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Efficiency improvement of product definition and verification through Product Lifecycle Management

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Abstract

The correct and complete geometrical definition of a product is nowadays a critical activity for most companies. To solve this problem, ISO has launched the GPS, Geometrical Product Specifications and Verification, with the goal of consistently and completely describe the geometric characteristics of the products. With this project, it is possible to define a language of communication between the various stages of the product lifecycle based on "operators": these are an ordered set of mathematical operations used for the definition of the products. However, these theoretical and mathematical concepts require a level of detail and completeness of the information hardly used in usual industrial activities. Consequently in industrial practice the definition and verification of products appears to be a slow process, error-prone and difficult to control.

Product Lifecycle Management (PLM) is the activity of managing the company's products throughout their lifecycle in the most efficient way. PLM describes the engineering aspects of the products, ensuring the integrity of product definition, the automatic update of the product information and then aiding the product to fulfil with international standards. Despite all these benefits, the concepts of PLM are not yet fully understood in industry and they are difficult to implement for SME's.

A first objective of this research is to develop a model to depict and understand processes. This representation is used as a tool during the application of a case study of a whole set of a GPS standards for one type of tolerance. This procedure allows the introduction of the GPS principles and facilitates its implementation within a PLM process.

Until now, PLM is presented on isolated aspects without the necessary holistic approach. Furthermore, industry needs people able to operate in PLM context, professional profiles that are not common on the market. There is therefore an educational problem; besides the technical knowledge, the new profile of engineers must be also familiar with the PLM philosophy and instruments to work effectively in a team. With the aim of solving this problem, this thesis presents a PLM solution that gives the guidelines for a correct understanding of these topics.

KEYWORDS: PLM, GPS, geometrical specification, model, verification.

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Introduction

PLM Product Lifecycle Management (PLM) is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it's retired and disposed of [1].

In order to keep track of the product, PLM manages all the information about it, including: items, documents, and BOM's, analysis results, test specifications, environmental component information, quality standards, engineering requirements, change orders, manufacturing procedures, product performance information, component suppliers, and so forth [2]. And not only, PLM must guarantee access to the right version of this information to the right people.

Technological advanced companies around the world are using PLM to run its business, while smaller ones will sooner or later will be required to do the same specially if they are part of the supply chain.

The PLM has proved to be an instrument of success during the Product Development Process. Nevertheless, most of the companies usually outsource the PLM implementation to software vendors and consultancy firms that hence administrate their internal processes. Such a cost cannot be afforded by Small and Medium Enterprises (SMEs). These, however, are strongly motivated by their major partners/clients to join their PLM systems and somehow understand that their internal processes would benefit too. Chapter 1 presents the theoretical framework of the current situation, the statement of the problem and the methods used during the development of this thesis.

Currently, the geometric definition of products, a key concept for manufacturing trade, is integrated in the information system of the firms. For the last 40 years the American standard ASME Y14.5 [3], Geometric Dimensioning and Tolerancing (GD&T), has provided the fundamentals for specifying and interpreting engineering drawings. However, its deficiencies are increasing with respect to the needs of the modern high precision industry [4].

Geometrical Product Specification and Verification (GPS) is a renovation of the GD&T language so that it can be better supported by mathematically well founded principles [5]. The innovative principles of the GPS undoubtedly create changes to the organization and mainly to the information system. Chapter number 2 gives an overview of the state of the art of GPS and PLM.

In order to help industry to shift to the GPS approach it is essential a framework to guide industry to implement the new principles. If this model wants to be applied in a PLM structure it must clearly define: the activities that must be done, the roles involved in such activities, the needs of information, the instruments and technology necessaries to achieve the result. This will lead to the optimization of the cost, the minimization of the uncertainty and time during the product definition and verification.

In chapter 3, is presented the Visualization Model (VM). It is a general framework that helps company to understand their processes and to implement PLM. It follows a top-down strategy and uses UML for workflows representation and RUP for graphical representation of tasks.

The aim of the job carried out in the GREAT 2020-Ecoprolab3 project was to transfer the concepts indicated by GPS to the industry by means of a PLM based protocol. For this purpose, it was necessary to examine "product definition and verification" stages of project partners. Through a reengineering process there were identified, evaluated and (eventually) implemented improvements. Chapter 4, presents the case study application of a whole set of a GPS standards for one type of tolerance and, and using the VM as a tool, the representation of the process. Finally, its implementation into a PDM software.

The complete result of this work is expected to drive the actions and the choices of designers, engineers and metrologists providing the right information to the right people at the right time in a GPS framework.

As stated before, PLM is the business paradigm that companies are employing as a key of success. From the experience acquired during the development of the GREAT 2020 project, there is a strong need of training people to work in a collaborative environment as PLM. The new profile of engineers must have the solid technological backgrounds as before and, in addition, they must be prepared to work in (international) teams. The issues at stake are the skills of collaboration and communication that are increasingly more valued by employers [6]. Through a pilot group, presented on chapter 5, the author tested the innovative contents of PLM as a support to the industry.

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Chapter 1. Research proposal

1.1 Theoretical framework and state-of-the-art

Nowadays, companies operate over several continents. A designer in one country can specify a product that is then made in another and probably assembled yet in another. Furthermore, the worldwide business environment is marked by an increase in the use of out-sourcing and sub-contracting.

Globalization of markets and augmented consumer sophistication have led to a rise in the variety of products that customers demand and a consequent growth in the number of variants of any given product line that a manufacturer must supply [1]. There is also an increasing demand for outstanding functions of workpieces at an economic price [2].

Organizations communicate routinely to and from their supply chain and within their own organization. Most of the information is created, stored and share as electronic files [3, 4]. An example on this is the extensive use of CAD/CAM-system in industry; it has become an important and widely used technology. Companies have invested large amounts in the systems and are becoming very dependent on CAD technology for the development of new products [5]. These circumstances have change, in recent years, the traditional communication channels in industry.

Companies need to communicate product design and manufacturing information in a reliable and unambiguous manner. Global manufacturing rely more than ever on international standards to assure trade and there is a strong need of Information Technology (IT) solutions in order to guarantee the correct distribution of the information.

In such a global market, Product Lifecycle Management (PLM) is the only stable means of communication. PLM deals with the creation, modification, and exchange of product information throughout the product's lifecycle [6]. PLM is an essential tool for coping with the challenges of more demanding global competition and ever-shortening product and component lifecycles and growing customer needs [7].

PLM is not just a technology, but is an approach in which processes are as important, or more important than data [8]. In other words, PLM is not a software solution, as many think, instead it is a business strategy enabled by the use of PDM (Product Data Management) software. PLM utilizes multiple types of technologies and methods, and it intersects with many technologies and methods.

According to different authors in different industry fields [9-15], the benefits of PLM focus around time, cost and quality. These benefits include:

- Faster time-to-market
- Improved cycle times
- Fewer Errors
- Less scrap & rework
- Greater productivity
- Greater Design efficiency

- Better product quality
- Decreased cost of new product introduction
- Insight into critical processes
- Better reporting and analytics
- Standards and regulatory compliance
- Improved design review and approval processes
- Improved communication
- Reduced product cost and greater profitability
- Better resource utilization

One of the principals aims of the Geometrical Product Specification and Verification (GPS) is to understand the role of uncertainties in the management of product information, thus in the Product Lifecycle Management (PLM).

