_1 - HOLE LINEAR PATTERN** → Coordinates of the feature in reference with origin: → For linear pattern [00;50;00] → For first hole [00;50;00] → Properties of the feature: → For holes: → Diameter: 8 [mm] → Length: 8 [mm] → Number: 2 [ad.] → For linear pattern: → Distance between hole centre: 100 [mm] → Volume of the feature: 402,12*2 [mm^3] → Area of the feature: 301,59*2 [mm^2] → Faces of the feature: → Circular_face_01.01*2 → Circular_face_01.02*2 → Cilindrical_face_01.01*2 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Cilindrical_face_01.01*2 → Specific tolerance: NO → Coating: NO

Table 95 Features of 4° block (assembly 1 – centrifugal pump original design)

	→ Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M8)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature:

	→ Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. type of thread of Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M8): M8 vs. M8 → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 232,64 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 2186,55[mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [μm] vs. Ra 1,6 [μm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 – HOLE (Plain washer ISO 7089 M8)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_1 –HOLE (Plain washer ISO 7089 M8): M8 vs. 8,4 [mm] → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 110,83 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 108,20 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [μm] vs. Ra 1,6 [μm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Grey cast iron → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_2 - HOLE CIRCULAR PATTERN (House bearing)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [05,00;32,15;77,61] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_2 - HOLE CIRCULAR PATTERN (House bearing): M8 vs. 8 [mm] → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 578,05 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 339,29 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_02.01

- → PMI vs. PMI:
    - → Specific roughness:
        - → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
            - → Cylindrical_face_01_01 vs. Cylindrical_face_02.01
    - → Specific tolerance: NO
    - → Coating: NO

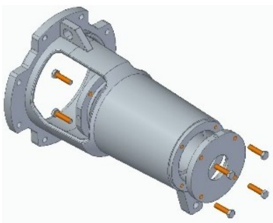
- → Material vs. material: Aisi 316 vs. Grey cast iron
- → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 - HOLE CIRCULAR PATTERN (Coupling)**
- → Coordinates of the feature vs. coordinates of the feature/s:
    - → [00,00;00,00;00,00] vs. [08,00;32,15;77,61]
- → Properties of the feature vs. properties of the feature:
    - → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_1 - HOLE CIRCULAR PATTERN (Coupling): M8 vs. 8 [mm]
- → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 2111,15 [mm^3]
- → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 1105,84 [mm^2]
- → Faces of the feature vs. faces of the feature/s:
    - → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
- → PMI vs. PMI:
    - → Specific roughness:
        - → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
            - → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
    - → Specific tolerance: NO
    - → Coating: NO

- → Material vs. material: Aisi 316 vs. Grey cast iron
- → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 - THREADED CIRCULAR PATTERN (Casing)**
- → Coordinates of the feature vs. coordinates of the feature/s:
    - → [00,00;00,00;00,00] vs. [34,00;32,15;77,61]
- → Properties of the feature vs. properties of the feature:
    - → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. type of thread of Feature_1 – THREADED HOLE CIRCULAR PATTERN (Coupling): M8 vs. M8 [mm]
- → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 508,43 [mm^3]
- → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 377,77 [mm^2]
- → Faces of the feature vs. faces of the feature/s:
    - → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
- → PMI vs. PMI:
    - → Specific roughness:
        - → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
            - → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
    - → Specific tolerance: NO
    - → Coating: NO

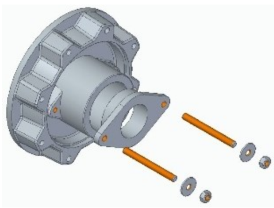
- → Material vs. material: Aisi 316 vs. Aisi 316
- → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. Feature_1 – HOLE (Plain washer ISO 7089 M10)**
- → Coordinates of the feature vs. coordinates of the feature/s:
  - → [00,00;00,00;00,00] vs. [00,00;00,00;00,00]
- → Properties of the feature vs. properties of the feature:
  - → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. diameter of Feature_1 – HOLE (Plain washer ISO 7089 M10): M10 vs. 10,5 [mm]
- → Volume of the feature vs. volume of the feature/s: 3534,29 [mm^3] vs. 216,47 [mm^3]
- → Area of the feature vs. area of the feature/s: 1570,80 [mm^2] vs. 255,65 [mm^2]
- → Faces of the feature vs. faces of the feature/s:
  - → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
- → PMI vs. PMI:
  - → Specific roughness:
    - → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
      - → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
  - → Specific tolerance: NO
  - → Coating: NO

- → Material vs. material: Aisi 316 vs. Aisi 316
- → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. Feature_1 – SLOT (Support)**
- → Coordinates of the feature vs. coordinates of the feature/s:
  - → [00,00;00,00;00,00] vs. [00,00;-74,50;48,00] [00,00;-74,50;25,00] [00,00;-85,50;48,00] [00,00;-85,50;25,00]
- → Properties of the feature vs. properties of the feature:
  - → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. width of Feature_1 – SLOT (Support): M10 vs. 11 [mm]
- → Volume of the feature vs. volume of the feature/s: 3534,29 [mm^3] vs. 1107,03 [mm^3]
- → Area of the feature vs. area of the feature/s: 1570,80 [mm^2] vs. 353,18 [mm^2]
- → Faces of the feature vs. faces of the feature/s:
  - → Cylindrical_face_01.01 vs. Rectangular_face_01.01 and Rectangular_face_01.02
- → PMI vs. PMI:
  - → Specific roughness:
    - → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
      - → Cylindrical_face_01_01 vs. Rectangular_face_01.01 and Rectangular_face_01.02
  - → Specific tolerance: NO
  - → Coating: NO

- → Material vs. material: Aisi 316 vs. Grey cast iron
- → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. Feature_1 - HOLE BASE (House bearing)**

	→ Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [235,00;00;00;77,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_1 - HOLE BASE (House bearing): M10 vs. 10 [mm] → Volume of the feature vs. volume of the feature/s: 3534,29 [mm^3] vs. 1178,10 [mm^3] → Area of the feature vs. area of the feature/s: 1570,80 [mm^2] vs. 549,78 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M10)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4016 M10 x 45) vs. type of thread of Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M10): M10 vs. M10 → Volume of the feature vs. volume of the feature/s: 3534,29 [mm^3] vs. 476,66 [mm^3] → Area of the feature vs. area of the feature/s: 1570,80 [mm^2] vs. 337,80 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO
	→ Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. Feature_1 - HOLE CIRCULAR PATTERN (Bearing cover)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;29,70;29,70] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. diameter of Feature_1 - HOLE CIRCULAR PATTERN (Bearing cover): M6 vs. 6 [mm] → Volume of the feature vs. volume of the feature/s: 706,86 [mm^3] vs. 254,47 [mm^3]

	→ Area of the feature vs. area of the feature/s: 527,79 [mm^2] vs. 197,92 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	  → Specific tolerance: NO
	  → Coating: NO
	
	→ Material vs. material: Aisi 316 vs. Grey cast iron
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. Feature_3 – THREADED HOLE CIRCULAR PATTERN (Bearing cover)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [255,00;29,70;29,70]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. type of thread of Feature_3 – THREADED HOLE CIRCULAR PATTERN (Bearing cover): M6 vs. M6
	→ Volume of the feature vs. volume of the feature/s: 706,86 [mm^3] vs. 471,24 [mm^3]
	→ Area of the feature vs. area of the feature/s: 527,79 [mm^2] vs. 409,72 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_03.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_03.01
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material vs. material: Aisi 316 vs. Aisi 316
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M8)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [00,00;00,00;00,00]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. type of thread of Feature_1 – THREADED HOLE (Nut DIN ISO 4032 M8): M8 vs. M8
	→ Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 232,64 [mm^3]
	→ Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 2186,55[mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_02.01

→ Specific tolerance: NO
→ Coating: NO

→ Material vs. material: Aisi 316 vs. Aisi 316
→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 – HOLE (Plain washer ISO 7089 M8)**
→ Coordinates of the feature vs. coordinates of the feature/s:
  → [00,00;00,00;00,00] vs. [00,00;00,00;00,00]
→ Properties of the feature vs. properties of the feature:
  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_1 –HOLE (Plain washer ISO 7089 M8): M8 vs. 8,4 [mm]
→ Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 110,83 [mm^3]
→ Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 108,20 [mm^2]
→ Faces of the feature vs. faces of the feature/s:
  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
→ PMI vs. PMI:
  → Specific roughness:
    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
  → Specific tolerance: NO
  → Coating: NO

→ Material vs. material: Aisi 316 vs. Grey cast iron
→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_1 - HOLE LINEAR PATTERN (Packing gland)**
→ Coordinates of the feature vs. coordinates of the feature/s:
  → [00,00;00,00;00,00] vs. [00,00;50,00;00,00]
→ Properties of the feature vs. properties of the feature:
  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. diameter of Feature_1 - HOLE LINEAR PATTERN (Packing gland): M8 vs. 8 [mm]
→ Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 402,12 [mm^3]
→ Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 251,33 [mm^2]
→ Faces of the feature vs. faces of the feature/s:
  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
→ PMI vs. PMI:
  → Specific roughness:
    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
  → Specific tolerance: NO
  → Coating: NO

→ Material vs. material: Aisi 316 vs. Grey cast iron
→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. Feature_2 - THREADED HOLE LINEAR PATTERN (Coupling)**
→ Coordinates of the feature vs. coordinates of the feature/s:
  → [00,00;00,00;00,00] vs. [45,00;50,00;00,00]

	→ Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Stud ISO 888 M8 x 85) vs. type of thread of Feature_2 - THREADED HOLE LINEAR PATTERN (Coupling): M8 vs. M8 → Volume of the feature vs. volume of the feature/s: 4272,57 [mm^3] vs. 653,70 [mm^3] → Area of the feature vs. area of the feature/s: 3946,04 [mm^2] vs. 445,06 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_02.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO

Table 96 Features of 1° block (assembly 1 part 16 – bearing cover updated design)

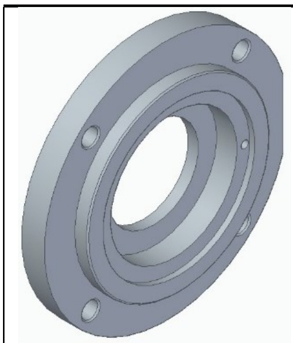
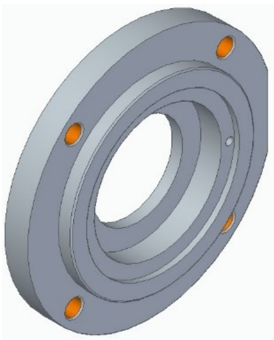
	→ Material: Aisi 316 → Shape: Axysimmetric → Volume: 58241,58 [mm^3] → Area: 18996,35 [mm^2] → Dimensions: 14,00*96,00*94,00 [mm]

Table 97 Features of 2° block (assembly 1 part 16 – bearing cover updated design)

