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# Design methodology for production systems retrofit in SMEs

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Investment in the productive systems of small and medium-sized enterprises (SMEs) in the manufacturing sector is usually quite limited. For this reason, normal practice is to apply minor developments internally, or upgrade equipment as it becomes obsolete to increase their productive capacity and competitiveness at lower cost. However, the work team, mostly made up of engineers, does not usually have experience in the use of design methodologies but also they are often familiar with the functioning of various design and quality-management tools. This paper presents a clear and simple design methodology that facilitates the development of adaptations to items of equipment that might be considered one-off products. It includes a selection of design tools that are, according to literature on the subject, the most common and best-known among engineers, and which are also best-suited to the environment of an SME. The design methodology was validated experimentally with the upgrading of a gear-rolling tester installed on the premises of an SME in the sector. The recommended techniques and tools were satisfactory applied opening the possibilities for further application of the methodology in similar machine's upgrades in the future.

Keywords: design methods; systematic design; manufacturing systems upgrade; one-off product; SMEs

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## 1 Introduction

### *1.1 Retrofit*

All productive processes involve the use of machinery which becomes obsolete after a given period of use. This state can be delayed by applying upgrades which usually suppose lower risk and less investment (Edwards 2004). These upgrades also improve the efficiency, versatility and performance of the original manufacturing systems concerned (Huang and Yan 1996; Yan, Lee, and Yen 2005), adapting at the same time the equipment to current safety or environmental legislation (Chen, Lin, and Lee 2013; Gough, Farrokhpanah, and Bulatov 2013).

The term "retrofit" encompasses any type of modernisation, update, upgrade, renovation, refurbishment, adaptation or remanufacturing, whatever its extent (Du et al. 2012; Esmaeilian, Behdad, and Wang 2016; Zolghadri and Couffin 2017). It can be differentiated in three main groups of retrofits.

The first includes large companies in the energy, transport or defence sectors with a large volume of business and products with a long or very long service life. They may need to upgrade their systems several times over a long life-cycle counted in decades (Zolghadri and Couffin 2017). As the investments and risks involved are so high, changes must be safe, controlled and backed up by rigorous economic and technical studies (C. Eckert, Clarkson, and Zanker 2004).

The second group consists of the automotive industry, the domestic appliance and technology sectors, all of which are forced to redesign and further develop their products so that performance and quality improve with each new model (Gu, Xue, and Nee 2009; Zolghadri and Couffin 2017). Upgrades in both groups are often carried out by specialist companies in the sector, normally with some connection to system maintenance or the provision of spare parts (C. Eckert, Clarkson, and Zanker 2004).

The third group, finally, is the one linked to SMEs which, due to their limitations, upgrade their existing productive resources as a cost-effective way of remaining competitive in an increasingly tough market (Ramírez-Cadena, Miranda, and Molina 2013). Upgrades in this last group tend to be carried out internally, particularly by companies dedicated to industrial production and machining that have sufficient human and technical resources at their disposal. Each update is usually different, and can be regarded as a prototype or one-off product. For this reason, it requires a special working methodology, as its development differs from the approach normally adopted for mass-production products (Ravai-Nagy et al. 2013).

### *1.2 Use of design methodologies*

Design methodologies have a large positive impact on product-development processes, helping designers to make better decisions (Yeh, Pai, and Yang 2009). Results from these design processes not only depend on the designer's experience of handling tools and techniques (Lutters et al. 2014), but also on the ability to select these elements (Booker 2012). Part of the industry is now aware of the benefits offered by design methodologies, although their implementation is still limited (Jagtap et al. 2014), especially in the case of SMEs.

They typically tend to employ approaches to design that are unstructured with a lack of systematic engineering methods, as they are normally developed in-house (Gherardini, Renzi, and Leali 2017). This is as a consequence of a hierarchy that usually bases decision-making on subjective factors (Kirkham et al. 2014), coupled with the uneven time-management and deployment of human resources that results from an excess of day-to-day tasks. Lack of resources (mainly economic) is presented as the main cause of different levels of success in the application of engineering methods among SMEs and large-sized enterprises respectively (Blackwell, Shehab, and Kay 2006; Marriott et al. 2013). Adapting the development of new design methodologies to requirements of a particular company or its area of activity might therefore improve its implementation (Booker 2012).

### *1.3 Approaching the problem*

Retrofitting the machinery or manufacturing systems of SMEs in the industrial sector is a low-investment way of improving their competitiveness. Doing so in-house provides accurate knowledge of customer needs and flexibility in the results. However, the engineer responsible of the process is usually neither a product development specialist nor familiar with design methodologies. This can reduce the successful development of retrofit, compromising the limited resources of the SME concerned.

Additionally, design methodologies and tools are not only related to the development of new products. The modification of products reduces the risk and cost of new developments (C. Eckert, Clarkson, and Zanker 2004). Nevertheless, the design process in this case demands same effort and caution that the development of a totally new set of equipment would entail (Edwards 2004). Indeed, the modification or extension of existing developments lies in finding the most appropriate solution while avoiding a cascade of changes in the rest of the system (C. M. Eckert et al. 2012). The different alternatives should in any case be explored in depth in the light of changes relative to space available, fixing methods and tolerances, so as not to compromise the functionality of the system (Medland and Mullineux 2000). We therefore need to understand throughout the upgrade process, both the context of the design and the functions to be performed, while analysing the subassemblies and superstructures that make up a piece of machinery (Urbanic and ElMaraghy 2009).

The in-house retrofits of SMEs generally tend to be highly technical developments with a large number of factors involved, including a need of being highly robust to any kind of noise factor that guarantees an uninterrupted operation. This is the basis of what robust design methodologies entail (Andersson 1997), encompassing several engineering methods linked primarily to insensitivity to variation (Jugulum and Frey 2007) and being closely connected with the concept of quality engineering (Arvidsson and Gremyr 2008). Designers can actually make a significant contribution to the robustness of the product applying straightforward principles, provided they are based on the three general rules proposed by Pahl and Beitz (2007): clarity, simplicity and safety. Better results are obtained if this is applied throughout all process and not just at the detailed-design stage (Fujita and Matsuo 2005; Jugulum and Frey 2007). Techniques such as Failure Mode and Effect Analysis (FMEA), Design for X (DfX) in any of their versions, plus Pugh's method, Gantt charts, benchmarking, brainstorming, and especially those related to Computer Aided Design (denominated "CAX") have a high impact on the performance of the product development cycle. Others, such as Quality Function Deployment (QFD), are used quite extensively, despite being less effective, because they provide a highly powerful means of identifying functional requirements and design parameters (Tomiyama et al. 2009; Yeh, Pai, and Yang 2009; Booker 2012). These logical and systematic tools doubtless provide, together with a methodology for effectively guiding the steps to follow, a suitable solution with limited time and effort investment.

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This paper proposes a methodology for design and retrofit processes carried out by SME's engineers who have to turn themselves temporarily into designers of a one-off product. The methodology establishes, in a clear and orderly manner, all the steps to follow and the tools to use, while identifying the stakeholders that need to be involved in each phase. Its main aim is to ensure that the engineer/designer obtains a valid functional solution with a guarantee of having taken the right decisions and without omitting any important point. The present work also includes a practical case study covering the application of this methodology to the upgrading and complete transformation of an obsolete gear profile tester to create a new gear-rolling tester (GRT), thereby showing its usefulness.