During the Product Development process, the designer describes a part through an engineering drawing [16]. Engineering drawings need to be language-independent so that any person working on that product can understand the information. Moreover, it is not enough to make technical drawings 'that can be understood'. The designer must make drawings 'that cannot be possibly misunderstood [17].

A complicated component may consist of tens of parts, each part may contain several to dozens of geometrical features and every feature may be defined by a couple of geometrical specifications [18]. During the Product definition and realization, the product specification is shared by designers and used by manufacturers to produce the part; then by metrologists, during verification, to create measurement programs and analyze results. The management of information is further complicated by the need to handle the specification revisions that will occur along the product lifecycle.

Currently, the geometric definition of products, a key concept for manufacturing trade, is integrated in the information system of the firms. For the last 40 years the American standard ASME Y14.5 [19], Geometric Dimensioning and Tolerancing (GD&T), has provided the fundamentals for specifying and interpreting engineering drawings. However, its deficiencies are increasing with respect to the needs of the modern high precision industry [20].

GPS is a renovation of the GD&T language so that it can be better supported by mathematically well founded principles [21]. In the GPS framework, the specification gives the mathematical rigor by being defined through operators and operations.

The GPS standards assure the unambiguous and unique definition of geometrical specifications during product design and verification. Nevertheless, it cannot guarantee the correct access to the exact version of the information regardless of the circumstances.

In the aerospace and aeronautic market, the complexity is not only about mechanical parts. Many companies spread around the world usually cooperate on the same product, leading to an intricate network of information exchange. For this reason, it is important not only to make the GPS principles usable, but also integrate them into each company's operative information flow.

A cooperative environment, as the one described above, could be the real work conditions that any student will find after leaving the university. Every future engineer, especially if working in the product development process, will need to use and understand engineering drawings and must be able to work in a team. Therefore an educational training to understand and work on a PLM environment is needed. It is essential that higher-level universities include the innovative aspects that industry is requiring, into their educational programs.

1.2 Statement of the problem

Currently, specification inadequacy is the Achilles heel for many of today's technologically advanced companies [22]. Specifications errors are propagated to other views of the product: product planning, manufacturing, quality control and inspection [23]. The later the drawing error is identified, the more it will cost.

In the modern industrial environment, the specification process is to "translate the design intent into requirement(s) for specific GPS characteristics" according to ISO/TS 17450-2 [19]. According to the ISO TC-213 the implementation of GPS:

- Reduce costs by avoiding the manufacture of inadequate workpieces due to incompletely defined specifications.
- Assure a continuous improvement of product quality and time to market.
- Enable optimum economical allocation of resources amongst specification, manufacturing and verification.

GPS standards define a language based on operators, which are ordered sets of mathematically defined operations used in the full definition of workpieces along their whole lifecycle.

Nevertheless, the standard by itself is of little use, its utility depends on industrial adoption [24]. GPS standards are available in ISO since 1996 but their application in industry is limited to specific cases, most of them are case study developed in research centers with the objective to evaluate the advantages of the GPS approach.

Some GPS concepts are now part of the cultural background of many designers, engineers and metrologists, but there is no evidence in the scientific literature that a complete GPS compliant system has been applied in any enterprise or university. In spite of the large amount of work and study devoted to the realization of a complete, coherent and reliable solution for the control of product shape, such result has not being achieved yet.

In industrial practices, the theoretical mathematical concepts of GPS often leave the way to faster simplified verification operations. This situation leads to incomplete information and to an increase of uncertainties. The final product often is very far from the customer's needs.

There is also a lack of correlation between design and verification stages. Each department works on a product until they had completed their tasks and then they hand it off to the next department. Few or any interaction is held during the product development.

Moreover, the communication in and out of the company is based on the use of computers. This information is stored and managed in the form of files that anyone can change and share by e-mail. The consequences of this practice are: a great confusion among project participants; loss of information; errors and redundancy.

Undoubtedly, GPS-based activities encompass the production of a great amount of information shared by different roles within the organization. A better definition of the product means also a better communication between all departments. This tighter control of the information can be achieved only by using a technology that integrates all product related data and processes.

The PLM paradigm provides a solution for information management issues and the development of a PLM model that supports the geometrical controls according to the GPS approach seems a promising solution.

PLM can significantly reduce non-value added activities during product definition while, at the same time, ensuring the correct distribution of the information to the others stages of the product lifecycle. It also guarantees the concurrent solution of problems and thus decreases discrepancies between design requirements and real products.

However, PLM is not a solution for all companies. PLM compels a high maturity level, technical resources and, in some cases, inversions. By definition PLM integrates product information, people and knowledge by controlling the company's processes. Yet, it is not clear which are the steps that an enterprise must follow in order to successfully control the product information.

PLM is primarily used in automotive and aerospace industries followed by machinery industry [25]. These industries are the only ones that have gained knowledge in PLM in the past years. Even though, this firms usually outsource the PLM implementation and maintenance to software vendors and consultancy firms that hence administrate their internal processes.

This is happening due to the complexity of PLM processes. It is said that you cannot improve something you have not measured; in the same way, you cannot control the information that you are not able to see. In the intricate network of processes is not clear who is doing what, when, how and which are the tangible results of tasks.

SME (Small and Medium Enterprises) are not able to afford the costs of PLM consultancy and they think of PLM as something targeted only for large companies.

In brief, the concepts of PLM are not yet fully understood in industry and they are difficult to implement for SME's.

The following research questions should be answered in this thesis:

Towards GPS:

- Can we achieve the level of detailed information required by GPS?
- Is it possible to integrate GPS in a PLM paradigm?

Towards PLM:

- It is possible to present graphically a PLM process?
- How can we help industry, and specially SME's, to implement PLM?

1.3 Research aims and objectives

This thesis aims to build a model that gives companies the fundamental understanding of the GPS principles by facilitating its implementation in a PLM environment. In order to help GPS dissemination in industry, this thesis should answer to some specific goals (SG):

- (SG.1) To establish the state of the art of the Geometrical Product Specifications and Product Lifecycle Management;
- (SG. 2) to develop an instrument for visual representation of PLM;
- (SG. 3) GPS implementation in a PLM business; and
- (SG. 4) a PLM solution as a support for the industry.

1.4 Methods and procedures

A single method cannot serve to all specific goals. For this reason different procedures are used to solve every SG.

SG 1. The state of the art is based on a qualitative descriptive research. The literature review provides a detailed outline on GPS and PLM. The research includes the analysis of books, journal articles, proceedings and white papers. In the case of GPS, the study includes the examination of the chain of standards under the direct responsibility of the ISO-TC 213.

SG 2. Concerning the definition of an instrument for visual representation of PLM, a top-bottom strategy is chosen. With the aim of getting a general PLM framework, this work establishes first, a classification of the main states of a product lifecycle. Inside each lifecycle state there are a series of processes with similar goals that are grouped in Process Areas (PA). A PA is a sequence of operations that can be depicted in a Workflow that follows UML rules. For a better understanding of every single operation of the workflow, it is necessary a Decomposition Diagram (DD). The DD is the partitioning of an operation into its component functions. The DD describes what is to be produced (Items), the necessary skills required

(Skills), the responsible of the operation (Role) and the step-by-step explanation describing how specific development goals are to be achieved (Activities).