	→ Material: Aisi 316 → Type of feature: **Feature_1 - HOLE CIRCULAR PATTERN_MOD** → Coordinates of the feature in reference with origin: → For circular pattern [00;00;00] → For first hole [00;29,7;29,7] → Properties of the feature: → For holes: → Diameter: 6,6 [mm] → Length: 9 [mm] → Number: 4 [ad.] → For circular pattern: → Diameter: 84 [mm] → Volume of the feature: 307,91*4 [mm^3] → Area of the feature: 255,03*4 [mm^2]

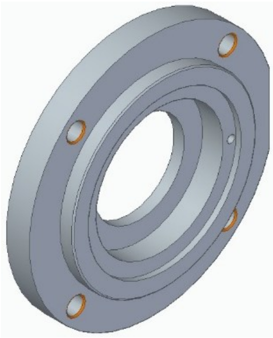
	→ Faces of the feature: → Circular_face_01.01*4 → Circular_face_01.02*4 → Cilindrical_face_01.01*4 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01*4 → Specific tolerance: NO → Coating: NO
	→ Material: Aisi 316 → Type of feature: **Feature_2 – CHAMFER CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [00;00;00] → For first chamfer [00;29,7;29,7] → Properties of the feature: → For chamfer: → Diameter: 6,6 [mm] → Angle: 45 [°] → Size: 0,5 [mm] → Number: 8 [ad.] → For circular pattern: → Diameter: 84 [mm] → Volume of the feature: 2,73*8 [mm^3] → Area of the feature: 15,77*8 [mm^2] → Faces of the feature: → Conical_face_02.01*8 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Conical_face_04.01*8 → Specific tolerance: NO → Coating: NO

Table 98 Features of 1° block (assembly 1 part 2 – casing updated design)

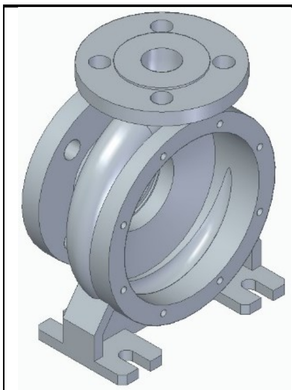
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 1185791,62 [mm^3] → Area: 271893,29 [mm^2] → Dimensions: 130,00*190,00*250,00 [mm]

Table 99 Features of 2° block (assembly 1 part 2 – casing updated design)

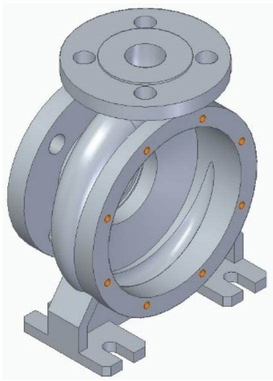
	→ Material: Grey cast iron → Type of feature: **Feature_2 – CHAMFER CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [34;00;00] → For first chamfer [34,00;32,15;77,61] → Properties of the feature: → For chamfer: → Diameter: M8 [mm] → Angle: 45 [°] → Size: 0,6 [mm] → Number: 8 [ad.] → For circular pattern: → Diameter: 168 [mm] → Volume of the feature: 4,07*8 [mm^3] → Area of the feature: 19,73*8 [mm^2] → Faces of the feature: → Conical_face_02.01*8 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Conical_face_02.01*8 → Specific tolerance: NO → Coating: NO

Table 100 Features of 1° block (assembly 1 part 20 – house bearing updated design)

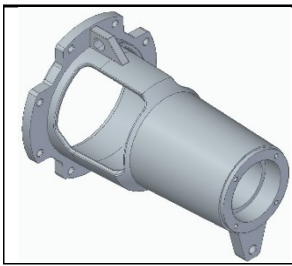
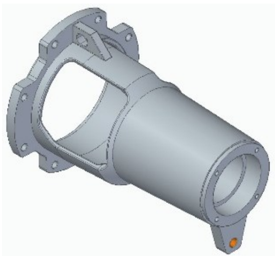
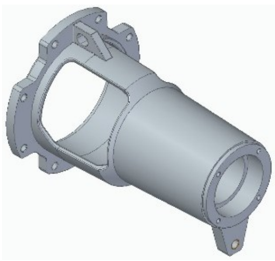
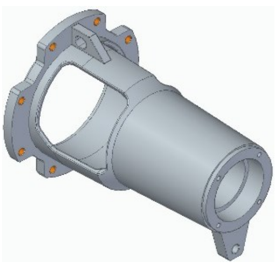
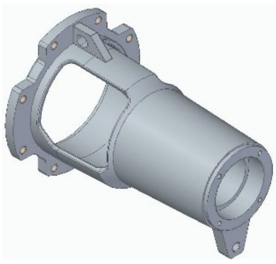
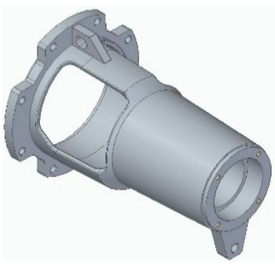
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 1012759,52 [mm^3] → Area: 180930,86 [mm^2] → Dimensions: 255,00*185,00*185,00 [mm]

Table 101 Features of 2° block (assembly 1 part 20 – house bearing updated design)

	→ Material: Grey cast iron → Type of feature: **Feature_1 - HOLE BASE_MOD** → Coordinates of the feature in reference with origin: [235;00;-77] → Properties of the feature: → Diameter: 10,5 [mm] → Length: 15 [mm] → Volume of the feature: 1298,85 [mm^3] → Area of the feature: 667,98 [mm^2] → Faces of the feature: → Circular_face_01.01 → Circular_face_01.02 → Cilindrical_face_01.01 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_4 – CHAMFER HOLE BASE** → Coordinates of the feature in reference with origin: [235;00;-77] → Properties of the feature: → Diameter: 10,5 [mm] → Angle: 45 [°] → Size: 0,6 [mm] → Number: 2 [ad.] → Volume of the feature: 6,16 [mm^3] → Area of the feature: 29,59 [mm^2] → Faces of the feature: → Conical_face_04.01 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Conical_face_04.01 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_2 - HOLE CIRCULAR PATTERN_MOD** → Coordinates of the feature in reference with origin: → For circular pattern [05;00;00] → For first hole [05;32,15;77,61] → Properties of the feature: → For holes: → Diameter: 8,4 [mm] → Length: 11,5 [mm] → Number: 8 [ad.] → For circular pattern: → Diameter: 168 [mm] → Volume of the feature: 637,30*8 [mm^3] → Area of the feature: 414,31*8 [mm^2] → Faces of the feature:

	→ Circular_face_02.01*8 → Circular_face_02.02*8 → Cilindrical_face_02.01*8 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_02.01*8 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_5 – CHAMFER HOLE CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [05;00;00] → For first chamfer [05;32,15;77,61] → Properties of the feature: → For chamfer: → Diameter: 8,4 [mm] → Angle: 45 [°] → Size: 0,6 [mm] → Number: 16 [ad.] → For circular pattern: → Diameter: 168 [mm] → Volume of the feature: 637,30*8 [mm^3] → Area of the feature: 414,31*8 [mm^2] → Faces of the feature: → Conical_face_05.01*16 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Conical_face_05.01*16 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_6 – CHAMFER THREADED HOLE CIRCULAR PATTERN** → Coordinates of the feature in reference with origin: → For circular pattern [255;00;00] and [119;00;00] → For first chamfer [255;29,7;29,7] and [119;29,7;29,7] → Properties of the feature: → For chamfer: → Diameter: M6 [mm] → Angle: 45 [°] → Size: 0,6 [mm] → Number: 8 [ad.] → For circular pattern: → Diameter: 84 [mm] → Volume of the feature: 2,09*8 [mm^3] → Area of the feature: 12,22*8 [mm^2] → Faces of the feature: → Conical_face_06.01*4 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Conical_face_06.01*8

	→ Specific tolerance: NO → Coating: NO

Table 102 Features of 1° block (assembly 1 part 5 – coupling updated design)

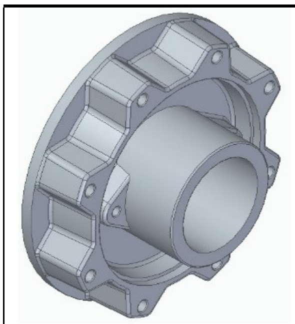
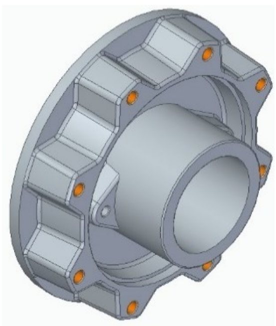
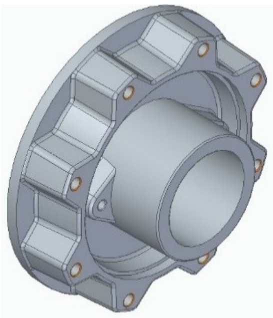
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 684497,45 [mm^3] → Area: 137257,20 [mm^2] → Dimensions: 85,00*190,00*190,00 [mm]

Table 103 Features of 2° block (assembly 1 part 5 – coupling updated design)

	→ Material: Grey cast iron
	→ Type of feature: **Feature_1 - HOLE CIRCULAR PATTERN_MOD**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern [08;00;00]
	  → For first hole [08;32,15;77,61]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 8,4 [mm]
	    → Length: 42 [mm]
	    → Number: 8 [ad.]
	  → For circular pattern:
	    → Diameter: 168 [mm]
	→ Volume of the feature: 2327,54*8 [mm^3]
	→ Area of the feature: 1219,19*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*8
	  → Circular_face_01.02*8
	  → Cilindrical_face_01.01*8
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Cilindrical_face_01.01*8
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: Grey cast iron
	→ Type of feature: **Feature_3 – CHAMFER HOLE CIRCULAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For circular pattern [08;00;00]
	  → For first chamfer [08;32,15;77,61]
	→ Properties of the feature:
	  → For chamfer:
	    → Diameter: 8,4 [mm]
	    → Angle: 45 [°]
	    → Size: 0,6 [mm]
	    → Number: 16 [ad.]
	  → For circular pattern:
	    → Diameter: 168 [mm]
	→ Volume of the feature: 4,98*16 [mm^3]
	→ Area of the feature: 23,99*16 [mm^2]
	→ Faces of the feature:
	  → Conical_face_03.01*16
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Conical_face_03.01*16
	  → Specific tolerance: NO
	  → Coating: NO