## 2 Methodology

The choice of the most appropriate design methodology depends on the application and the ability and experience of the designer (Tomiyama et al. 2009). The selection of tools is a difficult task that requires decision-making skills similar to those of the development process itself. The key aspects are the quality of the final product and the time and cost invested (Lutters et al. 2014). Finding a balance between these three factors is not easy, especially in an SME environment. The engineers in charge of retrofits in SMEs usually have certain technical knowledge on the tools but they are not expert in product-design processes.

In this regard, the proposed methodology follows a systematic approach based mainly on the design phases proposed by Pahl and Beitz (Pahl et al. 2007), thereby following certain guidelines of VDI 2221 (1993). Furthermore, it covers other phases similar to those proposed in VDI 2206 (2004) from initial consideration to the final validation of mechatronic systems. It also includes practical considerations and tools recommended by Ullman in mechanical design processes (Ullman 2010), as well as some general design principles (Pahl et al. 2007) to obtain a more robust design (Ebro and Howard 2016).

### *2.1 Methodology structure*

A retrofit begins with the requirements identification in the planning phase to address them in the most appropriate way (Figure 1) throughout the process. Planning tends to be subject to individual updates that depend on how the project is progressing. The Retrofit Evaluation Phase is the next step, in which is decided whether an in-house retrofit is the best option. Then the process continues with the Design and Manufacturing Phases, which also include the installation and integration processes of all the elements involved. Finally, the Validation Phase determines if the initial requirements have been met analysing the prototype as deliverable of the design process.

The proposed methodology is composed of seven phases (Figure 1), that allows to the responsible for the project not only to develop the process intuitively, but also following the proposed steps and taking into account all possible variables and actions in an organised way. This methodology also recommends working tools for each step, which can be adapted to the knowledge level of the engineers concerned, allowing them to make right decisions throughout development.

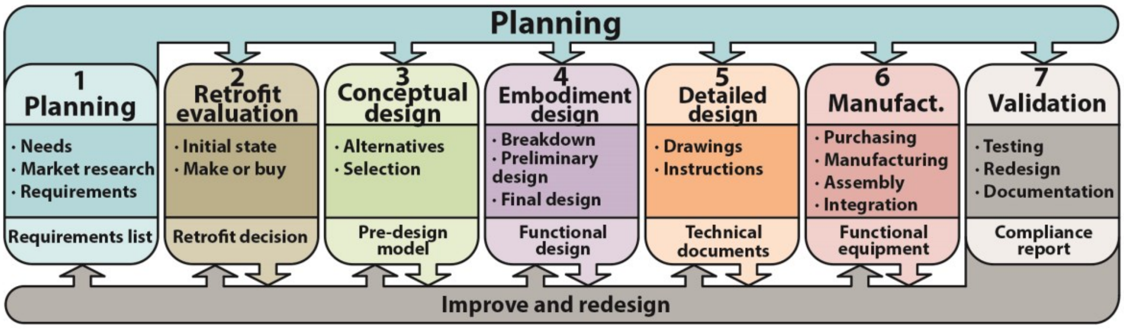


Figure 1. Methodology phases

### *2.2 Stakeholders*

It is impossible to establish the most common structure and distribution of functions at manufacturing SMEs. In fact, the same person carries out certain overlapping functions when a SME is very small. Although the shorter decision chain implies greater risk, it also has advantages such us its flexibility and capacity of adaptation to any eventuality (Gherardini, Renzi, and Leali 2017). However, this methodology can be adapted to any type of SME structure, regardless of its size. Figure 2 shows the resource allocation matrix (RAM) of a retrofit by process stages and department involved (function rather than something physical). The responsible engineer is not the only person involved in the retrofit development process but there are also several actors with diverse roles during stages. The following section describes each stage in detail.

| | |
|---|---|
| R: | Responsability |
| I: | Information |
| A: | Action |
| Q: | Quality inspection |

| Phase | Stage | Task | Lead engineer | Management | Engineering | Production | Quality | Purchasing | Sales | Supplier |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a | General planning | R | I | I | I | I | I | I | |
| | b | Needs identification | R | I | I | I | I | I | I | |
| | c | Market research | R | | I | | I | I | | I |
| | d | Requirements definition | R | | I | I | I | I | I | |
| 2 | a | Initial state evaluation | R | | | A | Q | | | |
| | b | Make or buy | R | A | | | | A | | I |
| 3 | a | Generation of alternatives | R | | A | | | I | | I |
| | b | Selection of alternatives | R | A | | | | | | |
| 4 | a | System breakdown | R | | A | | | | | |
| | b | Preliminary development | R | | A | | | I | | I |
| | c | Final development | R | | A | | | | | |
| 5 | a | Detailed drawings | R | | A | | | | | |
| | b | Instrutions description | R | | A | I | I | I | | I |
| 6 | a | Purchasing | I | | | | | R | | |
| | b | Manufacturing | I | | | R | Q | | | |
| | c | Assembly | I | | | R | Q | | | |
| | d | Integration | I | | | R | Q | | | A |
| 7 | a | Testing | I | | | A | R | | | |
| | b | Redesign | R | | A | A | Q | | | |
| | c | Documentation | R | | A | | Q | | | |

Figure 2. RAM of a manufacturing system retrofit

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### *2.3 Description of the phases*

The following sub-sections describe each phase in detail, including tasks to carry out and the recommended tools to reach the specific objectives. This methodology should not regard as something inflexible, but the design team should rather adapt the different stages to their needs and knowledge. Figure 3 shows a summary of the methodology.