SG 3. The implementation of the GPS on a PLM framework follows the method proposed by Stark [26]:

- Better understand the product lifecycle;
- Better understand the processes and activities across the lifecycle;
- Define the roles in the product lifecycle;
- Define information needs;
- Use a Product Data Management system effectively throughout the lifecycle.
- Train people to work effectively in a lifecycle environment;

The information about GPS processes comes from the GREAT 2020-Ecoprolab 3 Project. Product definition and verification processes of project partners are analyzed by means of a case study. The Visualization Model is used as a tool to represent the processes.

SG 4. The PLM solution as a support for the industry is developed within the frame of academic course. The innovative concepts of PLM are tested with a small group of students of the faculty of Automotive Engineering of Politecnico di Torino. The selection of a case study following FIAT rules allowed the evaluation and selection of contents.

1.5 Research scope and limitations

The natural scope of the Geometrical Product Specification and Verification sets the boundaries of this work. This thesis deals primarily with the process areas of: Product Requirements, Detailed Design and Product Testing. In these three areas major attention is devoted to the product information. Process information is envisioned as a further development.

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Chapter 2. State of the art

2.1 GPS

Nowadays, the GPS language is still in a state of dynamic change and continuous improvement [1]. While the main framework has already been drawn, innovative principles are still being studied by the ISO experts, academics and industry [2].

Standards for the specification and verification of product geometry form some of the earliest standards of the industrial age [3]. In order to achieve the consistency of information throughout the different phases of product development, the ISO/TC 213 is defining a new technical language completely based on mathematics. Such a language enhances the GD&T approach, preserving the semantics of geometrical tolerances while adding more prescriptions aimed at guiding the verification procedure. The breakthrough point with respect to GD&T is that these prescriptions are not provided aside the tolerance cartouche, but become part of the tolerance semantics: they are embedded in it by means of a detailed operation-based description, which sets clear limits for the interpretations and becomes a guideline for a proper verification [4].

2.1.1 GPS Masterplan

The Masterplan of GPS program [5] collects most of the fundamental concepts. The General GPS matrix (Fig. 1) represents the tolerances available in mechanical design; the rows contain the different tolerance types and the columns contain the six main steps needed in tolerance definition. Each cell defines a concept/activity involved in tolerance management and should be covered by one and only one ISO standard in the GPS program [5].

The GPS approach recognizes the existence of three different environments in product shape definition: the nominal model which is composed of ideal surfaces and is illustrated on drawings [18]; the skin model which takes into account the geometrical errors described by tolerance callouts; the physical model resulting from the application of a measurement process on the physical workpiece (Fig. 2).

There is a natural correspondence between the activities developed on the skin model by the designer and the activities carried out by the metrologist on the physical workpiece [18,19]. Such duality principle allows for the comparison of requirements defined in the specification phase and the measurements carried out in the verification phase (Fig. 3).

	1	2	3	4	5	6
	Product documentation indication	Definition of tolerances	Definition for actual features	Assessment of worpiece deviation	Measurement equipment requirements	Calibration requirements
Size						
Distance						
Radius						
Angle						
FORM of a line (independent of datum)						
FORM of a line (dependent of datum)						
FORM of a surface (independent of datum)						
FORM of a surface (dependent of datum)						
Orientation						
Location						
Circular run-out						
Total run-out						
Datums						
Roughness profile						
Waviness profile						
Surface defects						
Edges						

Fig. 1 – GPS Matrix

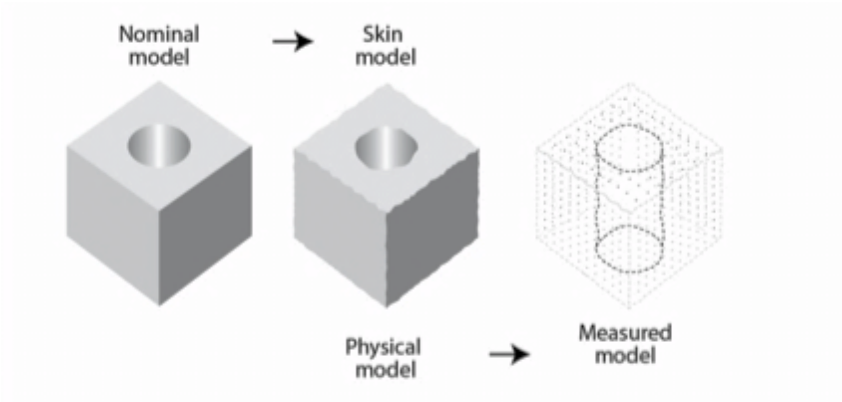

Fig. 2 – GPS Model domains

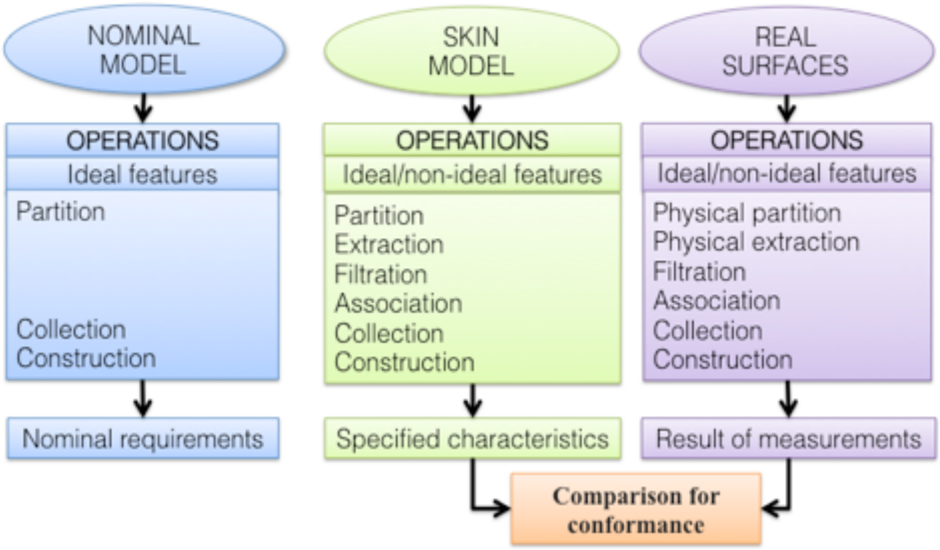

Fig. 3 – Duality Principle

2.1.2 Uncertainty

All the activities developed for the control of product shape in the specification and verification phases are defined by operators that are composed of operations and are affected by uncertainty [19]. A good geometrical control provides the lower total uncertainty given the available economical budget (Fig. 4).