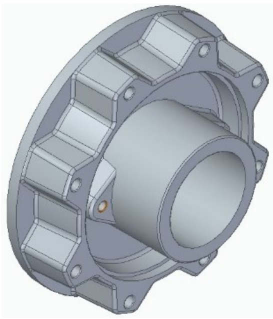
	→ Material: Grey cast iron
	→ Type of feature: **Feature_4 – CHAMFER THREADED HOLE LINEAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For linear pattern [45;50;00]
	  → For first chamfer [45;50;00]
	→ Properties of the feature:
	  → For chamfer:
	    → Type: M8 [mm]
	    → Angle: 45 [°]
	    → Size: 0,6 [mm]
	    → Number: 2 [ad.]
	  → For linear pattern:
	    → Distance between hole centre: 100 [mm]
	→ Volume of the feature: 4,07*8 [mm^3]
	→ Area of the feature: 19,73*8 [mm^2]
	→ Faces of the feature:
	  → Conical_face_04.01*2
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Conical_face_02.01*2
	  → Specific tolerance: NO
	  → Coating: NO

Table 104 Features of 1° block (assembly 1 part 9 – packing gland updated design)

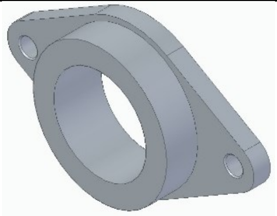
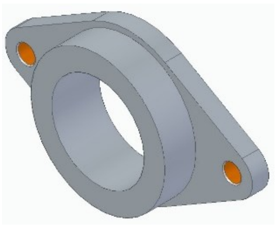
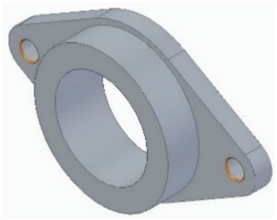
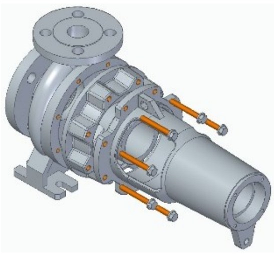
	→ Material: Grey cast iron → Shape: Axysimmetric → Volume: 55387,86 [mm^3] → Area: 16389,95 [mm^2] → Dimensions: 23,00*120,00*70,00 [mm]

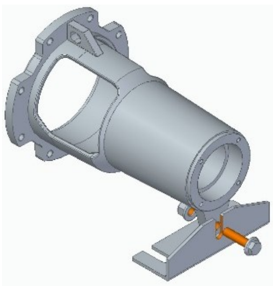
Table 105 Features of 2° block (assembly 1 part 9 – packing gland updated design)

	→ Material: Grey cast iron → Type of feature: **Feature_1 - HOLE LINEAR PATTERN** → Coordinates of the feature in reference with origin: → For linear pattern [00;50;00] → For first hole [00;50;00] → Properties of the feature: → For holes: → Diameter: 8,5 [mm] → Length: 8 [mm] → Number: 2 [ad.] → For linear pattern: → Distance between hole centre: 100 [mm] → Volume of the feature: 453,96*2 [mm^3] → Area of the feature: 327,12*2 [mm^2] → Faces of the feature: → Circular_face_01.01*2 → Circular_face_01.02*2 → Cilindrical_face_01.01*2 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01*2 → Specific tolerance: NO → Coating: NO
	→ Material: Grey cast iron → Type of feature: **Feature_2 – CHAMFER HOLE LINEAR PATTERN** → Coordinates of the feature in reference with origin: → For linear pattern [00;50;00] → For first hole [00;50;00] → Properties of the feature: → For holes: → Diameter: 8,5 [mm] → Angle: 45 [°] → Size: 0,6 [mm] → Number: 2 [ad.] → For linear pattern: → Distance between hole centre: 100 [mm] → Volume of the feature: 3,47*2 [mm^3]

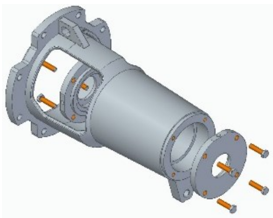
	→ Area of the feature: 19,99*2 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*2
	  → Circular_face_01.02*2
	  → Cilindrical_face_01.01*2
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Cilindrical_face_01.01*2
	  → Specific tolerance: NO
	  → Coating: NO

Table 106 Features of 4° block (assembly 1 – centrifugal pump updated design)

	→ Material vs. material: Aisi 316 vs. Grey cast iron
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. Feature_2 - HOLE CIRCULAR PATTERN_MOD (House bearing)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [05,00;32,15;77,61]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. diameter of Feature_2 - HOLE CIRCULAR PATTERN (House bearing): M8 vs. 8 [mm]
	→ Volume of the feature vs. volume of the feature/s: 3267,26 [mm^3] vs. 637,30 [mm^3]
	→ Area of the feature vs. area of the feature/s: 1734,16 [mm^2] vs. 414,31 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_02.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_02.01
	  → Specific tolerance: NO
	  → Coating: NO
	
	→ Material vs. material: Aisi 316 vs. Grey cast iron
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. Feature_1 - HOLE CIRCULAR PATTERN (Coupling)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [08,00;32,15;77,61]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. diameter of Feature_1 - HOLE CIRCULAR PATTERN (Coupling): M8 vs. 8 [mm]
	→ Volume of the feature vs. volume of the feature/s: 3267,26 [mm^3] vs. 2327,54 [mm^3]

	→ Area of the feature vs. area of the feature/s: 1734,16 [mm^2] vs. 1219,19 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Grey cast iron → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. Feature_1 - THREADED CIRCULAR PATTERN (Casing)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [34,00;32,15;77,61] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 65) vs. type of thread of Feature_1 – THREADED HOLE CIRCULAR PATTERN (Casing): M8 vs. M8 [mm] → Volume of the feature vs. volume of the feature/s: 3267,26 [mm^3] vs. 508,43 [mm^3] → Area of the feature vs. area of the feature/s: 1734,16 [mm^2] vs. 377,77 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO
	→ Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. Feature_1 – SLOT (Support)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;-74,50;48,00] [00,00;-74,50;25,00] [00,00;-85,50;48,00] [00,00;-85,50;25,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. width of Feature_1 – SLOT (Support): M10 vs. 11 [mm] → Volume of the feature vs. volume of the feature/s: 3141,59 [mm^3] vs. 1107,03 [mm^3] → Area of the feature vs. area of the feature/s: 1413,72 [mm^2] vs. 353,18 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Rectangular_face_01.01 and Rectangular_face_01.02 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:

	→ Cylindrical_face_01_01 vs. Rectangular_face_01.01 and Rectangular_face_01.02 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Grey cast iron → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. Feature_1 - HOLE BASE (House bearing)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [235,00;00;00;77,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. diameter of Feature_1 - HOLE BASE (House bearing): M10 vs. 10,5 [mm] → Volume of the feature vs. volume of the feature/s: 3141,59 [mm^3] vs. 1298,85 [mm^3] → Area of the feature vs. area of the feature/s: 1413,72 [mm^2] vs. 667,98 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: Aisi 316 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. Feature_1 – THREADED HOLE (Nut DIN ISO 4161 M10)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M10 x 40) vs. type of thread of Feature_1 – THREADED HOLE (Nut DIN ISO 4161 M10): M10 vs. M10 → Volume of the feature vs. volume of the feature/s: 3141,59 [mm^3] vs. 1060,29 [mm^3] → Area of the feature vs. area of the feature/s: 1413,72 [mm^2] vs. 581,19 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO

<table>
<tr>
<td></td>
<td>
→ Material vs. material: Aisi 316 vs. Aisi 316
→ Type of feature vs. type/s of feature/s: Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. Feature_1 - HOLE CIRCULAR PATTERN_MOD (Bearing cover)
→ Coordinates of the feature vs. coordinates of the feature/s:
  → [00,00;00,00;00,00] vs. [00,00;29,70;29,70]
→ Properties of the feature vs. properties of the feature:
  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. diameter of Feature_1 - HOLE CIRCULAR PATTERN_MOD (Bearing cover): M6 vs. 6,6 [mm]
→ Volume of the feature vs. volume of the feature/s: 706,86 [mm^3] vs. 307,91 [mm^3]
→ Area of the feature vs. area of the feature/s: 527,79 [mm^2] vs. 255,03 [mm^2]
→ Faces of the feature vs. faces of the feature/s:
  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
→ PMI vs. PMI:
  → Specific roughness:
    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
  → Specific tolerance: NO
  → Coating: NO

→ Material vs. material: Aisi 316 vs. Grey cast iron
→ Type of feature vs. type/s of feature/s: Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. Feature_3 – THREADED HOLE CIRCULAR PATTERN (Bearing cover)
→ Coordinates of the feature vs. coordinates of the feature/s:
  → [00,00;00,00;00,00] vs. [255,00;29,70;29,70]
→ Properties of the feature vs. properties of the feature:
  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4017 M6 x 25) vs. type of thread of Feature_3 – THREADED HOLE CIRCULAR PATTERN (Bearing cover): M6 vs. M6
→ Volume of the feature vs. volume of the feature/s: 706,86 [mm^3] vs. 471,24 [mm^3]
→ Area of the feature vs. area of the feature/s: 527,79 [mm^2] vs. 409,72 [mm^2]
→ Faces of the feature vs. faces of the feature/s:
  → Cylindrical_face_01.01 vs. Cylindrical_face_03.01
→ PMI vs. PMI:
  → Specific roughness:
    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
      → Cylindrical_face_01_01 vs. Cylindrical_face_03.01
  → Specific tolerance: NO
  → Coating: NO
</td>
</tr>
</table>

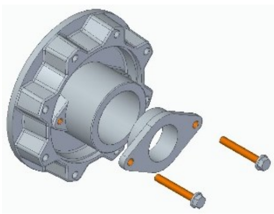
	→ Material vs. material: Aisi 316 vs. Grey cast iron
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 60) vs. Feature_1 - HOLE LINEAR PATTERN_MOD (Packing gland)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [00,00;50,00;00,00]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 60) vs. diameter of Feature_1 - HOLE LINEAR PATTERN_MOD (Packing gland): M8 vs. 8,5 [mm]
	→ Volume of the feature vs. volume of the feature/s: 3015,93 [mm^3] vs. 453,96 [mm^3]
	→ Area of the feature vs. area of the feature/s: 1608,49 [mm^2] vs. 327,12 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	  → Specific tolerance: NO
	  → Coating: NO
	
	→ Material vs. material: Aisi 316 vs. Grey cast iron
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 60) vs. Feature_2 - THREADED HOLE LINEAR PATTERN (Coupling)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [45,00;50,00;00,00]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M8 x 60) vs. type of thread of Feature_2 - THREADED HOLE LINEAR PATTERN (Coupling): M8 vs. M8
	→ Volume of the feature vs. volume of the feature/s: 3015,93 [mm^3] vs. 653,70 [mm^3]
	→ Area of the feature vs. area of the feature/s: 1608,49 [mm^2] vs. 445,06 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_02.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_02.01
	  → Specific tolerance: NO
	  → Coating: NO

Table 107 Features of 1° block (assembly 2 part 13 – column original design)