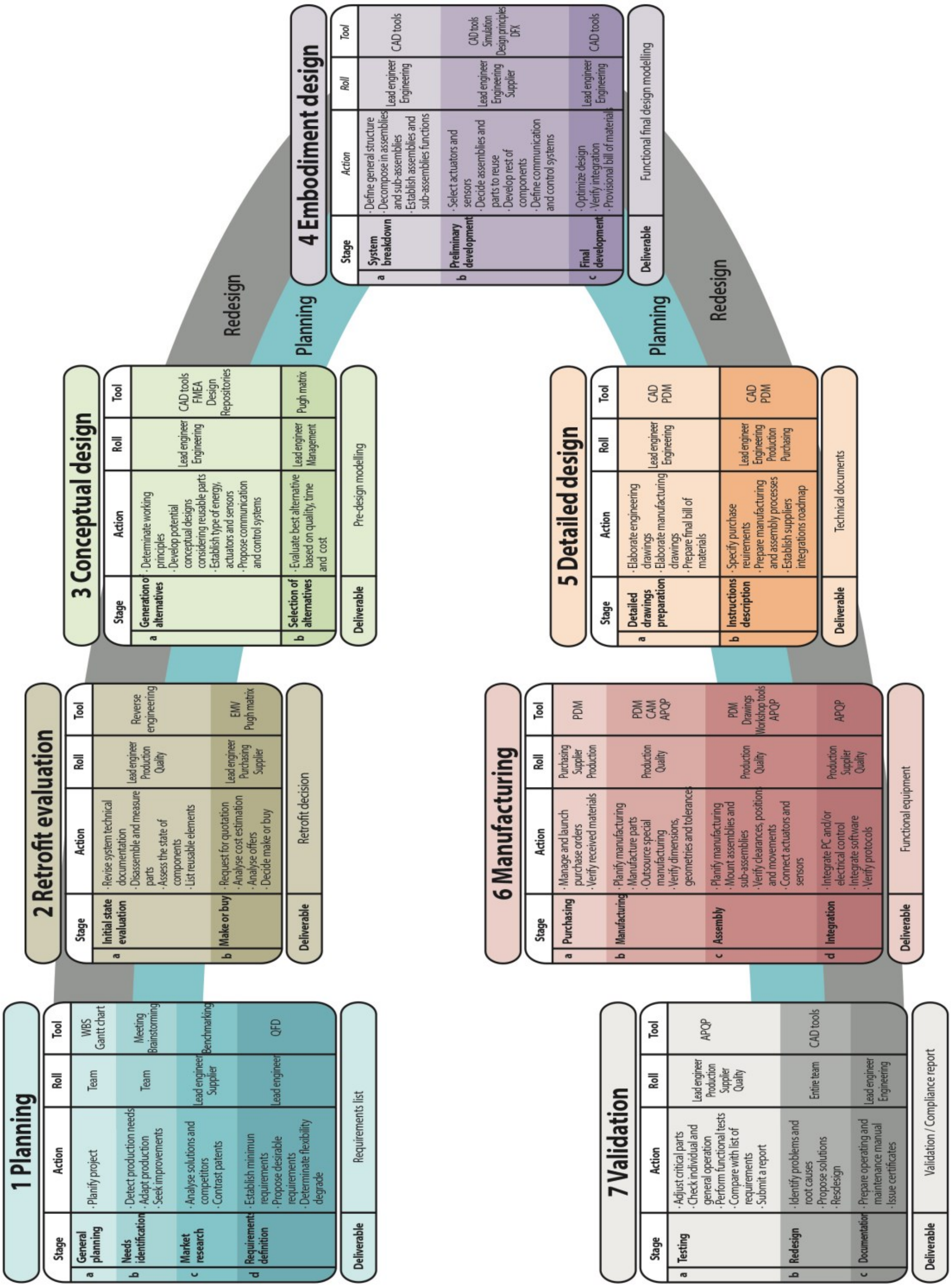


Figure 3. Summary of methodology

### *2.3.1 Phase 1: Planning*

This phase aims to determine those technical requirements to be incorporated to the company's manufacturing system, based on the identified needs and the market situation. We therefore need to plan the following stages:

1a) General planning

The first step is to plan how to develop the process as a whole, including high-level planning of activities and resources, and the scheduling of the remaining phases, using a Work Breakdown Structure (WBS) and a Gantt chart (Barczak, Griffin, and Kahn 2009). Planning involves all departments who have to contribute with their knowledge and experience. This phase also includes the planning of the quality-related activities required for development of the retrofit, using Advanced Project Quality Planning (APQP).

1b) Needs identification

This stage identifies the needs and possible shortcomings of production systems, involving the improvement of existing processes or the anticipation of future demands. Joint meetings between different departments are required to incorporate different points of view (Barczak, Griffin, and Kahn 2009). Pahl et al. (2007, chap. 3) supply a series of key guidelines for carrying this out correctly.

1c) Market research

A market research allows us to evaluate any technical and commercial solutions that might be available, and to assess the investment required. Benchmarking is a rich source of ideas for the design of products and processes alike (Ulrich and Eppinger 2012). It lets users in all manner of sectors take advantage of knowledge generated by other companies analysing and improving in-house resources (Thevenot and Simpson 2009). Furthermore, if in-house development is proposed, there is a need to examine patents so as to avoid intellectual-property disputes during new-product development.

1d) Requirements definition

The final stage has to link the identified needs to engineering specifications. This could be performed using QFD tool that takes into account the customer satisfaction, the design times and costs involved (Ullman 2010, chap. 6). Designers with less experience are however recommended to apply the improvements proposed by Leary and Burvill (2007) to avoid any loss of effectiveness. The result is a list of vital "minimum" requirements and "desirable" alternative requirements of the product. Internal retrofits are normally more flexible in this respect, and certain requirements can be modified if development is affected by some limiting factor.

### *2.3.2 Phase 2: Retrofit evaluation*

Its objective is to determine if the upgrade of an existing manufacturing system is the best investment for a specific SME, assessing the current state of the manufacturing system before drawing up a cost estimate. This is compared to suppliers' proposals, to decide if a "make" solution could be more profitable than an outsourced one:

2a) Initial-state evaluation

This stage entails verifying the current condition of the equipment parts and components, determining their adequacy for being rejected, recycled or reused (Mabee, Bommer, and Keat 1999). The first step is to verify that the original technical documentation matches the current reality of the product. If the original technical documentation is no longer valid, reverse engineering techniques would need to be applied (Urbanic and ElMaraghy 2009; Curtis, Harston, and Mattson 2011).

2b) Make or buy

The cost estimate is based on a qualitative analysis of project risks and an economic evaluation of their possible impact, using the technique of Expected Monetary Value (EMV). Cost could be a key variable in the decision-making process to reach a final decision on whether to proceed with the in-house retrofit or an external outsourcing.

*2.3.3 Phase 3: Conceptual design*

If the objective of the retrofit is an in-house upgrade, the conceptual design phase is the first stage in the design process, generating a draft design after considering different alternatives:

3a) Generation of design alternatives

Engineers have at their disposal information from suppliers, the corresponding lists of reusable components and the most-promising ideas from their team to come up with possible solutions. General principles and their corresponding individual working structures are established at this stage, and work begins with the definition of the types of drives and sensors required, among other matters. CAD tools are essential for global developments that take into account the main dimensions and geometric factors, for efficient application throughout the design phases (Yeh, Pai, and Yang 2009). They are normally combined with analytical techniques like FMEA to study the critical aspects of performance during the design stage (Lutters et al. 2014). They let us identify and eliminate potential errors during the design process, thereby improving the reliability of the end-product (Ullman 2010, chap. 11). Moreover, design repositories can provide with information about materials, components, CAD models and even initial design alternatives (Raoufi, Manoharan, and Haapala 2018). Non-mechanical factors, such as communications, system control and specialized assistance are considered at the same time.

3b) Selection of design alternatives

This stage is crucial for the rest of development and the decision will influence the final result. For that, it is necessary to assess each alternative depending on its cost and development time, as limiting resources. The decision matrix (Pugh's method) allows to select the best alternative, based on established criteria (Ullman 2010, chap. 8). It is a simple and straightforward method, and is therefore well-known and widely used by companies (Tomiyama et al. 2009).

*2.3.4 Phase 4: Embodiment design*

The draft design is transformed into the final version during this phase, being theoretically functional. The whole product is divided into smaller assemblies for determining shapes, characteristics and materials of each component. The following steps show the aspects to be considered in this phase:

4a) System breakdown

First, it is necessary to break the problem down to facilitate the decision-making. The structure of items of machinery and production systems is often based on smaller subassemblies, which are able to perform small individual functions in a top-down manner. Once minimum units have been established, the process is reversed to focus on a detailed bottom-up approach verifying the compatibility of subassemblies (Urbanic and ElMaraghy 2009). This process is coordinated by the lead engineer working in collaboration with the development department.