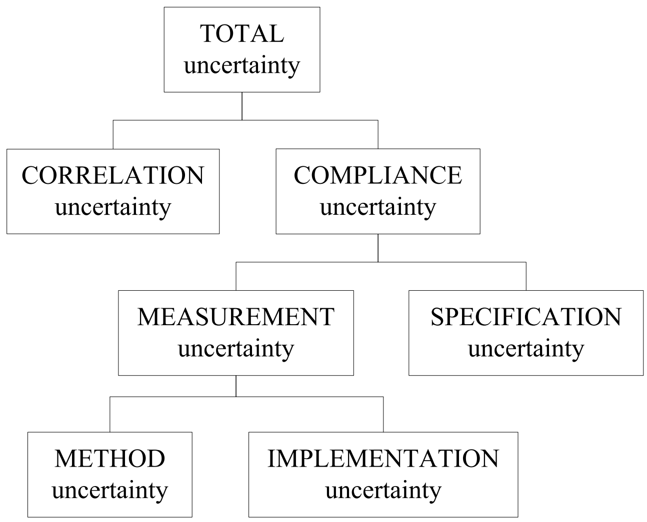

Fig. 4 – Composition scheme for the GPS uncertainty contributions

The total amount of uncertainty is composed by:

- Correlation Uncertainty: Incorrect or incomplete relationship between intended functionality and geometrical control specification.
- Compliance Uncertainty:
  - Specification Uncertainty: Incorrect or incomplete geometrical product definitions that could lead to ambiguities.
  - Measurement Uncertainty:
    - Method: differences between specification and verification operator.
    - Implementation: standard deviation of measurement process.

The GPS language looks at products on a perspective that is broader than that of GD&T, going further the definition of geometrical specifications and compliance verification [6]. The final aim of a workpiece is to perform a function (on its own or in the assembly of a more complex machine), therefore a proper assessment of its quality has to consider the consistency of the actual workpiece geometry with the functionality it is designed and demanded to satisfy. Though it may seem to be a nuance, this is a breakthrough point with respect to GD&T. It gives birth to a series of uncertainty contributions that join the consolidated concept of measurement uncertainty in order to consider also the completeness and unambiguity of specifications (specification uncertainty), the capability to state the compliance of geometry with respect to the geometrical specifications (compliance uncertainty) and the adequacy of the geometrical specification to guarantee the functional needs (correlation uncertainty) [7]. All these uncertainty contributions participate in the total uncertainty, which describes the adequacy of the actual (measured) feature to guarantee the intended workpiece functionality, according to the scheme presented in Fig. 4.

Moreover, GPS standards provide us a decision rule to test if the measured feature is compliant with specifications [8]. The result of a measurement (y), and an error evaluation, is completely defined only when it is stated together with its uncertainty (U). So, it can be represented as an interval (y').

In order to have a feature certainly compliant with specification, the measurement interval must be completely included in the specification interval. If it is completely outside the feature is certainly out of specification. But what happens if it partially covers one of the specification limits? It cannot be stated neither its compliancy, nor its non-compliancy.

In this case standards say that uncertainty of measurement always counts against the party who is providing the proof of conformance or non-conformance and therefore it goes against to who is making the measurement. This guarantees that the measurement is performed in the best way.

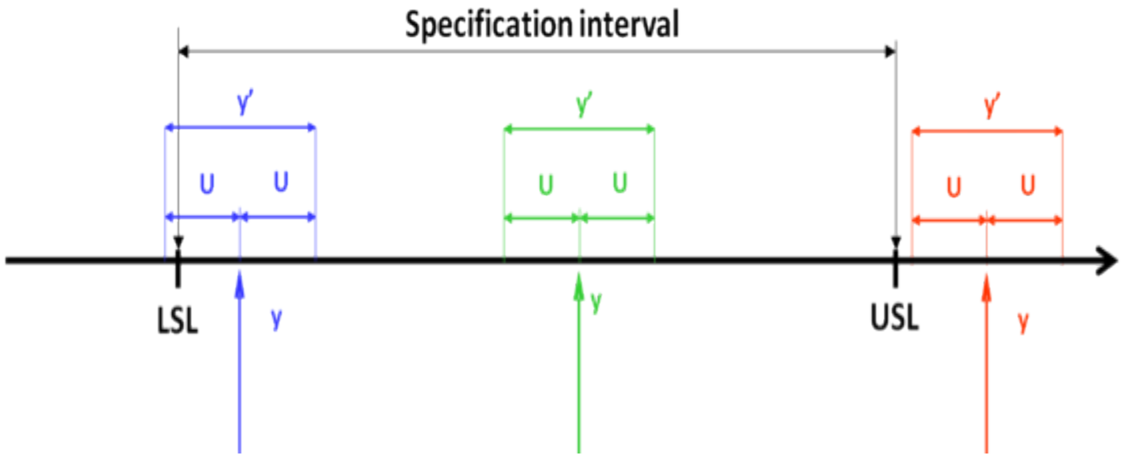

Fig. 5 – Decision rules for proving conformance or non-conformance

2.1.3 Fundamental operations

The GPS language is based on seven operations that can be combined in operators to define geometrical specifications and verification procedures (Fig. 3). According to the duality principle [7, 9] these operations are defined by the designer on the skin model (a mental representation that is used to imagine the deviations from the nominal geometry that could be introduced by manufacturing processes), registered in the tolerance callout, and then replicated by the metrologist during verification procedures on the real workpiece. Verification operations are labeled perfect if compliant with the specification operators, simplified if they intentionally introduce some deviations. For a thorough description it is recommend the reading of ISO/TS 17450-2 [7], while a graphical example of the operations necessary for defining and verifying a flatness specification (tolerance) is given in Fig. 6. In the order, the operations consist of:

- Partition: isolation of the feature to which the specification refers to.
- Extraction: acquisition of the information necessary to define the feature characteristics. In the case of Fig. 6, it is a measurement where the distance between sampling points is minor than 0.357 mm in order to comply with the filter cut-off wavelength [10].
- Filtration: elaboration of measurement results in order to separate the content of deviation to which the specification refers to. Only the error components with a wavelength greater than 2.5 mm are to be considered for the assessment of the flatness deviation.
- Association: a nominal flatness feature is fitted to the filtered measurement points according to the specified association criterion (Minimum Zone).
- Evaluation: operation that returns the value of flatness deviation as the maximum distance of the filtered measurement points from the associated nominal feature.
- Collection and Construction: these operations, not represented in Fig. 6, are used to identify and consider together some features which jointly play a functional role (e.g. symmetry plane of two flatness features), and to build ideal features starting from other ideal features (e.g. a line defined as the intersection of two nominal planes) respectively.

After the verification operator has been implemented, the compliance with specifications can be assessed by comparing the results of the evaluation operation against the geometrical specification, according to the default rule provided by ISO [11] or to different agreements between customer and supplier.