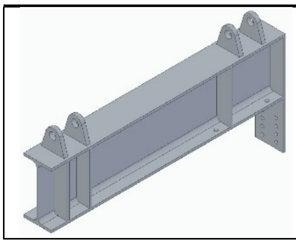
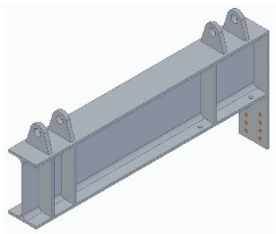
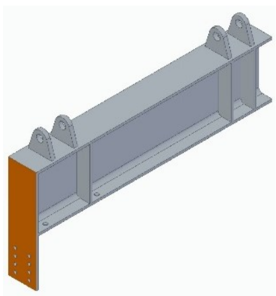
	→ Material: S 275JR → Shape: Prismatic → Volume: 5488375,96 [mm^3] → Area: 1242147,61 [mm^2] → Dimensions: 120,00*1010,00*530,00 [mm]

Table 108 Features of 2° block (assembly 2 part 13 – column original design)

	→ Material: S 275JR → Type of feature: **Feature_1 - HOLE RECTANGULAR PATTERN** → Coordinates of the feature in reference with origin: [30,00;1010,00;-325,00]; [30,00;1010,00;-355,00]; 30,00;1010,00;-385,00]; [30,00;1010,00;-415,00]; [-30,00;1010,00;-325,00]; [-30,00;1010,00;-355,00]; -30,00;1010,00;-385,00]; [-30,00;1010,00;-415,00] → Properties of the feature: → For holes: → Diameter: 13 [mm] → Length: 10 [mm] → Number: 8 [ad.] → Volume of the feature: 1327,32*8 [mm^3] → Area of the feature: 673,87*8 [mm^2] → Faces of the feature: → Circular_face_01.01*8 → Circular_face_01.02*8 → Cilindrical_face_01.01*8 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01*8 → Specific tolerance: NO → Coating: NO
	→ Material: S 275JR → Type of feature: **Feature_2 – RECTANGULAR PAD** → Coordinates of the feature in reference with origin: [60,00;1010,00;00,00]; [-60,00;1010,00;00,00]; [60,00;1010,00;-440,00]; [-60,00;1010,00;-440,00] → Properties of the feature: → Height: 10 [mm] → Volume of the feature: 528000,00 [mm^3] → Area of the feature: 116800,00 [mm^2] → Faces of the feature: → Rectangular_face_02.01 → Rectangular_face_02.02 → Rectangular_face_02.03 → Rectangular_face_02.04 → Rectangular_face_02.05

	→ Rectangular_face_02.06 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Rectangular_face_02.01 → Rectangular_face_02.02 → Specific tolerance: NO → Coating: NO

Table 109 Features of 1° block (assembly 2 part 6 – arm original design)

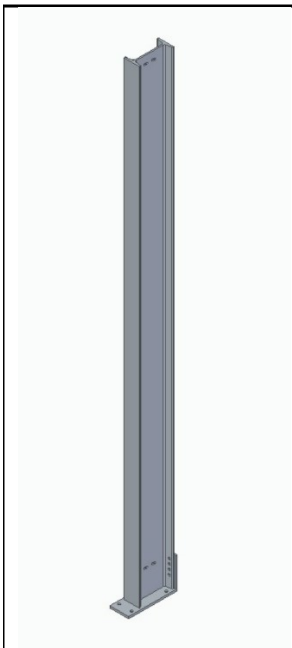
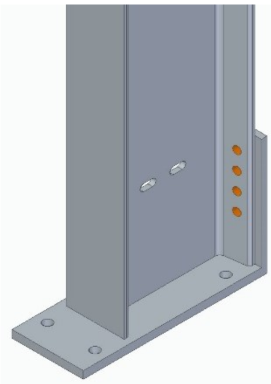
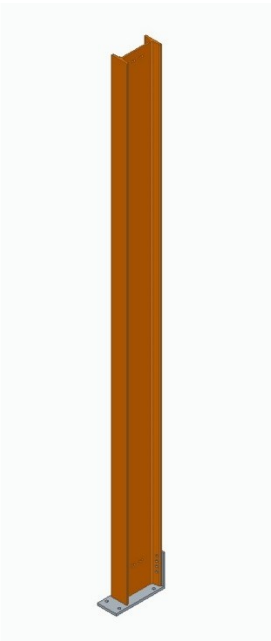
	→ Material: S 275JR → Shape: Prismatic → Volume: 12500959,16 [mm^3] → Area: 2432092,41 [mm^2] → Dimensions: 120,00*310,00*3012,70 [mm]

Table 110 Features of 2° block (assembly 2 part 6 – arm original design)

	→ Material: S 275JR
	→ Type of feature: **Feature_1 – HOLE RECTANGULAR PATTERN**
	→ Coordinates of the feature in reference with origin:
	  → For rectangular pattern [-30,00;230,00;72,30]; [-30,00;230,00;102,30]; [-30,00;230,00;132,30]; [-30,00;230,00;162,30]; [30,00;230,00;72,30]; [30,00;230,00;102,30]; [30,00;230,00;132,30]; [30,00;230,00;162,30]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 13 [mm]
	    → Length: 22,33 [mm]
	    → Number: 8 [ad.]
	→ Volume of the feature: 2963,91*8 [mm^3]
	→ Area of the feature: 1177,44*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*8
	  → Circular_face_01.02*8
	  → Cilindrical_face_01.01*8
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [µm] on:
	      → Cilindrical_face_01.01*8
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material: S 275JR
	→ Type of feature: **Feature_2 – T-EXTRUSION**
	  → Coordinates of the feature in reference with origin: [49,00;220,00;3000,00]; [49,00;215,00;3000,00]; [44,78;210,65;3000,00]; [11,03;205,92;3000,00]; [4,05;197,90;3000,00]; [4,05;22,10;3000,00]; [11,03;14,08;3000,00]; [44,78;9,35;3000,00]; [49,00;4,50;3000,00]; [49,00;00,00;3000,00]; [-49,00;220,00;3000,00]; [-49,00;215,00;3000,00]; [-44,78;210,65;3000,00]; [-11,03;205,92;3000,00]; [-4,05;197,90;3000,00]; [-4,05;22,10;3000,00]; [-11,03;14,08;3000,00]; [-44,78;9,35;3000,00]; [-49,00;4,50;3000,00]; [-49,00;00,00;3000,00]
	→ Properties of the feature:
	  → Lenght: 3000 [mm]
	→ Volume of the feature: 11846220,00 [mm^3]
	→ Area of the feature: 2337007,48 [mm^2]
	→ Faces of the feature:
	  → T_face_02.01
	  → T_face_02.02
	  → Rectangular_face_02.01
	  → Rectangular_face_02.02
	  → Rectangular_face_02.03
	  → Rectangular_face_02.04
	  → Rectangular_face_02.05
	  → Rectangular_face_02.06
	  → Rectangular_face_02.07
	  → Rectangular_face_02.08

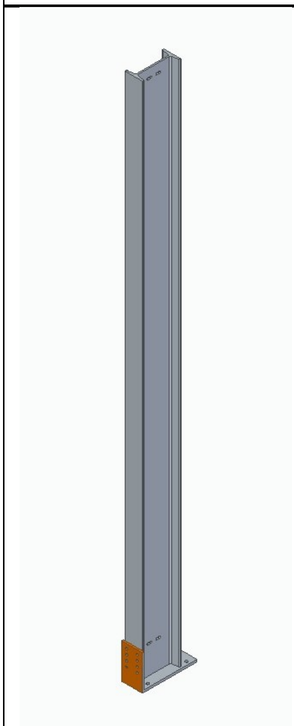
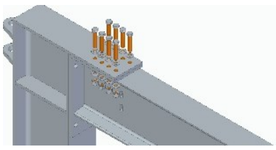
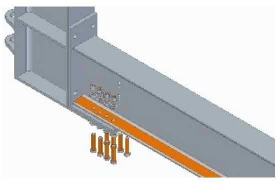
	→ Rectangular_face_02.09 → Rectangular_face_02.10 → Rectangular_face_02.11 → Rectangular_face_02.12 → Cilindrical_face_02.01 → Cilindrical_face_02.02 → Cilindrical_face_02.03 → Cilindrical_face_02.04 → Cilindrical_face_02.05 → Cilindrical_face_02.06 → Cilindrical_face_02.07 → Cilindrical_face_02.08 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Rectangular_face_02.05 → Rectangular_face_02.06 → Specific tolerance: NO → Coating: NO
	→ Material: S 275JR → Type of feature: **Feature_3 – RECTANGULAR PAD** → Coordinates of the feature in reference with origin: [-60,00;230,00;-12,70]; [60,00;230,00;-12,70]; [60,00;230,00;187,30]; [-60,00;230,00;187,30] → Properties of the feature: → Height: 10 [mm] → Volume of the feature: 240000,00 [mm^3] → Area of the feature: 54400,00 [mm^2] → Faces of the feature: → Rectangular_face_03.01 → Rectangular_face_03.02 → Rectangular_face_03.03 → Rectangular_face_03.04 → Rectangular_face_03.05 → Rectangular_face_03.06 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Rectangular_face_03.01 → Specific tolerance: NO → Coating: NO

Table 111 Features of 4° block (assembly 2 – jib crane original design)

	→ Material vs. material: 39NiCrMo3 vs. Aisi 316
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_1 – HOLE (Plain washer ISO 7089 M12)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [00,00;00,00;00,00]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. diameter of Feature_1 –HOLE (Plain washer ISO 7089 M12): M12 vs. 13 [mm]
	→ Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 331,83 [mm^3]
	→ Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 367,57[mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material vs. material: 39NiCrMo3 vs. S 275JR
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_1 - HOLE RECTANGULAR PATTERN (Column)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	  → [00,00;00,00;00,00] vs. [-30,00;230,00;72,30]
	→ Properties of the feature vs. properties of the feature:
	  → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. diameter of Feature_1 - HOLE RECTANGULAR PATTERN (Column): M12 vs. 13 [mm]
	→ Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 1327,32 [mm^3]
	→ Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 673,87 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	  → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] vs. Ra 1,6 [μm] on:
	      → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	  → Specific tolerance: NO
	  → Coating: NO

	→ Material vs. material: 39NiCrMo3 vs. S 275JR → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_1 - HOLE RECTANGULAR PATTERN (Arm)** → Coordinates of the feature vs. coordinates of the feature/s:

	→ [00,00;00,00;00,00] vs. [-30,00;230,00;72,30] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. diameter of Feature_1 - HOLE RECTANGULAR PATTERN (Arm): M12 vs. 13 [mm] → Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 2963,91 [mm^3] → Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 1177,44 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: 39NiCrMo3 vs. 39NiCrMo3 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_1 – THREADED HOLE (Hex nut ISO 7417 M12)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. type of thread of Feature_1 – THREADED HOLE (Hex nut ISO 7417 M12): M12 vs. M12 → Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 1357,17 [mm^3] → Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 678,58 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO
	→ Material vs. material: 39NiCrMo3 vs. S 275JR → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_2 – T-EXTRUSION (Arm)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. ([49,00;220,00;3000,00]; [49,00;215,00;3000,00]; [44,78;210,65;3000,00]; [11,03;205,92;3000,00]; [4,05;197,90;3000,00]; [4,05;22,10;3000,00]; [11,03;14,08;3000,00]; [44,78;9,35;3000,00]; [49,00;4,50;3000,00]; [49,00;00,00;3000,00]; [-49,00;220,00;3000,00]; [-49,00;215,00;3000,00]; [-44,78;210,65;3000,00]; [-11,03;205,92;3000,00]; [-4,05;197,90;3000,00]; [-