4b) Preliminary development

Despite a retrofit could limit the freedom of the designer it supposes easier processes due to the previous established dimensions and different characteristics of the elements. The most common retrofit is the replacement of obsolete components with more updated ones. Sometimes the replacement is almost total maintaining only the main structure. At this point, it is necessary to do a particular study of the machinery, identifying the necessity of drives, sensors or new functional elements. The ongoing process of decision-making and modification continues until the design suits our requirements. CAX tools allow to adjust dimensions and predict the performance of key elements, validating the design prior to production (Lutters et al. 2014). Pahl et al. (2007) propose three basic design rules for a successful outcome: clarity of function, free of ambiguity; simplicity of form and a limited number of components for speed and ease of production; plus safety in terms of reliability, accident prevention and protection of the environment.

The tools used should therefore ensure the robustness of the design based on its insensitivity to variation caused by noise factors, and not merely its reliability in terms of fault prediction (Arvidsson and Gremyr 2008; Eifler, Christensen, and Howard 2013). Ebro and Howard (2016) present a set of 15 design principles for this purpose, according to the design sensitivity, parameter and performance variation. Most of them can be applied in any design stage, using several of the Design-for-X guidelines provided by Pahl et al. (2007) and Ullman (2010, chap. 11) that include recommendations and practical examples of suitable application of these techniques. "Design for manufacturing" (DFM) and "design for assembly" (DfA) are the most common ones.

4c) Final development

The Embodiment Phase ends with a final functional system design. All items and subassemblies have to be verified to ensure their successful integration with each other, after repeated iterations and modifications. This implies that each part has to be manufactured and assembled to verify its functionality. As a final step, a provisional list of components and a starting planning for possible purchases and supplies of materials are generated.

### *2.3.5 Phase 5: detailed design*

During this phase all the information required for the retrofit is presented into the technical documentation, including drawings and instruction for the definition of each detail (Pahl et al. 2007; Lutters et al. 2014). As in the previous phase, the different actions from this stage run sequentially or in parallel for each subassembly. This phase also habitually overlaps with the previous one in those tasks with broad deadlines (Ravai-Nagy et al. 2013):

5a) Detailed drawings preparation

This stage entails the drafting of detailed manufacturing drawings for all non-commercial items, as well as for possible modifications of original parts. The contents of the bill of materials are sent to production and purchasing to facilitate progress in the following stages. It is usual practice to carry out this process via Product Data Management (PDM) with a direct link to the CAD program. This prevents transcription errors among the different actors involved.

5b) Description of instructions

Drawings may be complemented with some type of instruction, such as information for the planning and management of manufacturing and/or assembly processes. Other important factors include final specifications of materials and the purchase of components from external suppliers.

### *2.3.6 Phase 6: manufacturing and assembly*

The Manufacturing Phase consists of the acquisition of materials, the manufacturing of the in-house materials, the final assembling and the integration of all the elements involved. In this phase, it is crucial to keep a properly updated task-planning because it is usual an overlapping between manufacturing and assembly. During this phase it is necessary to carry out testing and verification of the functionality of systems and subsystems at the different stages of this phase's progress (VDI 2004).

6a) Purchasing

The purchasing stage includes the acquisition of material for manufacturing, as well as of standard trade components, drives and sensors. Procurement planning is important to avoid modifications during provisional planning or create unnecessary stock of materials. The purchasing department normally deals with this stage. In the smallest SMEs, this is usually the direct responsibility of production, or even of the responsible of the retrofit.

6b) Manufacturing

The aim of this phase is to speed up the costly and time-consuming processes, while optimising available resources to meet the envisaged requirements. Outsourcing may help us greatly to avoid the overloading of in-house production resources. On the other hand, it is necessary to include here, previously to assembling, dimensional controls and brief checks on how the pieces joined. During this stage, the production, quality management department and suppliers have to be coordinated to fulfil the project planning.

6c) Assembly

This phase begins gathering the smaller assemblies, verifying their functions, and then incorporating them into the main structure, checking their movements and positions. The drives, actuators and sensors may have a wide range of characteristics, from electric motors, pneumatic actuators or hydraulic pumps to electronic positioning elements like detectors or encoders. The proper connection of all wiring is vital for ensuring that there is no interference with the routing of other elements. The production department should ensure that these tasks are carried out correctly.

6d) Integration

This stage includes the integration of the operator panel, the electrical cabinet and/or a PC for controlling and manoeuvring the functions of the remaining systems. Once everything has been connected, we need to ensure that all the readings and instructions are correct. There are also checks to verify the compliance of the safety protocols to avoid any risk for the operator, in the start-up and regarding to the equipment's emergency stop function. The newly upgraded equipment is then ready for the start of validation testing.

*2.3.7 Phase 7: validation*

The last phase consists of the compliance verification of the requirements established in the first phase. After a series of tests previously established in the APQP, points for improvement are identified in case of not meeting the requirements (VDI 2004). During the final documentation stage, after making appropriate changes and carrying out any new validation tests that might be required, all the relevant documentation needed for operation and maintenance of the new manufacturing system will be registered.

7a) Equipment validation

The aim of this stage is to adjust the movements and positions of the different elements repeatedly, as well as checking the operation of the actuators and sensors. These validation tests, included in the APQP definition, are sometimes regulated by standards, while others might be carried out in the light of needs and experience in the field, assuring in all cases the fulfilment of the corresponding safety aspects.

The list of requirements is compared with the results obtained during the checking of the control plan. The quality management department and the engineer in charge issue a joint validation report for the equipment concerned. In the event of non-compliance, they describe problems and their possible causes, classifying them according to their criticality. They also indicate corrective actions to be carried out in an Improvement and Redesign Phase that involves returning to any of previous stages in the process as a whole, including the initial establishment of requirements.

7b) Improvement and redesign

During the retrofit projects is very usual to find problems after assembly and validation phases. They sometimes involve minor problems caused by manufacturing and assembly defects or errors in the information plan. Others may arise from some conceptual error requiring thereby more-radical changes or even the amendment of requirements. So it is therefore important to analyse, by the entire team, the impact that the required changes might imply, before carrying out any improvement.

7c) Documentation

Once the system is definitive and fully validated, the last stage consists of preparing all the documentation for the final version of the equipment. This consists mainly of drafting the operating and maintenance manuals, together with the issuing of certificates in accordance with safety standards and environmental legislation.

## 3 Application of the methodology

Companies dedicated to machining require machine tools and verification equipment that entail major long-term investments. They usually are high accuracy robust machines, subjected to specific standards, with a long service life that consist of mechatronic systems. For this reason, the methodology proposed is perfectly suited to SMEs in that sector.

### *3.1 Case study*

Echeverría Construcciones Mecánicas (ECM) is a Spanish SME specialized in the design and manufacture of gears and transmissions. ECM has used the proposed methodology to upgrade and adapt an obsolete gear profile tester, converting it into a new gear-rolling tester (GRT) for its metrology lab (Figure 4). Authors provided to ECM the design methodology and checked its usability during all phases without taking part in the retrofit process. The ECM staff had already carried out some in-house upgrade and small development of manufacturing tools although of smaller size and difficulty without methodological basis. It should be emphasised that the company's knowledge and 50+ years' experience in the sector have also been vital to the project's success.