However, in the fundaments of the GPS language, there is the awareness that some uncertainty arises anytime the product information is exchanged between two parties or when it comes to cope with the limits of real measuring instruments, which represent the only window through which we can know the actual shape of workpieces. The operation-based formalism allows a consistent definition of specification and verification operators, a substantial improvement of the workpiece data management, and the minimization of the uncertainty related to the possible interpretations of geometrical specifications (drawings become more prescriptive)

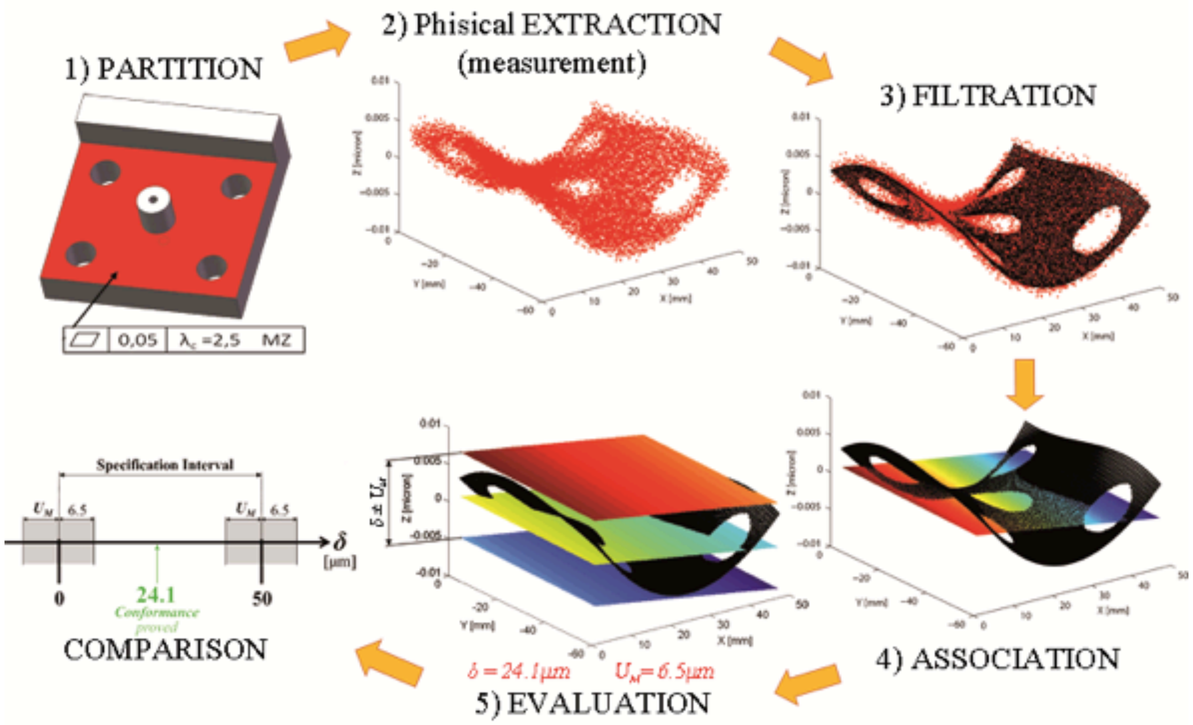

Fig. 6 – Operations that define a verification operator fully compliant with specifications

The different terms of uncertainty presented above are powerful estimators of the quality of each instant of the product lifecycle, starting from the first phase of design until the verification prior to delivery. Hence, if they are quantitatively estimated, they can become the currency for an effective product management [2]. E.g. a high specification uncertainty means that more efforts should be concentrated on the design phase while a too high measurement uncertainty underlines a verification process that is too poor for the job purpose.

2.1.4 Problems of GPS

The work of the ISO Technical Committee 213 (ISO/TC 213) on Geometrical Product Specification and Verification (GPS) started in 1992 as a modernization and improvement/evolution based on more than fifty years of industrial drawing and tolerancing practice [12].

The aim of TC-213 is to provide tools (the GPS technical language) for the economic management of variability in product and processes. Proper implementation of the GPS concepts will enable optimum economical allocation of resources amongst specification, manufacturing and verification [13]. The GPS language starts from the GD&T standards, which have proved to be vital for the correct and efficient verification of mechanical engineering designs [14], to enhance the mathematical foundations and introduce an operation-based representation of specification and verification procedures. Finally, it uses the concept of uncertainty for quantifying the system efficiency and identifying the process areas on which to focus investments or reduce costs.

The GPS language is completely based on mathematics, so the first user's impression is usually that of something targeted on academy rather than on industry. This would be a barrier for the standards to be implemented in the industry. Since a standard by itself is of little use, its utility is measured on the basis of the industrial adoption [15], GPS principles need to be encapsulated into user friendly applications to become popular throughout industry.

Product specifications must be read and interpreted at different stages in the product lifecycle [15]. In the actual conditions of global market, these stages usually involve suppliers or clients scattered around the world. Geometrical specifications directly affect every aspect of the product realization (process planning, manufacturing, quality control and inspection), hence the importance of managing the geometrical variations along the whole product lifecycle into an integrated way is evident [16].

GPS ensures the unambiguous declaration of the products geometrical requirements. However, the way this information is created, modified and exchanged is out of its declared bounds. Nevertheless, the GPS approach settles the ground for a Product Lifecycle Management (PLM) system to assess and minimize the uncertainty generated at different steps of product lifecycle. PLM integrates all the information throughout the different phases of a product lifecycle and allows its sharing within and between organizations [17].

While the main framework has already been drawn, innovative principles are still being studied by the ISO experts, academics and industry [2]. At the same time, a similar effort is being devoted to integrate these new principles in the Product Data Management (PDM) practices. The effort is both on a tool level, to deliver software able to handle the new kind of geometrical information, and on an educational level, to spread the concepts on which the GPS relies.

Discipline-specific standards used in engineering are one of the pillars of engineering knowledge in every culture [18]. It is crucial for the industry that their future workers understand and dominate the rules that are essential for the business environment in global manufacturing.

2.2 Product Lifecycle Management

Over the last decade PLM has become one of the key technological and organizational approaches and enablers for the effective management of product development and product creation processes [19]. The management of the life cycle of products and related services is becoming a central factor in the manufacturing industry.

2008 was a record year for the PLM Market. However due to the global economic crisis in 2009 and generally difficult business climate, PLM investments had a decline in growth. The PLM Market has still not fully recovered but it is really uprising again, and that is earlier than expected [20].

PLM no longer simply equals CAD data management and engineering workgroup collaboration. Researches reveals that PLM systems can be used to manage product portfolios, capture customer needs, and integrate nonengineering staff into the product design process, a domain historically dominated by engineers [21].

PLM is currently used by the major companies in automotive and aerospace industries followed by machinery industry [22]. Until recently, PLM solutions were designed exclusively for large, distributed manufacturing enterprises that had the extensive resources required to deploy and maintain them [23].

However, Small and Medium Enterprises (SMEs) are strongly motivated and they are searching to integrate PLM into its business practice. SME's are a massive part of the world economy but a tiny part of the PLM marketplace. In the USA they contribute up to 30% of industrial output, while in countries such as Italy they form up to 95% of the industrial sector [24]. Despite the promises made by some of the largest PLM software vendors, they have not delivered any PLM product to the market of small manufacturing companies. Fortunately, there are open source solutions aimed for SME's as Aras Innovator [25]. Companies can download, install, customize and use the software without any financial obligation to Aras.

PLM solutions deeply impacts the business process and requires the analysis and, if necessary, the re-engineering of the process itself [26]. Whether companies are big or small they need to understand their process to apply PLM.