	4,05;22,10;3000,00]; [-11,03;14,08;3000,00]; [-44,78;9,35;3000,00]; [-49,00;4,50;3000,00]; [-49,00;00,00;3000,00]) → Properties of the feature vs. properties of the feature: → Angle between axis of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Rectangular_face_02.05 and Rectangular_face_02.06 of Feature_2 – T-EXTRUSION (Arm): 97,97 [°] → Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 11846220,00 [mm^3] → Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 2337007,48 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Rectangular_face_02.05 → Cylindrical_face_01.01 vs. Rectangular_face_02.06 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [μm] vs. Ra 1,6 [μm] on: → Cylindrical_face_01_01 vs. Rectangular_face_02.05 → Cylindrical_face_01_01 vs. Rectangular_face_02.05 → Specific tolerance: NO → Coating: NO

Table 112 Features of 1° block (assembly 2 part 13 – column updated design)

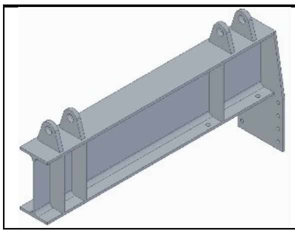
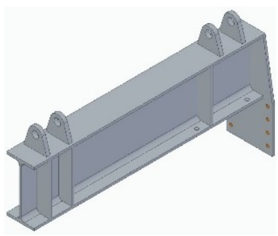
	→ Material: S 275JR → Shape: Prismatic → Volume: 5744375,96 [mm^3] → Area: 1294213,82 [mm^2] → Dimensions: 120,00*1010,00*530,00 [mm]

Table 113 Features of 2° block (assembly 2 part 13 – column updated design)

	→ Material: S 275JR → Type of feature: **Feature_1 - HOLE RECTANGULAR PATTERN_MOD** → Coordinates of the feature in reference with origin: [80,00;1010,00;-260,00]; [80,00;1010,00;-310,00]; 80,00;1010,00;-360,00]; [80,00;1010,00;-410,00]; [-80,00;1010,00;-260,00]; [-80,00;1010,00;-310,00]; -80,00;1010,00;-360,00]; [-80,00;1010,00;-410,00] → Properties of the feature: → For holes: → Diameter: 13 [mm] → Length: 10 [mm] → Number: 8 [ad.]

	→ Volume of the feature: 1327,32*8 [mm^3]
	→ Area of the feature: 673,87*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*8
	  → Circular_face_01.02*8
	  → Cilindrical_face_01.01*8
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Cilindrical_face_01.01*8
	  → Specific tolerance: NO
	  → Coating: NO

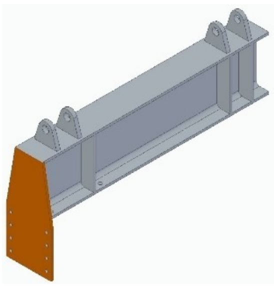
	→ Material: S 275JR
	→ Type of feature: **Feature_2 – PAD**
	  → Coordinates of the feature in reference with origin: [60,00;1010,00;00,00]; [100,00;1010,00;-240,00]; [100,00;1010,00;-440,00]; [-60,00;1010,00;00,00]; [-100,00;1010,00;-240,00]; [-100,00;1010,00;-440,00]
	→ Properties of the feature:
	  → Height: 10 [mm]
	→ Volume of the feature: 784000,00 [mm^3]
	→ Area of the feature: 168.866,20 [mm^2]
	→ Faces of the feature:
	  → Trapezoidal_face_02.01
	  → Trapezoidal_face_02.02
	  → Rectangular_face_02.01
	  → Rectangular_face_02.02
	  → Rectangular_face_02.03
	  → Rectangular_face_02.04
	  → Rectangular_face_02.05
	  → Rectangular_face_02.06
	→ PMI:
	  → Specific roughness:
	    → Ra 1,6 [μm] on:
	      → Trapezoidal_face_02.01
	      → Trapezoidal_face_02.02
	  → Specific tolerance: NO
	  → Coating: NO

Table 114 Features of 1° block (assembly 2 part 6 – arm updated design)

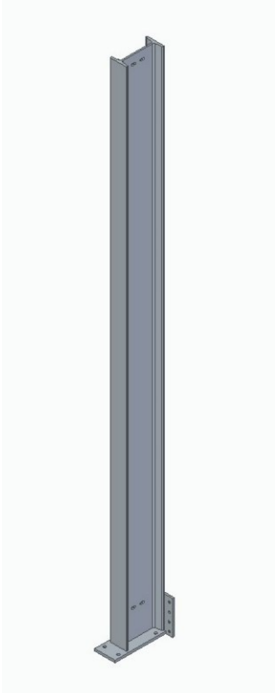
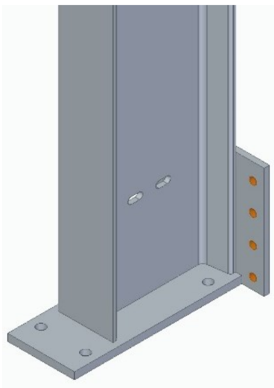
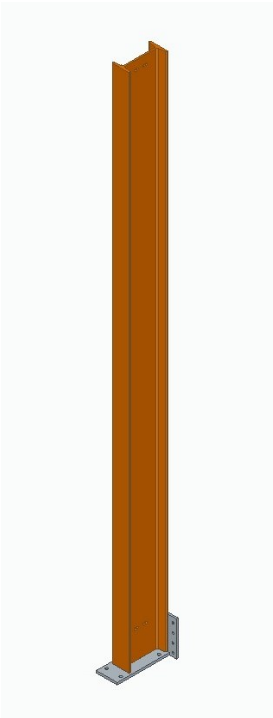
	→ Material: S 275JR → Shape: Prismatic → Volume: 12673087,58 [mm^3] → Area: 2461970,95 [mm^2] → Dimensions: 200,00*310,00*3012,70 [mm]

Table 115 Features of 2° block (assembly 2 part 6 – arm updated design)

	→ Material: S 275JR
	→ Type of feature: **Feature_1 – HOLE RECTANGULAR PATTERN_MOD**
	→ Coordinates of the feature in reference with origin:
	  → For rectangular pattern [-80,00;230,00;7,30]; [-80,00;230,00;57,30]; [-80,00;230,00;107,30]; [-80,00;230,00;157,30]; [80,00;230,00;7,30]; [80,00;230,00;57,30]; [80,00;230,00;107,30]; [80,00;230,00;157,30]
	→ Properties of the feature:
	  → For holes:
	    → Diameter: 13 [mm]
	    → Length: 10 [mm]
	    → Number: 8 [ad.]
	→ Volume of the feature: 1327,32*8 [mm^3]
	→ Area of the feature: 673,87*8 [mm^2]
	→ Faces of the feature:
	  → Circular_face_01.01*8
	  → Circular_face_01.02*8

	→ Cilindrical_face_01.01*8 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Cilindrical_face_01.01*8 → Specific tolerance: NO → Coating: NO
	→ Material: S 275JR → Type of feature: **Feature_2 – T-EXTRUSION** → Coordinates of the feature in reference with origin: [49,00;220,00;3000,00]; [49,00;215,00;3000,00]; [44,78;210,65;3000,00]; [11,03;205,92;3000,00]; [4,05;197,90;3000,00]; [4,05;22,10;3000,00]; [11,03;14,08;3000,00]; [44,78;9,35;3000,00]; [49,00;4,50;3000,00]; [49,00;00,00;3000,00]; [-49,00;220,00;3000,00]; [-49,00;215,00;3000,00]; [-44,78;210,65;3000,00]; [-11,03;205,92;3000,00]; [-4,05;197,90;3000,00]; [-4,05;22,10;3000,00]; [-11,03;14,08;3000,00]; [-44,78;9,35;3000,00]; [-49,00;4,50;3000,00]; [-49,00;00,00;3000,00] → Properties of the feature: → Lenght: 3000 [mm] → Volume of the feature: 11846220,00 [mm^3] → Area of the feature: 2337007,48 [mm^2] → Faces of the feature: → T_face_02.01 → T_face_02.02 → Rectangular_face_02.01 → Rectangular_face_02.02 → Rectangular_face_02.03 → Rectangular_face_02.04 → Rectangular_face_02.05 → Rectangular_face_02.06 → Rectangular_face_02.07 → Rectangular_face_02.08 → Rectangular_face_02.09 → Rectangular_face_02.10 → Rectangular_face_02.11 → Rectangular_face_02.12 → Cilindrical_face_02.01 → Cilindrical_face_02.02 → Cilindrical_face_02.03 → Cilindrical_face_02.04 → Cilindrical_face_02.05 → Cilindrical_face_02.06 → Cilindrical_face_02.07 → Cilindrical_face_02.08 → PMI: → Specific roughness: → Ra 1,6 [µm] on: → Rectangular_face_02.05 → Rectangular_face_02.06 → Specific tolerance: NO → Coating: NO

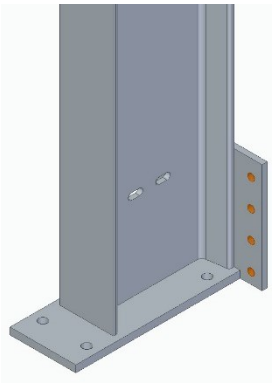
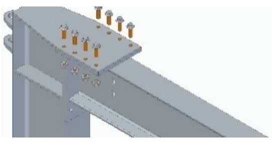
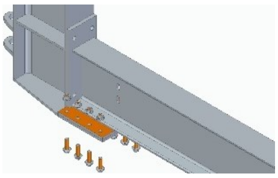
	→ Material: S 275JR → Type of feature: **Feature_3 – RECTANGULAR PAD** → Coordinates of the feature in reference with origin: [-100,00;230,00;-12,70]; [100,00;230,00;-12,70]; [100,00;230,00;187,30]; [-100,00;230,00;187,30] → Properties of the feature: → Height: 10 [mm] → Volume of the feature: 400000,00 [mm^3] → Area of the feature: 88000,00 [mm^2] → Faces of the feature: → Rectangular_face_03.01 → Rectangular_face_03.02 → Rectangular_face_03.03 → Rectangular_face_03.04 → Rectangular_face_03.05 → Rectangular_face_03.06 → PMI: → Specific roughness: → Ra 1,6 [μm] on: → Rectangular_face_03.01 → Rectangular_face_03.02 → Specific tolerance: NO → Coating: NO