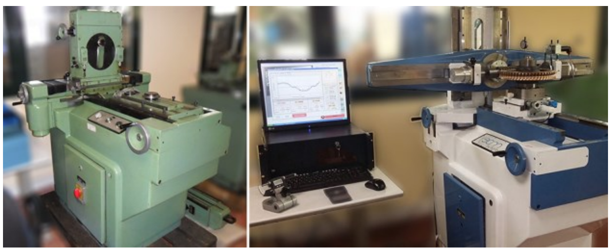

Figure 4. The original gear profile tester and its upgrade into a gear-rolling tester

#### *3.1.1 Needs*

The verification of gears on a rolling tester is a special measuring procedure in which the test gear is rolled against a master gear of higher quality. There are two types of rolling gear tests: single-flank and double-flank that involve different measuring techniques VDI/VDE 2608

(2001). The single-flank rolling test determines the transmission error by calculating the difference in the rotated angle between the master gear and the test gear, at the nominal centre distance (Figure 5 a). The double-flank rolling test detects eccentricity and gear-cutting errors by measuring the rocking motion that occurs when the gears mesh, without backlash, at a centre distance of less than the nominal amount (Figure 5 b). The results are expressed as a sinusoidal curve whose data can be broken down into their long- and short-wave components, using the Fourier transform. The values obtained, just a few microns and arcsecs, are compared with the reference standard ISO 1328-1 (2013) and ISO 1328-2 (1997) to determine the test gear's quality degree.

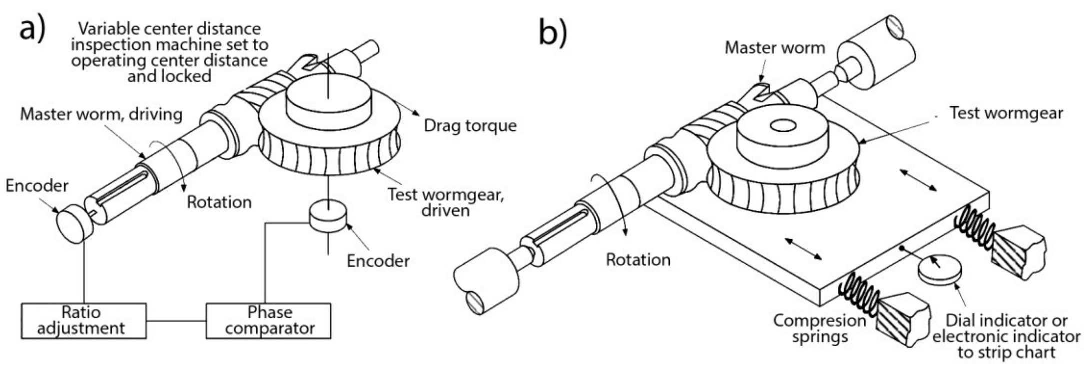


Figure 5. Functioning principle of rolling tests for worm gear transmissions conforming to ANSI/AGMA 2111-A98 (1998): a) Single-flank test; b) Double-flank test.

Although ECM already had a double-flank rolling gear test equipment, business forecasts envisaged a need to be able to measure worm gears of a larger size. It was an interesting opportunity to perform rolling tests on a single flank, which – despite being more difficult to interpret – provide more information. These specifications go beyond the usual capabilities of the equipment commercially available. The high cost of acquiring customised equipment, along with an extensive knowledge of gear testing, raised the possibility of an in-house retrofit.

### *3.2 Process of retrofit*

The following section contains some summarised examples of the most relevant points of the design methodology considered in the context of this retrofit.

#### *3.2.1 General planning*

The upgrade of the GRT, from the defining of needs to the final acceptance, took approximately 24 weeks to complete. Figure 6 illustrates the timescale by phases and stages established by the methodology. First, four weeks were devoted to planning, defining the requirements and deciding on the best design option. Then the definitive design drawings were developed during the seven further weeks. Manufacturing and assembly occupied eight weeks, overlapping some tasks. This helped to shorten delivery lead times for the more laborious items and the most-specialised components. The last eight weeks were accounted for commissioning and validation, which included procedures related to the system redesign and improvement.