Nevertheless, the complexity of PLM concepts creates a lack of deep understanding of what it really means in practice [27]. Universities are working in order to fulfill this gap and big efforts in academic and research activities are being held. Some examples of this international efforts are the PACE program [28] and Tempus MAS PLM [29].

In short, PLM is definitely growing as a market, as the kind of industries that are using it and as efforts to understand it better.

2.2.1 What it is?

For years, there has been a lot of confusion around the acronym "PLM". The definitions used by the different players in the sector have often been contradictory and the many acronyms used in industry do not help to have a clear definition [30].

PLM systems have its origins in the product data management (PDM) practices. PDM was a first step for satisfying the needs of information traceability by including more information about the product than just the geometric data [31]. PLM extends PDM out of engineering and manufacturing into other areas like marketing, finance and after sale service and at the same time, addresses all the stakeholders of product throughout its lifecycle [31].

PDM evolved during the 1990's to become PLM, providing decision support at an enterprise level as well as continuing to handle traditional PDM functions [32]. The PLM concept integrates all the information produced throughout all phases of a product's life cycle to everyone in an organization at every managerial and technical level, along with key suppliers and customers [17].

PLM addresses not only to one company but a globally distributed, interdisciplinary collaboration between producers, suppliers, partners and customers. This is why PLM is often thought of as a huge bundle of complex IT tools and applications which support digital design and manufacturing practices in several ways [33]. The IT solutions to support PLM (Fig. 7) results from the integration between enterprise resource planning (ERP), product data management (PDM) and other related systems, such as human capital management (HCM) and costumer relationship management (CRM) [34].

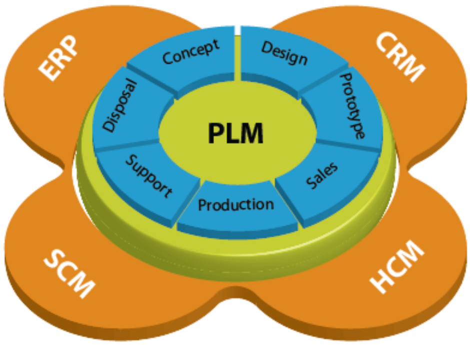

Fig. 7 – IT solution and PLM

Nevertheless, PLM is an integrated approach including a consistent set of methods, models and, only as a third member, IT solution [35]. This approach connects people, information and processes in a PLM system.

PLM systems are tools where PLM concepts are implemented. As such, they need the capability to serve up the information, and they need to ensure the cohesion and traceability of product data [35].

There are a lot of PLM systems software on the market. They offer different services according to the industry they try to reach but they all share some PLM core services [32, 36-38]:

- Engineering data management (MCAD, CAM, CAE, ECAD, and software)
- Document and information access, navigation and retrieval
- Data vault
- Change management
- Classification management
- Structure management
- Digital validation
- Design in context
- Audit management
- Information security
- Workflow management
- Project Management

At first look, it may look as a confusing unrelated system functionality.

2.2.2 How it works?

Collaboration in PLM is made through the exchange of information related to the product; this exchange may regard different kinds of data (design specifications, drawings, customer's feedback, maintenance instructions, etc) [39]. From a production point of view, PLM is mainly about structuring product information in an orderly fashion so it is always available and can be accounted for on all levels in the manufacturing process and throughout the whole life cycle of each product.

A PLM-system works like a nervous system that communicates with all participants in a product manufacturing process, where the whole entirety leads to a developed product that can be verified in each step of the design and manufacturing process [40]. A server holds the brain function and the communication is responsibility of the core services of the PLM system.

2.2.3 PLM Information system architecture

The physical design of a PLM information system is associated regularly to one or more servers with a set of applications designed to publish services on the network of an organization [41]. The information system consists of a database that is governed by a server application to which the different departments of the organizations access.

As there are many PLM vendors, there are many different configurations of the information system (Fig. 8). In general a PLM information system is composed by (web) clients, application server(s), database(s) and file server(s) [42-44].

- Server: The server is a physical hardware that performs tasks on behalf of clients. On the server operates a relational database that stores and manages all the information.
- Metadata base: The task of the metadata base is to handle relationships between individual pieces of product data, the structure of the information, and the rules and principles needed to ensure the systematic recording of the information.
    - Database: The core of any PLM system is the database it runs on. It contains the dynamic information.
    - Fileserver (file vault): it is a warehouse for information data, stored in files, which meets certain set demands [42]. It holds information of particular importance that must be frozen in a state (static information).
- Application Server (Web application server): The user access to the server is made by a client application installed on the PC's. This access can be made either via local network or remotely via web [45].
- (Web) client (user): Is the end user that performs activities using different applications software (Office, CAD software, etc).

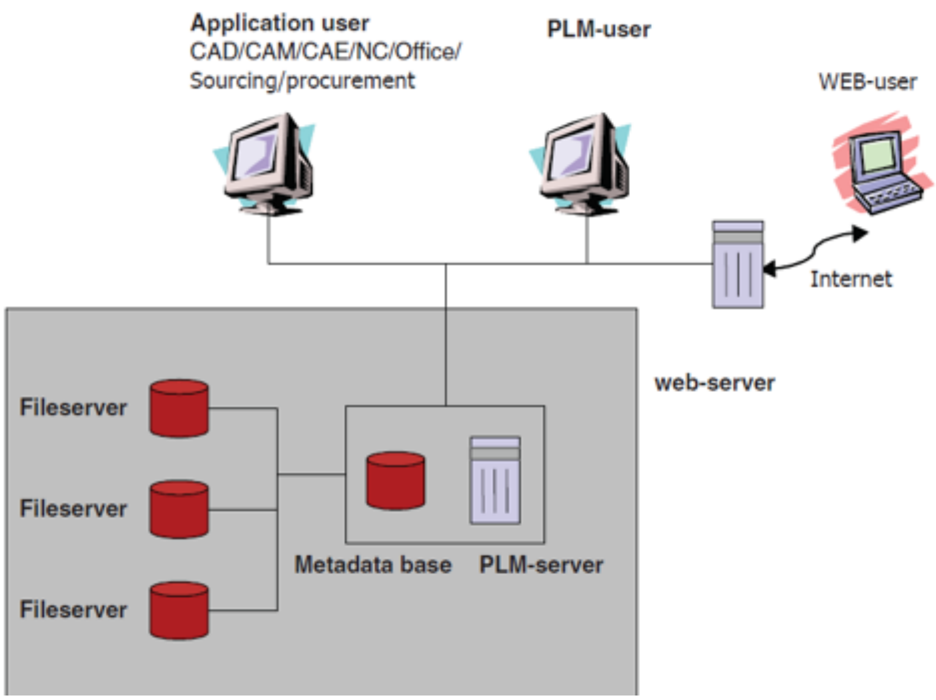

Fig. 8 – PLM system architecture [42]

2.2.4 PLM principles

Items and item revisions are the fundamental data objects used to manage information in PLM. Items are structures that are generally used to represent a product, parts, components or documents [46]. An item is a unique record of the information maintained in a workspace about a specific product, person, organization, or asset [47]. Items can contain other data objects including other items and folders. An item can be thought of as a package contains all data related to that item [42]. Each item has at least one item revision (Fig. 9). Item revisions are data objects used to manage revisions to items. Each item revision has one or more associated sequence IDs. Each item revision has at lease one sequence ID. Items store all revisions of the item ID.