Table 116 Features of 4° block (assembly 2 – jib crane updated design)

	→ Material vs. material: 39NiCrMo3 vs. Aisi 316 → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. Feature_1 – HOLE (Plain washer ISO 7089 M12)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. [00,00;00,00;00,00] → Properties of the feature vs. properties of the feature: → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw ISO 4018 M12 x 60) vs. diameter of Feature_1 –HOLE (Plain washer ISO 7089 M12): M12 vs. 13 [mm] → Volume of the feature vs. volume of the feature/s: 6785,84 [mm^3] vs. 331,83 [mm^3] → Area of the feature vs. area of the feature/s: 2488,14 [mm^2] vs. 367,57[mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [μm] vs. Ra 1,6 [μm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_01.01 → Specific tolerance: NO → Coating: NO → Material vs. material: 39NiCrMo3 vs. S 275JR

	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. Feature_1 - HOLE RECTANGULAR PATTERN_MOD (Column)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	    → [00,00;00,00;00,00] vs. [80,00;1010,00;-260,00]
	→ Properties of the feature vs. properties of the feature:
	    → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. diameter of Feature_1 - HOLE RECTANGULAR PATTERN_MOD (Column): M12 vs. 13 [mm]
	→ Volume of the feature vs. volume of the feature/s: 3958,41 [mm^3] vs. 1327,32 [mm^3]
	→ Area of the feature vs. area of the feature/s: 1545,66 [mm^2] vs. 673,87 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	    → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	    → Specific roughness:
	        → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
	            → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	    → Specific tolerance: NO
	    → Coating: NO
	
	→ Material vs. material: 39NiCrMo3 vs. S 275JR
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. Feature_1 - HOLE RECTANGULAR PATTERN_MOD (Arm)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	    → [00,00;00,00;00,00] vs. [-80,00;230,00;7,30]
	→ Properties of the feature vs. properties of the feature:
	    → Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. diameter of Feature_1 - HOLE RECTANGULAR PATTERN_MOD (Arm): M12 vs. 13 [mm]
	→ Volume of the feature vs. volume of the feature/s: 3958,41 [mm^3] vs. 1327,32 [mm^3]
	→ Area of the feature vs. area of the feature/s: 1545,66 [mm^2] vs. 673,87 [mm^2]
	→ Faces of the feature vs. faces of the feature/s:
	    → Cylindrical_face_01.01 vs. Cylindrical_face_01.01
	→ PMI vs. PMI:
	    → Specific roughness:
	        → Ra 1,6 [µm] vs. Ra 1,6 [µm] on:
	            → Cylindrical_face_01_01 vs. Cylindrical_face_01.01
	    → Specific tolerance: NO
	    → Coating: NO
	
	→ Material vs. material: 39NiCrMo3 vs. 39NiCrMo3
	→ Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. Feature_1 – THREADED HOLE (Hex nut DIN ISO 6923 M12)**
	→ Coordinates of the feature vs. coordinates of the feature/s:
	    → [00,00;00,00;00,00] vs. [00,00;00,00;00,00]
	→ Properties of the feature vs. properties of the feature:

	→ Type of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. type of thread of Feature_1 – THREADED HOLE (Hex nut DIN ISO 6923 M12): M12 vs. M12 → Volume of the feature vs. volume of the feature/s: 3958,41 [mm^3] vs. 1357,17 [mm^3] → Area of the feature vs. area of the feature/s: 1545,66 [mm^2] vs. 678,58 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Cylindrical_face_01.01 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Cylindrical_face_02.01 → Specific tolerance: NO → Coating: NO
	→ Material vs. material: 39NiCrMo3 vs. S 275JR → Type of feature vs. type/s of feature/s: **Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40) vs. Feature_3 – RECTANGULAR PAD (Arm)** → Coordinates of the feature vs. coordinates of the feature/s: → [00,00;00,00;00,00] vs. ([-100,00;230,00;-12,70]; [100,00;230,00;-12,70]; [100,00;230,00;187,30]; [-100,00;230,00;187,30]) → Properties of the feature vs. properties of the feature: → Angle between axis of thread of Feature_1 – THREADED CYLINDRICAL PAD (Hex head screw DIN 6921 M12 x 40)) vs. Rectangular_face_03.01 and Rectangular_face_03.02 of Feature_3 – RECTANGULAR PAD (Arm): 90,00 [°] → Volume of the feature vs. volume of the feature/s: 3958,41 [mm^3] vs. 400000,00 [mm^3] → Area of the feature vs. area of the feature/s: 1545,66 [mm^2] vs. 88000,00 [mm^2] → Faces of the feature vs. faces of the feature/s: → Cylindrical_face_01.01 vs. Rectangular_face_03.01 → Cylindrical_face_01.01 vs. Rectangular_face_03.02 → PMI vs. PMI: → Specific roughness: → Ra 1,6 [µm] vs. Ra 1,6 [µm] on: → Cylindrical_face_01_01 vs. Rectangular_face_03.01 → Cylindrical_face_01_01 vs. Rectangular_face_03.02 → Specific tolerance: NO → Coating: NO

Appendix C. Questionnaire for software and method evaluation

C.1. Software usability

Table 117 "Software usability" questionnaire

1	**Compatibility**
a	Are the steps to perform to execute an analysis clear?
b	Is easy to understand how to activate a specific tool function?
c	Are the tool icons easily associated with their specific functions?
d	Are the required informations easy to enter through the interface?
e	Is the tool aesthetically pleasing and satisfying to the user?
2	**Consistency & Standards**
a	Are the software functions able to produce all necessary DFA/DFM rules?
b	Are the DfM rules compliant with the personal and company knowledge?
c	Are the geometric KPIs (Dimensions, weight/volume, number of parts, raw material waste, machining direction, total weld length) calculated by the software reasonably correct?
d	Is the cost calculated by the software reasonably correct?
e	Is the cost breakdown details calculated by the software reasonably correct?
f	Is the default stock selected by the software correct enough?
g	Is the machining direction calculated by the software reasonably correct?
h	Is the 3D Model information displayed by the software correct?
i	Does the report generated by the analysis clearly summarize the main results with sufficient and adequate information?
3	**Error Prevention & Correction**
a	Are the error messages displayed when incompatible data is entered useful for the user and easy to understand? (example: assembly 3D model analysed whit single component strategies; material not compatible whit strategy used; etc...)
b	Is the user easily able to understand why errors messages appear?
c	Is easy to correct incomplete or incorrect input data through the tool interface?
d	Does the software allow the user to easily check input data to minimise errors?
4	**Explicitness**

a	Are the workflow analysis clear and easy to identify?
5	**Flexibility & Control**
a	Is the structure of the tool flexible, allowing the user to perform the analysis steps according to his/her needs?
b	Is the user able to perform the analysis which he/she considers best for his/her needs?
6	**Functionality**
a	Are all the respected/not respected DFA/DFM rules a useful result of the analysis?
b	Is the cost calculated by the software a useful result of the analysis?
c	Is the cost breakdown details calculated by the software a useful result of the analysis?
d	Is the default stock selected by the software a useful result of the analysis?
e	Are the DFA/DFM rules useful to evaluate design choices or to suggest improvements in the product you are analysing?
f	Are the calculated cost, the cost breakdown and the default selected stock useful to help evaluate design choices or suggest improvements to the product you are analysing?
7	**Language & Content**
a	Are the DFA/DFM rules easy to understand and shown in a comprehensive way?
b	Are the respected/not respected DFA/DFM rules easy to understand and shown in a comprehensive way?
c	Are the geometric KPI easy to understand and shown in a comprehensive way?
e	Is the cost calculated by the tool easy to understand and shown in a comprehensive way?
f	Is the cost breakdown easy to understand and shown in a comprehensive way?
g	Is the default stock selected by the tool easy to understand and shown in a comprehensive way?
h	Is the machining directions calculated by the tool easy to understand and shown in a comprehensive way?
i	Are the 3D model informations provided by the tool easy to understand and shown in a comprehensive way?
j	Is the language used throughout the tool easily understandable for the user?
8	**Navigation**
a	Does the tool structure allow to rapidly perform the required analysis?
b	Are the sections where input data is required quickly and easily identifiable within the interface?
c	Are the tool evaluation/calculation icons quickly and easily identifiable within the interface?

d	Are the main interface icons easy to find and accessible?
e	Does the navigation within the tool allow the user to easily and quickly access all functions?
9	**Privacy**
a	Is the user confident that any company data input into the tool will be protected?
10	**User Guidance & Support**
a	Does the software contain guidance material which supports and helps the user to understand how it works?
b	Is the user manual easy to understand for supporting the user during initial usage of the tool?
c	Is the user manual written in a simple and direct language?
11	**Visual Clarity Description**
a	Are the information displayed on the interface clear?
b	Are the information displayed on the interface well organised?

C.2. Impact on company traditional process

Table 118 "Impact on company traditional process" questionnaire

1	**Impact on the traditional design process**
a	Is the impact of "DfM/DfA and cost tool" use in terms of time dedicated to the analysis admissible and compatible with the traditional time of the design process?
b	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase in terms of time dedicated to the design process?
c	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase of the design process phases?
d	Is the impact of "DfM/DfA and cost tool" use in terms of competence to acquire, admissible and compatible with the actual company employee's competency or are necessary specific skills?
e	Is the modification of the traditional design process with "DfM/DfA and cost tool", admissible for your company and easy to realize?
f	Could "DfM/DfA and cost tool" help to speed up the learning of the design knowledge necessary for correct part design?
2	**Data integration between traditional design and "DfM/DfA and cost tool"**
a	Is the software able to retrieve necessary information from the company systems CAD?
b	Are the data retrieved automatically from the company CAD 3D systems, useful for your analysis and adequate to conduct and perform analysis?
3	**Training activities**
a	Are the training sessions organized for "DfM/DfA and cost tool", adequate and sufficient to be able to perform analysis?
b	Is the timing requested for the training sessions adequate in relation to the company traditional time dedicated to training activities?
c	Is the time needed to have a complete skill on "DfM/DfA and cost tool" functionalities (excluded the training activities time) not excessive according to the company standards in terms of training timing?
d	Are the training activities too specific to be followed by a wide range of company staff?
e	Are the language and the support materials used during the training activities adequate and easily to be understandable?
4	**Personnel to involve**

a	Are the personnel inside the company able to use “DfM/DfA and cost tool” and to interpret its results? (after appropriate training activities)

C.3. Questionnaire results (Software usability)

Table 119 "Software usability" questionnaire (Perini)