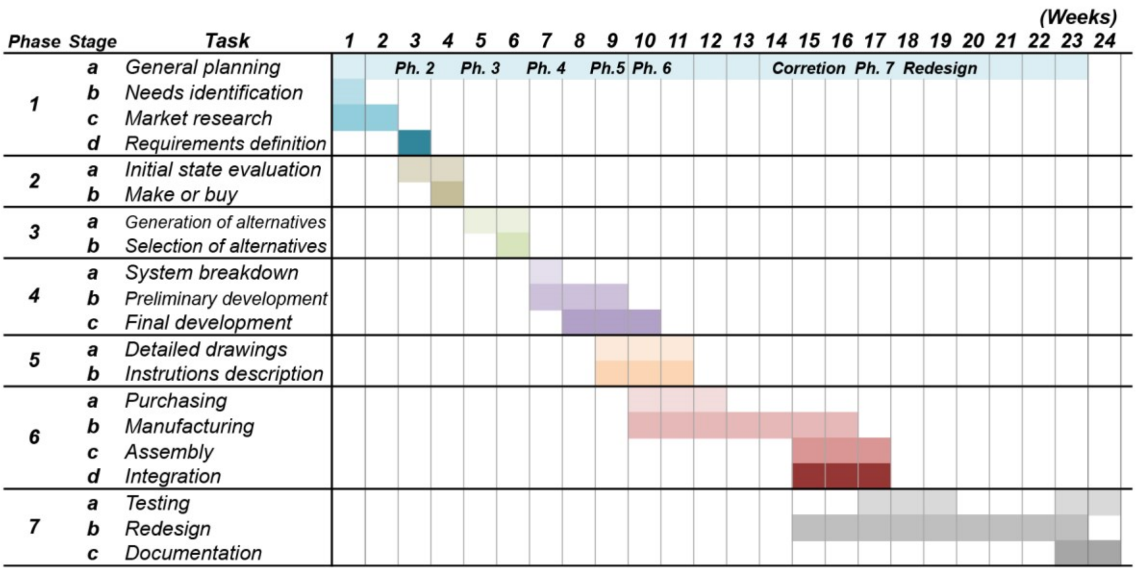


Figure 6. Gantt-chart summary of the retrofit

| | Product characteristics / Customer needs | Importance (1-5) | Centre distance displacement (mm) | Height displacement (mm) | Worm gear self- centering fixture | Torque min (Nm) | Custom software | Cost (EUR) | Lead time (weeks) | Slide movement precision (µm) | Worm gear rotation angle precision (arcseg) | Worm rotation angle precision (arcseg) | ⋮ | ECM product (1-5) | Competitor A - Standard product (1-5) | Competitor B - Custom product (1-5) | Technical target (1-5) | Improvement ratio | Market preferences (1 /1.2/1.5) | Absolute weight | Relative weight (%) | Ranking |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technical features** | Compliance VDI 2068/AGMA915 | 5 | 3 | 1 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | ⋮ | 3 | 3 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | Accuracy Grade 6 (ISO 1328) | 5 | 1 | 1 | 9 | | | 3 | 3 | 9 | 9 | 9 | | 3 | 3 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | High measurement repeatability | 5 | 3 | 1 | 9 | | 1 | 9 | 9 | 9 | 9 | 9 | | 3 | 3 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | High durability | 5 | | | | 3 | | | | | | | | 5 | 5 | 5 | 5 | 1 | 1 | 5 | 3.2 | 11 |
| | Gear diameter up to 600 mm (w/ hole) | 5 | 9 | | 3 | 9 | | | | | | 1 | | 3 | 1 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | Worm height up to 150 mm | 5 | | 1 | | 3 | | | | | | | | 3 | 1 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | Worm gear diameter up to 150 mm | 5 | 3 | 1 | | 9 | | | | | 1 | | | 3 | 1 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | Worm gear length up to 1000 mm | 5 | | | | 3 | | | | | | | | 3 | 1 | 5 | 5 | 1.6 | 1 | 8.3 | 5.4 | 1 |
| | Gear diameter up to 900 mm (w/ hole) | 1 | 9 | | 3 | 9 | | | | | | | | 2 | 1 | 5 | 3 | 1.5 | 1 | 1.5 | 1 | 28 |
| | Adaptability to 150 mm gear b/ tips | 4 | | 9 | | | 3 | | | | | | | 3 | 1 | 5 | 5 | 1.6 | 1 | 6.6 | 4.3 | 8 |
| | Modularity to other gear types | 2 | 3 | 3 | | 3 | 3 | | | | | | | 1 | 3 | 3 | 1 | 1 | 1 | 2 | 1.3 | 27 |
| **Assembling** | Worm gear easy fixing | 4 | 1 | 1 | | | | | 1 | 1 | | | ⋮ | 5 | 5 | 5 | 5 | 1 | 1 | 4 | 2.6 | 22 |
| … | … | … | … | | | | | | | | | … | | | … | | | | | | … |
| | ***Absolute importance*** | | 1.8 | 2 | 2.2 | 2 | 4 | 4.6 | 3.3 | 2.1 | 1.8 | 1.8 | ⋮ | | | | | | | | | |
| | ***Relative importance (%)*** | | 4.7 | 5.2 | 5.7 | 5.4 | 11 | 12 | 8.8 | 5.5 | 4.8 | 4.8 | | | | | | | | | | |
| | ***Ranking*** | | 10 | 7 | 4 | 6 | 2 | 1 | 3 | 5 | 9 | 8 | | | | | | | | | | |
| | ***Competition analysis of technology*** | | | | | | | | | | | | | | | | | | | | | |
| | Product in study | | 250 | 50 | Y | 3 | Y | 100 | 20 | 1 | 3 | 3 | | | | | | | | | | |
| | Competitor A | | 200 | 50 | Y | 1.5 | N | 200 | 16 | 1 | 3 | 3 | | | | | | | | | | |
| | Competitor B | | 400 | 300 | Y | 5 | Y | 300 | 36 | 1 | 3 | 3 | | | | | | | | | | |
| | ***Target specification*** | | 400 | 300 | Y | 4.8 | Y | 150 | 24 | 1 | 3 | 3 | | | | | | | | | | |
| | ***Technical difficulty to reach target (1-5)*** | | 2 | 3 | 3 | 1 | 4 | 4 | 3 | 3 | 3 | 3 | ⋮ | | | | | | | | | |

| ***Correlation matrix*** |
|---|
| Strong correlation (9) |
| Ordinary correlation (3) |
| Weak correlation (1) |

Figure 7. QFD excerpt for a gear-rolling tester

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*3.2.2 List of requirements*

The QFD method, a technique related to Design for Quality, was used to establish 34 requirements of the machine based on 28 customer-needs raised by ECM. Quantification of the relationship between them, together with comparison with competitors and developments in relation to the current situation of the machine at ECM, allowed us to establish an order of priority for selection purposes. Figure 7 shows a QFD based on the main requirements considered during the machine retrofit. The three main factors were cost (12%), customised software (10.7%) and delivery lead-time (8.8%). Additional items identified as important requirements (from 3% to 6%) included those linked to the performance of tests in accordance with legislation, along with measuring accuracy and machine capacity, the worm gear mounting, drive torque, displacements and rotations.

*3.2.3 Retrofit decision*

Once the status of the machine was defined, it was drawn up a checklist. In this case, the subassemblies and components of the original gear profile tester could not be reused because their operation was based on different measurement principles. Neither the drives and measuring instruments nor the electrical system could be used. Then, using an initial 3D model based on main-dimension readings, the team project determines that the risk of an internal update could be assumed, since there was enough knowledge and capacity, reducing it by up to 50% compared with subcontracted proposals.

*3.2.4 Alternatives and selection*

Four possible conceptual design alternatives were developed according to the list of requirements and based on the ECM's existing machine. They follow some premises: the design had to be adapted to the geometry and dimensions of the existing bench and its manual drives; the orientation of the worm had to be horizontal (as its dimensions did not make a vertical position feasible); vertical positioning displacement was not to be carried out by the worm gear assembly (on account of being too complex); it was necessary to include, with the appropriate precision, two rotating movements (one for each gear), one vertical displacement and another main horizontal (plus one secondary) movement.

FMEA analysis was used to determine the possibility of failures likely to affect the reliability of measurements. A decision matrix was used to select the best alternative (Figure 8), being all of them very similar. In fact, the determining criteria amounted to very small nuances, such as the master worm having to complete fewer displacements to reduce sources of error, or the centre of gravity of the subassembly having to be centred up as far as possible during the test. Finally, design alternative “d” was selected.

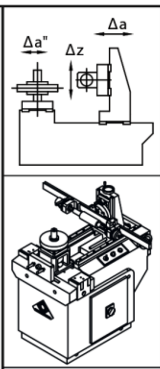
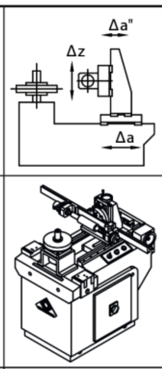
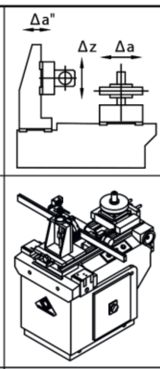
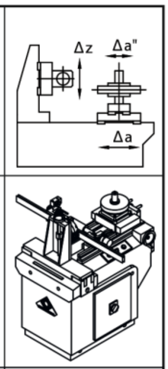
| **Criteria (1-5)** | **Weight (%)** |  Alternative a) |  Alternative b) |  Alternative c) |  Alternative d) |
|---|---|---|---|---|---|
| Test's repetibility | 15 | 5 | 5 | 5 | 5 |
| Stability | 10 | 4 | 4 | 5 | 5 |
| Master gear displacements | 10 | 3 | 2 | 3 | 4 |
| Easy gears mounting | 10 | 4 | 4 | 4 | 4 |
| Accessibility | 10 | 3 | 3 | 4 | 4 |
| Security | 10 | 3 | 3 | 4 | 4 |
| Adaptability | 10 | 3 | 4 | 3 | 4 |
| Similarity with other rolling testers | 5 | 5 | 5 | 5 | 5 |
| Cost | 15 | 4 | 4 | 4 | 4 |
| Lead time | 5 | 4 | 4 | 4 | 4 |
| **Weighted total** | 100 | 3,80 | 3,80 | 4,10 | 4,30 |
| **Raking** | | 3 | 3 | 2 | 1 |

Figure 8. Decision matrix of the design alternatives

*3.2.5 Development of the design*

The GRT was structured in three main elements (Figure 9): the bedplate, the worm holder column and the worm gear holder carriage. The worm holder column, which maintains a fixed position, is at one end of the bedplate. This column incorporates an adjustment mechanism for both the height and angle of the worm shaft. It is equipped with a crosspiece that can move freely between the driving spindle and tailstock to allow the fitting of worms of different length. The worm gear holder carriage on the other side, which positions the gears at the nominal centre distance, is operated manually via a handwheel and threaded spindle. It is also fitted with an upper carriage, which provides the shuttle movement needed to double-flank test. The latter engages with a high-precision spindle with angular encoder and adjustable brake, as required for single-flank test, where the worm gears are positioned during tests.