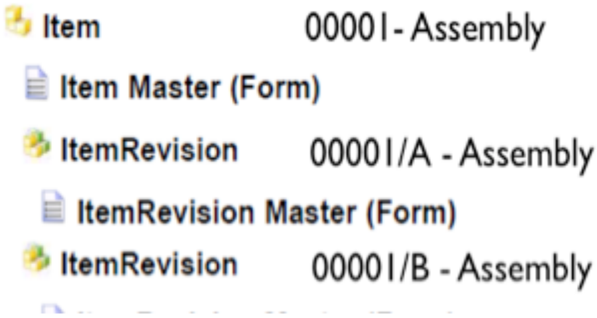

Fig. 9 – Item and item revision [48]

In PLM items are referenced, this means that the item goes once on the database and all users get only an address (position) of the object (Fig. 10). The object reference increases flexibility and fosters collaboration. Many people can access to the same data without altering the data itself

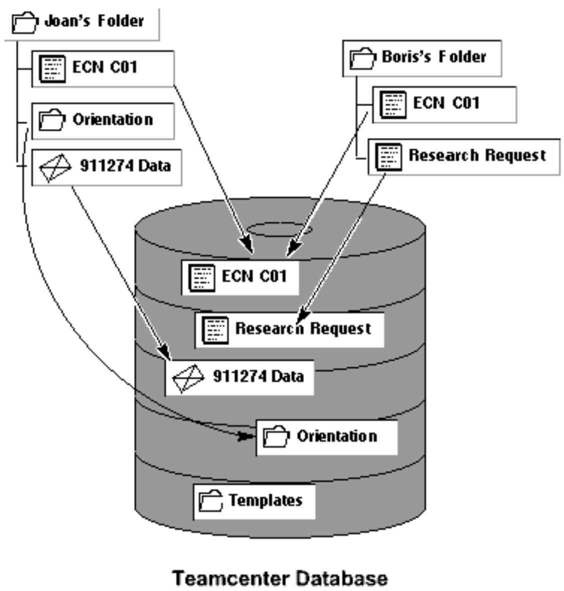

Fig. 10 – Object reference [48]

With the purpose of giving access to only one person at a time working on an item (not on a reference item) the check in – check out task is compulsory (Fig. 11). When you work on an object, the system checks-out the object, this ensures that only changes made by the current user are to be transferred when modifications on the object are finished. The object is set to a non-modifiable state and other users can only visualize it. When the work is finished, the system checks-in the item and now it can be modified by another user that holds the right to do it.

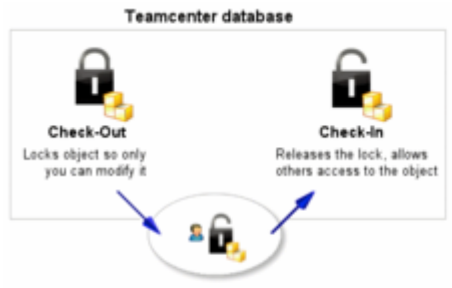

Fig. 11 – Check in - Check out [48]

In order to have access to items (information) it is necessary to authenticate that the persons have the rights to do it. Handling item protection and ownership is crucial in a computerized environment. Items represent actual product information; they must be protected from illegal or accidental access, alteration and deletion.

An access rule (Fig. 12) means that a subject can manipulate an object (item) through an operation [49]. A system is secured only if items are accessed according to the defined access rules. The access rules can be [50]:

- Rules based: simple read/write privilege for defined groups of users
- Object based: each object containing data hidden by encapsulation and accessible only specific rules defined on the object.

Fig. 12 – Access rules [51]

PLM systems execute, control and automate the various processes that users have to do with information by using a workflow graphical representation. Workflows are used in PLM to model the actions required to get from one state to another or to pass from one role of the organization to another.

With workflows, item owners can track down the state of the information on real time. It is possible also to audit files to know when and who modified an item.

In Fig. 13 is presented an automatic workflow composed of three activities. The user will be asked if he has ended an assembly. If yes the assembly will take a Release status while if not the part will end the workflow without adding a status to the part.

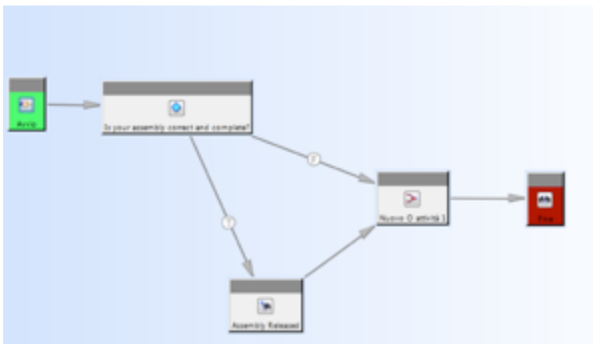

Fig. 13 – Example of an automatic workflow

2.2.5 Configuration and Change Management

Product information change is a never-ending activity and the challenge for all organization is to keep track of the correct information while it evolves. Just the same as a product, every document in a PLM system will have it lifecycle (i.e. Working, Released or Obsolete).

A key component of business process improvement is to effectively manage all information that could impact safety, security, quality, schedule, cost, profit, the environment or an organization's reputation [52]. This information is to be documented, placed under formal change control

ISO 10007 [53] uses four basic functions for Configuration Management:

- Configuration Identification: activities comprising determination of the product structure and selection of configuration items. It regards the item identification (naming).
- Configuration Control: after the initial release of configuration documents, all changes should be controlled.
- Configuration Status Accounting: should provide information on all configuration identifications and all departures from the specified baselines.
- Configuration Audits: performed before the acceptance of a configuration baseline to assure the product complies with its specified requirements and to assure the product is accurately reflected by its configuration documents.

Formal release records are generated and retained for each document that has been validated and released. The release control can be a very simple control (Fig. 13) of the document (auto releasing where the owner of the part states the completion of the item) or standardized activities as Engineering Change Notice (ECN), Engineering Change Request (ECR) and Problem Report (PR).

Document release records include evidence that the proper validation activities have been accomplished. A history record of release activity is retained for the full lifecycle of each document. Release history records are protected against unauthorized access and are readily accessible to authorized personnel.

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Chapter 3. Definition of a visual model representation of PLM

This chapter presents a formal visualization model of enterprise processes for a PLM system. It offers a graphic representation of the main elements of a product lifecycle.

Visualization information is generally applied to the visual representation of large-scale collections of non-numerical information, such as files and lines of code in software systems [1]. A visual representation provides some means to see what lies within to determine the answer to a question, find relations, and perhaps apprehend things which could not be seen so readily in other forms [2].

A PLM system is composed of several components (product data, persons, activities, tasks, projects, workflows, etc.) that are interconnected and change during time. Understanding the relationship between these components becomes crucial so does the need of a visual representation. The main objective of a visualization model is to make clear to everyone what happens in a particular process [3]. For this reason the visualization model looks forward to identify all the information needed to model a PLM framework.