		Evaluation	Score	Weight	Recommended improvements (optional)
1	**Compatibility**		**8,4**	**2**	**-**
a	Are the steps to perform to execute an analysis clear?	Yes	9	-	-
b	Is easy to understand how to activate a specific tool function?	Yes	9	-	-
c	Are the tool icons easily associated with their specific functions?	Yes, but further improvements may be useful	6	-	Bigger icons
d	Are the required informations easy to enter through the interface?	Yes	9	-	-
e	Is the tool aesthetically pleasing and satisfying to the user?	Yes	9	-	-
2	**Consistency & Standards**		**8,3**	**3**	**-**
a	Are the software functions able to produce all necessary DFA/DFM rules?	Yes, but further improvements may be useful	6	-	According customer needs
b	Are the DfM rules compliant with the personal and company knowledge?	Yes	9	-	-
c	Are the geometric KPIs (Dimensions, weight/volume, number of parts, raw material waste, machining direction, total weld length) calculated by the software reasonably correct?	Yes	9	-	-
d	Is the cost calculated by the software reasonably correct?	Yes	9	-	-
e	Is the cost breakdown details calculated by the software reasonably correct?	Yes	9	-	-
f	Is the default stock selected by the software correct enough?	Yes	9	-	-
g	Is the machining direction calculated by the software reasonably correct?	Yes	9	-	-
h	Is the 3D Model information displayed by the software correct?	Yes	9	-	-
i	Does the report generated by the analysis clearly summarize the	Yes, but further	6	-	Would be useful an additional

	main results with sufficient and adequate information?	improvements may be useful			report easier to read
3	**Error Prevention & Correction**		**7,5**	**3**	**-**
a	Are the error messages displayed when incompatible data is entered useful for the user and easy to understand? (example: assembly 3D model analysed whit single component strategies; material not compatible whit strategy used; etc...)	Yes, but further improvements may be useful	6	-	They are not always easy to understand
b	Is the user easily able to understand why errors messages appear?	Yes, but further improvements may be useful	6	-	They are not always easy to understand
c	Is easy to correct incomplete or incorrect input data through the tool interface?	Yes	9	-	-
d	Does the software allow the user to easily check input data to minimise errors?	Yes	9	-	-
4	**Explicitness**		**9**	**2**	**-**
a	Are the workflow analysis clear and easy to identify?	Yes	9	-	-
5	**Flexibility & Control**		**9**	**2**	**-**
a	Is the structure of the tool flexible, allowing the user to perform the analysis steps according to his/her needs?	Yes	9	-	-
b	Is the user able to perform the analysis which he/she considers best for his/her needs?	Yes	9	-	-
6	**Functionality**		**9**	**3**	**-**
a	Are all the respected/not respected DFA/DFM rules a useful result of the analysis?	Yes	9	-	-
b	Is the cost calculated by the software a useful result of the analysis?	Yes	9	-	-
c	Is the cost breakdown details calculated by the software a useful result of the analysis?	Yes	9	-	-
d	Is the default stock selected by the software a useful result of the analysis?	Yes	9	-	-
e	Are the DFA/DFM rules useful to evaluate design choices or to suggest improvements in the product you are analysing?	Yes	9	-	-

f	Are the calculated cost, the cost breakdown and the default selected stock useful to help evaluate design choices or suggest improvements to the product you are analysing?	Yes	9	-	-
7	**Language & Content**		**8,3**	**1**	**-**
a	Are the DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes, but further improvements may be useful	6	-	Not all the information are easy to be found
b	Are the respected/not respected DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes	9	-	-
c	Are the geometric KPI easy to understand and shown in a comprehensive way?	Yes	9	-	-
e	Is the cost calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
f	Is the cost breakdown easy to understand and shown in a comprehensive way?	Yes	9	-	-
g	Is the default stock selected by the tool easy to understand and shown in a comprehensive way?	Yes, but further improvements may be useful	6	-	Could be improved the graphical interface
h	Is the machining directions calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
i	Are the 3D model informations provided by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
j	Is the language used throughout the tool easily understandable for the user?	Yes	9	-	-
8	**Navigation**		**7,2**	**2**	**-**
a	Does the tool structure allow to rapidly perform the required analysis?	Yes	9	-	-
b	Are the sections where input data is required quickly and easily identifiable within the interface?	Yes, but further improvements may be useful	6	-	-
c	Are the tool evaluation/calculation icons quickly and easily identifiable within the interface?	Yes, but further improvements may be useful	6	-	-
d	Are the main interface icons easy to find and accessible?	Yes	9	-	-

e	Does the navigation within the tool allow the user to easily and quickly access all functions?	Yes, but further improvements may be useful	6	-	-
9	**Privacy**		**9**	**3**	**-**
a	Is the user confident that any company data input into the tool will be protected?	Yes	9	-	-
10	**User Guidance & Support**		**7**	**1**	**-**
a	Does the software contain guidance material which supports and helps the user to understand how it works?	Yes, but further improvements may be useful	6	-	-
b	Is the user manual easy to understand for supporting the user during initial usage of the tool?	Yes, but further improvements may be useful	6	-	Would be improved by video and animations
c	Is the user manual written in a simple and direct language?	Yes	9	-	-
11	**Visual Clarity Description**		**6**	**1**	**-**
a	Are the information displayed on the interface clear?	Yes, but further improvements may be useful	6	-	-
b	Are the information displayed on the interface well organised?	Yes, but further improvements may be useful	6	-	-

Table 120 "Software usability" questionnaire (Loccioni tester 1)

		Evaluation	**Score**	**Weight**	**Recommended improvements (optional)**
1	**Compatibility**		**7,8**	**2**	**-**
a	Are the steps to perform to execute an analysis clear?	Yes	9	-	-
b	Is easy to understand how to activate a specific tool function?	Yes	9	-	-
c	Are the tool icons easily associated with their specific functions?	Yes, but further improvements may be useful	6	-	Icon to change material is not so easy to find
d	Are the required informations easy to enter through the interface?	Yes, but further improvements may be useful	6	-	It is not possible to change treatment after analysis has been executed

e	Is the tool aesthetically pleasing and satisfying to the user?	Yes	9	-	-
2	**Consistency & Standards**		**8,7**	**3**	**-**
a	Are the software functions able to produce all necessary DFA/DFM rules?	Yes	9	-	-
b	Are the DfM rules compliant with the personal and company knowledge?	Yes	9	-	-
c	Are the geometric KPIs (Dimensions, weight/volume, number of parts, raw material waste, machining direction, total weld length) calculated by the software reasonably correct?	Yes	9	-	-
d	Is the cost calculated by the software reasonably correct?	Yes	9	-	-
e	Is the cost breakdown details calculated by the software reasonably correct?	Yes	9	-	-
f	Is the default stock selected by the software correct enough?	Yes, but further improvements may be useful	6	-	Would be needed further materials and raw geometry
g	Is the machining direction calculated by the software reasonably correct?	Yes	9	-	-
h	Is the 3D Model information displayed by the software correct?	Yes	9	-	-
i	Does the report generated by the analysis clearly summarize the main results with sufficient and adequate information?	Yes	9	-	-
3	**Error Prevention & Correction**		**9**	**3**	**-**
a	Are the error messages displayed when incompatible data is entered useful for the user and easy to understand? (example: assembly 3D model analysed whit single component strategies; material not compatible whit strategy used; etc...)	Yes	9	-	-
b	Is the user easily able to understand why errors messages appear?	Yes	9	-	-
c	Is easy to correct incomplete or incorrect input data through the tool interface?	Yes	9	-	-
d	Does the software allow the user to easily check input data to minimise errors?	Yes	9	-	-

4	**Explicitness**		**9**	**2**	**-**
a	Are the workflow analysis clear and easy to identify?	Yes	9	-	-
5	**Flexibility & Control**		**9**	**2**	**-**
a	Is the structure of the tool flexible, allowing the user to perform the analysis steps according to his/her needs?	Yes	9	-	-
b	Is the user able to perform the analysis which he/she considers best for his/her needs?	Yes	9	-	-
6	**Functionality**		**8**	**3**	**-**
a	Are all the respected/not respected DFA/DFM rules a useful result of the analysis?	Yes, but further improvements may be useful	6	-	Some rules are not so useful
b	Is the cost calculated by the software a useful result of the analysis?	Yes	9	-	-
c	Is the cost breakdown details calculated by the software a useful result of the analysis?	Yes	9	-	-
d	Is the default stock selected by the software a useful result of the analysis?	Yes	9	-	-
e	Are the DFA/DFM rules useful to evaluate design choices or to suggest improvements in the product you are analysing?	Yes, but further improvements may be useful	6	-	In our case we use LD mostly for costing
f	Are the calculated cost, the cost breakdown and the default selected stock useful to help evaluate design choices or suggest improvements to the product you are analysing?	Yes	9	-	-
7	**Language & Content**		**9**	**1**	**-**
a	Are the DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes	9	-	-
b	Are the respected/not respected DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes	9	-	-
c	Are the geometric KPI easy to understand and shown in a comprehensive way?	Yes	9	-	-
e	Is the cost calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
f	Is the cost breakdown easy to understand and shown in a comprehensive way?	Yes	9	-	-

g	Is the default stock selected by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
h	Is the machining directions calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
i	Are the 3D model informations provided by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
j	Is the language used throughout the tool easily understandable for the user?	Yes	9	-	-
8	**Navigation**		**8,4**	**2**	**-**
a	Does the tool structure allow to rapidly perform the required analysis?	Yes	9	-	-
b	Are the sections where input data is required quickly and easily identifiable within the interface?	Yes, but further improvements may be useful	6	-	It is difficult to change the coating or treatment
c	Are the tool evaluation/calculation icons quickly and easily identifiable within the interface?	Yes	9	-	-
d	Are the main interface icons easy to find and accessible?	Yes	9	-	-
e	Does the navigation within the tool allow the user to easily and quickly access all functions?	Yes	9	-	-
9	**Privacy**		**9**	**3**	**-**
a	Is the user confident that any company data input into the tool will be protected?	Yes	9	-	-
10	**User Guidance & Support**		**9**	**1**	**-**
a	Does the software contain guidance material which supports and helps the user to understand how it works?	Yes	9	-	-
b	Is the user manual easy to understand for supporting the user during initial usage of the tool?	Yes	9	-	-
c	Is the user manual written in a simple and direct language?	Yes	9	-	-
11	**Visual Clarity Description**		**9**	**1**	**-**
a	Are the information displayed on the interface clear?	Yes	9	-	-
b	Are the information displayed on the interface well organised?	Yes	9	-	-

Table 121 "Software usability" questionnaire (Loccioni tester 2)