As the project concerned a one-off precision product, it was important to ensure that the components were reliable and hard-wearing, with dimensions and geometries designed to facilitate – as efficiently as possible – manufacture, assembly and, above all, commissioning. The principles of embodiment design were therefore applied to the development of each item, along with the Design for Manufacturing and Assembly guidelines (Pahl et al. 2007; Ullman 2010) and those of Robust Design (Ebro and Howard 2016), all with the objective of Design for Precision. The following section contains some examples of how they were applied to the GRT upgrade.

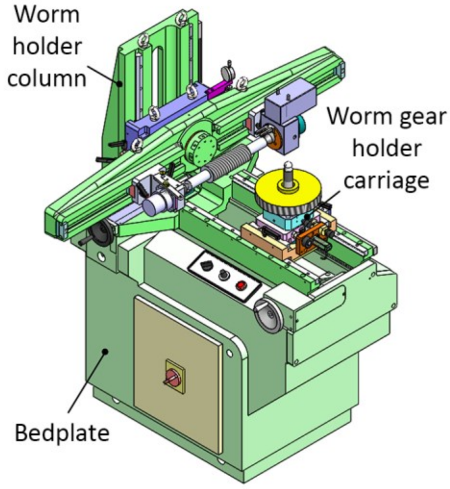



Figure 9. GRT structure

1) GRT structure

The principle of division of tasks for distinct functions was applied, as can be seen in the main structure of the tester. When it comes to precision machines, the functions of each element should take place independently. This prevents sources of error affecting the other elements, while guaranteeing repeatability for each individual system. We therefore opted for a modular design that let us expand measurement capacity to include gears of other types, even allowing for future upgrades of the equipment without affecting the remaining systems. The crosspiece, for example, is mounted on a large-diameter shaft fixed to the vertical carriage, thereby allowing the attachment of any other type of accessory that might be required for the movement concerned (Figure 10a). Another example is the shaft of the worm gear mounting, which constitutes a subassembly independent of the horizontal displacement of the centre distance (Figure 10b).

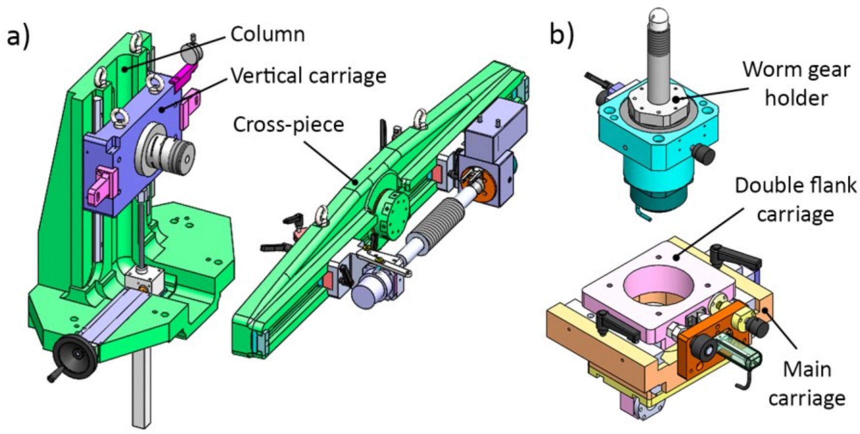



Figure 10. Module-compatible design: a) Crosspiece independent of the vertical carriage; b) Worm-gear holder subassembly independent of the horizontal carriage

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2) Carriage displacements

The principle of fault-free design was applied to the displacements of both the worm gear holder carriage and the vertical carriage. The incorporation of an adjustment system for the linear guides, using grub screws designed to eliminate backlash, allowed for better assembly with lower machine-part tolerances (Figure 11). This allowed us to optimise cost and time considerations in what is one of the key parts of the machine. The design itself was also subject to the "direct and short force transmission path" principle, given that the thrusting movement of the carriages was centre-aligned.

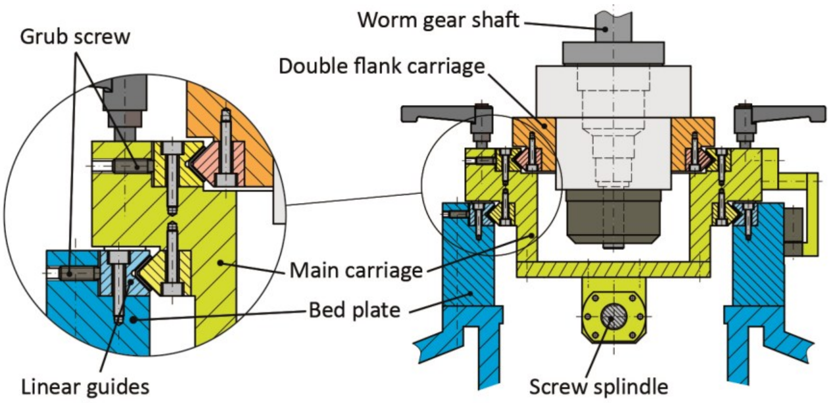


Figure 11. Principle of fault-free design applied to assembly of the high-precision linear guides

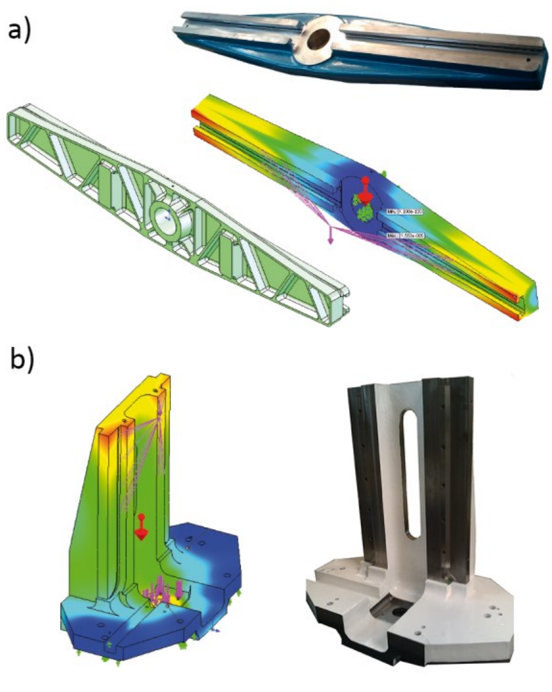


Figure 12. Example of cast-iron parts: a) Crosspiece; b) Column

3) Special components

The column and the crosspiece were two important pieces at the design stage. Their large dimensions obliged us to perform an analysis by means of finite elements to ensure their rigidity. There were manufactured in cast steel using an expanded polystyrene (EPS) model designed to ensure their stability over time. It is for this reason that their design took into account the main guidelines applying to cast components; namely open cross-sections, tapering from the dividing line, uniform thicknesses (with gradual changes where applicable), proper orientation, and support surfaces designed for easy re-machining at a later date, etc. (Figure 12).

4) Robust design principles for reducing variation

The driving-spindle and tailstock supports were matched and machined at the same time to ensure accurate assembly, and so that both items are at the same distance from the supporting face at the centre of the stock (Figure 13a). The elastic two-flank testing system was also designed to be interchangeable and adjustable to the ideal size of spring, as regulations did not clearly define the most-appropriate amount of force for worm gears of larger dimensions (Figure 13b). The fail-safe principle was furthermore applied by adding a manual lock to the carriages to fix them in position during tests, even though the thrust systems were free of backlash (Figure 13c).

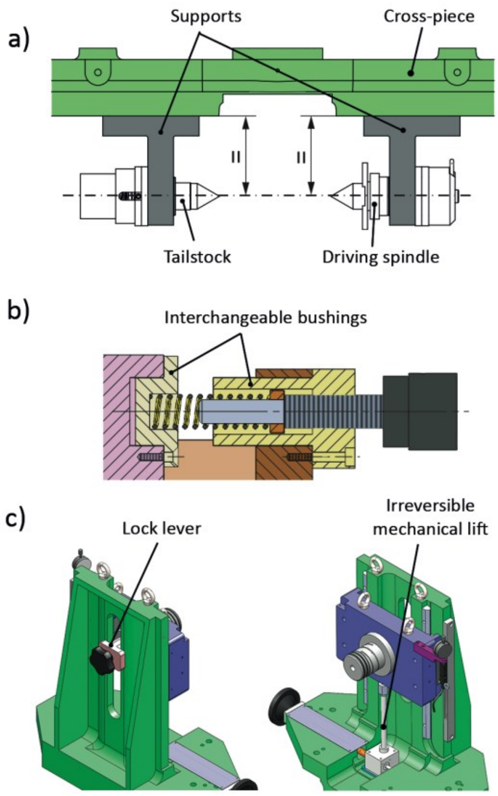


Figure 13. Examples of the principles of robust design: a) Duplicate machining of the driving-spindle and tailstock supports; b) Interchangeable bushings to vary the sizes of spring of the double-flank test elastic system; c) Fail-safe locking mechanism to guarantee correct positioning

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*3.2.6 Assembly and validation testing*

After the Design and Manufacturing Phases, the monitoring plan envisaged dimensional and geometric verification of components, as well as the checking of clearances to ensure the correct functioning of subassemblies. This allowed us to correct minor manufacturing defects. The piece of equipment was completely assembled, including drives, encoders and PC connections.

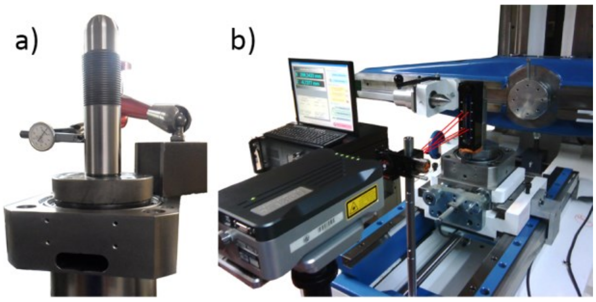


Figure 14. a) Verification of eccentricity; b) Calibration using laser interferometry

The validation of measuring of this machine tool was develop using the standard of calibration procedures of Gear Measuring Instruments (GMI) and Coordinate Measuring Machines (CMM), as there are no specific regulations to cover this type of testing (Pueo et al. 2017). First, the eccentricity of the axes, the squareness between them and the displacement guides were verified and adjusted (Figure 14a). Then, a laser interferometer was used to calculate movement errors and carry out numerical compensation for the operating software (Figure 14b). Finally, after calibrating, a series of repeatability tests were carried out, which allowed us to characterise the performance of the machine and validate its accuracy in compliance with the established requirements.

*3.2.7 Redesign*

Excessive eccentricity in the rotation of the drive spindle was detected during operating trials, which produced errors in the test results. Checks were carried out to verify whether dimensions, tolerances and component assembly matched the information in the plans. We eventually came to the conclusion that the design being applied, which was based on ECM's existing machine, was insufficiently precise for larger worm drives. The solution entailed the drafting of a new design with a configuration similar to that of the worm gear support shaft, which included the fitting of tapered roller bearings (Figure 15).

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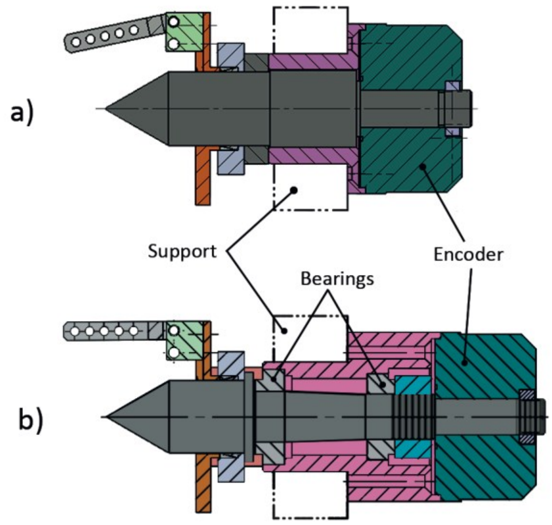


Figure 15. Example of a redesigned drive spindle: a) Initial design without bearings; b) Definitive design with greater accuracy

**4 Conclusions**

The upgrading of manufacturing systems is becoming more and more common in companies of all types, regardless of their size or industrial sector, especially for SMEs. It is generally due to the fact that it entails greater control of development risk, and that it implies less investment. The engineers responsible for these upgrades nevertheless have to tackle the designing of a one-off product, and their lack of experience in design methodologies and techniques may hinder the success of the development, despite their familiarity with the problem and its possible solutions.

Currently, there is no a design methodology for the upgrading of manufacturing systems carried out in-house by an SME. This paper proposes a specially adapted and simplified methodology that is nevertheless rigorous in its approach to development. This methodology does not deliver an absolutely optimum outcome, but rather a functional design that meets the essential requirements and which is best adapted to time and cost considerations. However, the fact that it is systematic helps the engineer in charge not to overlook any of the key steps involved. At the same time, recommendation of the most-appropriate and simplest techniques facilitates the work of engineers and helps them to appreciate the usefulness of design methodologies in an industrial environment.

The methodology has been validated experimentally with the upgrading of a gear-rolling tester installed on the premises of an SME that manufactures gears. It followed, step-by-step, the detailed information imparted by the methodology. Those involved used the recommended techniques and tools in an orderly manner, despite their lack of previous experience of development projects of this type. The authors through control sessions checked the methodology's development and implementation. In the closing session, participants admitted that the methodology had helped them to meet deadlines because tasks were clear and precise. The feedback confirmed that they had not forgotten any important point of the retrofit process.

This case study results in a system with special features for the rolling verification of gears, which includes all the initial design requirements. This experience raises the possibility not only of ECM carrying out another in-house upgrade in the future, but of it tackling upgrades of similar machines as a service for other companies in the sector. Authors also suggest that it could likewise be used in certain technological developments by small research groups in the engineering sector, which normally reuse components from previous studies.

As future research directions, authors propose to standardize the use of the methodology by means of software, design repositories and different tools templates that could simplify its implementation in SMEs. Furthermore, it would be interesting to deploy the methodology on different retrofit types and complexities in companies of diverse sizes and sectors. This would allow a quantitative and global validation of the methodology in terms of the time and cost related.

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