		Evaluation	Score	Weight	Recommended improvements (optional)
1	**Compatibility**		**9**	**2**	**-**
a	Are the steps to perform to execute an analysis clear?	Yes	9	-	-
b	Is easy to understand how to activate a specific tool function?	Yes	9	-	-
c	Are the tool icons easily associated with their specific functions?	Yes	9	-	-
d	Are the required informations easy to enter through the interface?	Yes	9	-	-
e	Is the tool aesthetically pleasing and satisfying to the user?	Yes	9	-	-
2	**Consistency & Standards**		**9**	**3**	**-**
a	Are the software functions able to produce all necessary DFA/DFM rules?	Yes	9	-	-
b	Are the DfM rules compliant with the personal and company knowledge?	Yes	9	-	-
c	Are the geometric KPIs (Dimensions, weight/volume, number of parts, raw material waste, machining direction, total weld length) calculated by the software reasonably correct?	Yes	9	-	-
d	Is the cost calculated by the software reasonably correct?	Yes	9	-	-
e	Is the cost breakdown details calculated by the software reasonably correct?	Yes	9	-	-
f	Is the default stock selected by the software correct enough?	Yes	9	-	-
g	Is the machining direction calculated by the software reasonably correct?	Yes	9	-	-
h	Is the 3D Model information displayed by the software correct?	Yes	9	-	-
i	Does the report generated by the analysis clearly summarize the main results with sufficient and adequate information?	Yes	9	-	-
3	**Error Prevention & Correction**		**9**	**3**	**-**

a	Are the error messages displayed when incompatible data is entered useful for the user and easy to understand? (example: assembly 3D model analysed whit single component strategies; material not compatible whit strategy used; etc...)	Yes	9	-	-
b	Is the user easily able to understand why errors messages appear?	Yes	9	-	-
c	Is easy to correct incomplete or incorrect input data through the tool interface?	Yes	9	-	-
d	Does the software allow the user to easily check input data to minimise errors?	Yes	9	-	-
4	**Explicitness**		**9**	**2**	**-**
a	Are the workflow analysis clear and easy to identify?	Yes	9	-	-
5	**Flexibility & Control**		**9**	**2**	**-**
a	Is the structure of the tool flexible, allowing the user to perform the analysis steps according to his/her needs?	Yes	9	-	-
b	Is the user able to perform the analysis which he/she considers best for his/her needs?	Yes	9	-	-
6	**Functionality**		**8,5**	**3**	**-**
a	Are all the respected/not respected DFA/DFM rules a useful result of the analysis?	Yes	9	-	-
b	Is the cost calculated by the software a useful result of the analysis?	Yes	9	-	-
c	Is the cost breakdown details calculated by the software a useful result of the analysis?	Yes	9	-	-
d	Is the default stock selected by the software a useful result of the analysis?	Yes, but further improvements may be useful	6	-	More automatization by the tool. It would be good the minimizations of the choices made by the user such as profiles, milled blocks
e	Are the DFA/DFM rules useful to evaluate design choices or to	Yes	9	-	-

	suggest improvements in the product you are analysing?				
f	Are the calculated cost, the cost breakdown and the default selected stock useful to help evaluate design choices or suggest improvements to the product you are analysing?	Yes	9	-	-
7	**Language & Content**		**9**	**1**	**-**
a	Are the DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes	9	-	-
b	Are the respected/not respected DFA/DFM rules easy to understand and shown in a comprehensive way?	Yes	9	-	-
c	Are the geometric KPI easy to understand and shown in a comprehensive way?	Yes	9	-	-
e	Is the cost calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
f	Is the cost breakdown easy to understand and shown in a comprehensive way?	Yes	9	-	-
g	Is the default stock selected by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
h	Is the machining directions calculated by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
i	Are the 3D model informations provided by the tool easy to understand and shown in a comprehensive way?	Yes	9	-	-
j	Is the language used throughout the tool easily understandable for the user?	Yes	9	-	-
8	**Navigation**		**9**	**2**	**-**
a	Does the tool structure allow to rapidly perform the required analysis?	Yes	9	-	-
b	Are the sections where input data is required quickly and easily identifiable within the interface?	Yes	9	-	-
c	Are the tool evaluation/calculation icons quickly and easily identifiable within the interface?	Yes	9	-	-
d	Are the main interface icons easy to find and accessible?	Yes	9	-	-

e	Does the navigation within the tool allow the user to easily and quickly access all functions?	Yes	9	-	-
9	**Privacy**	**Yes**	**9**	**3**	**-**
a	Is the user confident that any company data input into the tool will be protected?	Yes	9	-	-
10	**User Guidance & Support**		**9**	**1**	**-**
a	Does the software contain guidance material which supports and helps the user to understand how it works?	Yes	9	-	-
b	Is the user manual easy to understand for supporting the user during initial usage of the tool?	Yes	9	-	-
c	Is the user manual written in a simple and direct language?	Yes	9	-	-
11	**Visual Clarity Description**		**9**	**1**	**-**
a	Are the information displayed on the interface clear?	Yes	9	-	-
b	Are the information displayed on the interface well organised?	Yes	9	-	-

C.4. Questionnaire results (Impact on company traditional process)

Table 122 "Impact on company traditional process" questionnaire (Perini)

		Evaluation	Score	Recommended improvements (optional)
1	**Impact on the traditional design process**		**9**	**-**
a	Is the impact of "DfM/DfA and cost tool" use in terms of time dedicated to the analysis admissible and compatible with the traditional time of the design process?	Yes	9	-
b	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase in terms of time dedicated to the design process?	No	9	-
c	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase of the design process phases?	No	9	-
d	Is the impact of "DfM/DfA and cost tool" use in terms of competence to acquire, admissible and compatible with the actual company employee's competency or are necessary specific skills?	Yes	9	-
e	Is the modification of the traditional design process with "DfM/DfA and cost tool", admissible for your company and easy to realize?	Yes	9	-
f	Could "DfM/DfA and cost tool" help to speed up the learning of the design knowledge necessary for correct part design?	Yes	9	-
2	**Data integration between traditional design and "DfM/DfA and cost tool"**		**0**	**-**
a	Is the software able to retrieve necessary information from the company systems CAD?		0	N.A.
b	Are the data retrieved automatically from the company CAD 3D systems, useful for your analysis and adequate to conduct and perform analysis?		0	N.A.

3	**Training activities**		**9**	**-**
a	Are the training sessions organized for "DfM/DfA and cost tool", adequate and sufficient to be able to perform analysis?	Yes	9	-
b	Is the timing requested for the training sessions adequate in relation to the company traditional time dedicated to training activities?	Yes	9	-
c	Is the time needed to have a complete skill on "DfM/DfA and cost tool" functionalities (excluded the training activities time) not excessive according to the company standards in terms of training timing?	Yes	9	-
d	Are the training activities too specific to be followed by a wide range of company staff?	Yes	9	-
e	Are the language and the support materials used during the training activities adequate and easily to be understandable?	Yes	9	-
4	**Personnel to involve**		**9**	**-**
a	Are the personnel inside the company able to use "DfM/DfA and cost tool" and to interpret its results? (after appropriate training activities)	Yes	9	-

Table 123 "Impact on company traditional process" questionnaire (Loccioni tester 1)

		Evaluation	Score	Recommended improvements (optional)
1	**Impact on the traditional design process**		**9**	**-**
a	Is the impact of "DfM/DfA and cost tool" use in terms of time dedicated to the analysis admissible and compatible with the traditional time of the design process?	Yes	9	-
b	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase in terms of time dedicated to the design process?	No	9	-

c	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase of the design process phases?	No	9	-
d	Is the impact of "DfM/DfA and cost tool" use in terms of competence to acquire, admissible and compatible with the actual company employee's competency or are necessary specific skills?	Yes	9	-
e	Is the modification of the traditional design process with "DfM/DfA and cost tool", admissible for your company and easy to realize?	Yes	9	-
f	Could "DfM/DfA and cost tool" help to speed up the learning of the design knowledge necessary for correct part design?	Yes	9	-
2	**Data integration between traditional design and "DfM/DfA and cost tool"**		**9**	**-**
a	Is the software able to retrieve necessary information from the company systems CAD?	Yes	9	-
b	Are the data retrieved automatically from the company CAD 3D systems, useful for your analysis and adequate to conduct and perform analysis?	Yes	9	-
3	**Training activities**		**0**	**-**
a	Are the training sessions organized for "DfM/DfA and cost tool", adequate and sufficient to be able to perform analysis?		0	N.A.: they didn't attend a training session
b	Is the timing requested for the training sessions adequate in relation to the company traditional time dedicated to training activities?		0	N.A.: they didn't attend a training session
c	Is the time needed to have a complete skill on "DfM/DfA and cost tool" functionalities (excluded the training activities time) not excessive according to the company standards in terms of training timing?		0	N.A.: they didn't attend a training session
d	Are the training activities too specific to be followed by a wide range of company staff?		0	N.A.: they didn't attend a training session
e	Are the language and the support materials used during the training activities adequate and easily to be understandable?		0	N.A.: they didn't attend a training session

4	**Personnel to involve**		9	**-**
a	Are the personnel inside the company able to use "DfM/DfA and cost tool" and to interpret its results? (after appropriate training activities)	Yes	9	-

Table 124 "Impact on company traditional process" questionnaire (Loccioni tester 2)

		Evaluation	**Score**	**Recommended improvements (optional)**
1	**Impact on the traditional design process**		**8,5**	**-**
a	Is the impact of "DfM/DfA and cost tool" use in terms of time dedicated to the analysis admissible and compatible with the traditional time of the design process?	Yes, but further improvements may be useful	6	More automation would be needed for a reduction of time dedicated in design process
b	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase in terms of time dedicated to the design process?	Yes	9	-
c	In comparison whit traditional design process, "DfM/DfA and cost tool" use causes an increase of the design process phases?	Yes	9	-
d	Is the impact of "DfM/DfA and cost tool" use in terms of competence to acquire, admissible and compatible with the actual company employee's competency or are necessary specific skills?	Yes	9	-
e	Is the modification of the traditional design process with "DfM/DfA and cost tool", admissible for your company and easy to realize?	Yes	9	-
f	Could "DfM/DfA and cost tool" help to speed up the learning of the design knowledge necessary for correct part design?	Yes	9	-
2	**Data integration between traditional design and "DfM/DfA and cost tool"**		**9**	**-**
a	Is the software able to retrieve necessary information from the company systems CAD?	Yes	9	-

b	Are the data retrieved automatically from the company CAD 3D systems, useful for your analysis and adequate to conduct and perform analysis?	Yes	9	-
3	**Training activities**		**0**	**-**
a	Are the training sessions organized for “DfM/DfA and cost tool”, adequate and sufficient to be able to perform analysis?		0	N.A.: they didn’t attend a training session
b	Is the timing requested for the training sessions adequate in relation to the company traditional time dedicated to training activities?		0	N.A.: they didn’t attend a training session
c	Is the time needed to have a complete skill on “DfM/DfA and cost tool” functionalities (excluded the training activities time) not excessive according to the company standards in terms of training timing?		0	N.A.: they didn’t attend a training session
d	Are the training activities too specific to be followed by a wide range of company staff?		0	N.A.: they didn’t attend a training session
e	Are the language and the support materials used during the training activities adequate and easily to be understandable?		0	N.A.: they didn’t attend a training session
4	**Personnel to involve**		**9**	**-**
a	Are the personnel inside the company able to use “DfM/DfA and cost tool” and to interpret its results? (after appropriate training activities)	Yes	9	-