Over the years, industry has developed different display frames, methodological approaches and modeling languages in order to better understand complex organizational systems. Some of these tools are: Balanced scorecard, BPM (Business Process Model), EFQM (European Foundation for Quality Management), COBIT (Control Objectives for Information and related Technology), PMBOK (A guide to the Project Management Body of Knowledge), CMMI (Capability and Maturity Model Integrated), UML (Unified Model Language) and many others. Even if all representations share a common goal, the specific objectives of each model change according to the nature of the sector they belong to, and the characteristics of processes and activities involved.

With the aim of getting a general PLM framework (Fig. 14), this work establishes a classification of the main states of a product lifecycle. Then, for each stage, the involved process areas (PA) have to be categorized. A PA is a sequence of operations that can be depicted in a Workflow. In order to understand every single operation of the workflow better it is necessary to have a Decomposition Diagram (DD). The DD is the partitioning of an operation into its component functions. The DD describes what is to be produced (Items), the necessary skills required (Skills), the responsible of the operation (Role) and the step-by-step explanation describing how specific development goals are to be achieved (Activities).

Definitions of the lifecycle states and process areas were taken from different organizational fields: Project Management Model (PMM) [4] for the activities related to management, and CMMI [5] as reference for process areas. Visual representation follows the basis of:

- UML diagrams for workflows;
- Rational Unified Process (RUP) for activities.
- Finally, the information is settled in a display frame for an easy comprehension of all the information.

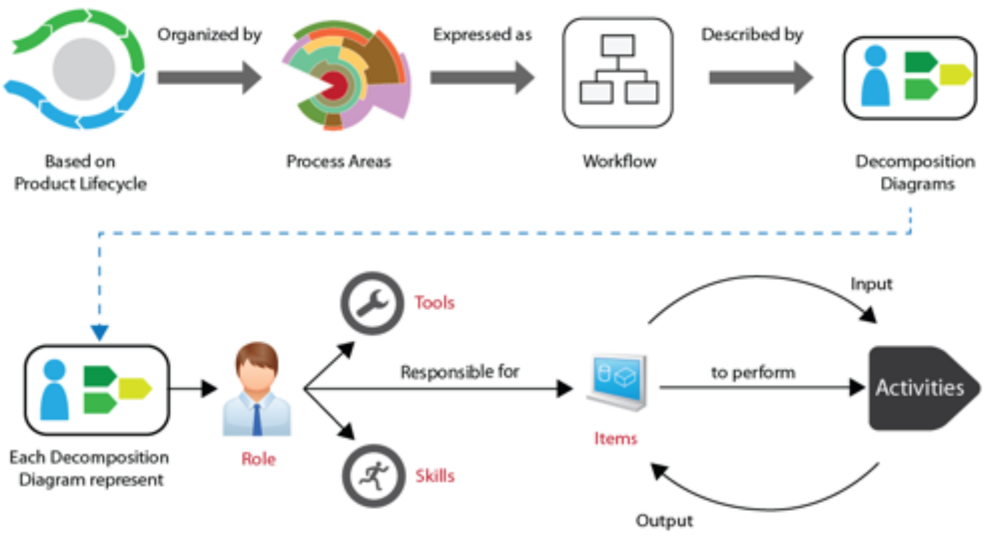


Fig. 14 – Visualization model overview

3.1 Product Lifecycle

From the global resource viewpoint, there is an environmental product lifecycle in which a natural resource (e.g. an ore or oil) is extracted from the earth, it is then processed, and finally it is used in the manufacturing of the product (Fig. 15). The product is used and when it is no longer needed, the resource/waste is managed - perhaps reused, recycled or disposed of [3].

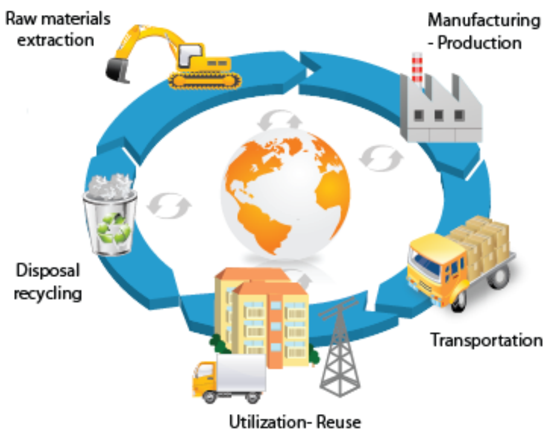


Fig. 15 – Product Lifecycle

On the other hand, as seen by a manufacturer of a product, there are six phases in a product's lifecycle: imagination, definition, production, commercialization, support and disposal. From a PLM perspective, these are six sequential phases, where each phase ends by a major milestone; every single phase is essentially a span of time between two major milestones. At the end of a phase an assessment is performed to determine whether the objectives of the phase have been met or not. A satisfactory assessment allows the project to move to the next phase. The framework is built on the basis of these product lifecycle phases (Fig. 16):

- Imagination phase (concept): At the beginning of the project, the company receives all the information about the product from many sources: stakeholders, customers, marketing and production. Creativity workshops are held for the first product draft, the ideas are turned into sketches, drawings and diagrams explaining the product preliminaries.
- Definition phase (design): The sketches are transformed into technical drawings, modeling is done and product is defined (materials, dimensions and tolerances). A realistic product definition must be clear and verifiable (design shall meet user requirements); complete and accurate (design shall state user's real needs); and feasible [6].
- Production phase (manufacturing): Production is planned and pre-series and series of production are carried out based on the capability of the company. Suppliers' relationships are set. A proper design of packaging is made. This phase ends with the final assembly and storage.
- Commercialization phase (distribution and sales): Marketing strategy is defined along with the transportation systems and distribution logistics to ensure that the product reaches customers' hands in the best conditions.
- Use-support phase (use and maintenance): From the user viewpoint, this phase starts with the use of the product until the end of its useful life. From the business process perspective, it is the beginning of the support and maintenance phase.
- Disposal phase: This phase is the end of product lifecycle and is open to three different scenarios: Recycle, Waste or Reuse. Here is where the environmental impact of product throughout its lifecycle can be assessed (in terms of resources consumed and emissions released) and the related effects on human health can be estimated [7].

Fig. 16 – Product Lifecycle phases

3.2 Process Areas

A process area (Fig. 17) is a cluster of related practices in a domain that, when implemented collectively, satisfies a set of goals considered important for making improvement in that area [5]. Process areas do not start and end within a lifecycle stage. Some process areas (i.e. product requirements) are evaluated constantly during the product lifecycle. Every lifecycle phase represents different aspects of product lifecycle and contains different *Process Areas* (PA):

3.2.1. Configuration and Change Management:

Its purpose is to establish and maintain the integrity of work products using configuration identification, configuration control, configuration status accounting, and configuration audits [9]. Configuration management allows products to be customized according to customer wishes [5]. It is at the center of PLM; all the information about the product must be controlled and accounted by the configuration and change management PA.

3.2.2. Imagination phase

- PA Project Management: It is the discipline of planning, project evaluation, monitoring and controlling activities and resources consumed during the project.
- PA Requirements Management: Its purpose is to handle the requirements of the project products and of product components. Also to identify inconsistencies between requirements, project plans and work products [9].

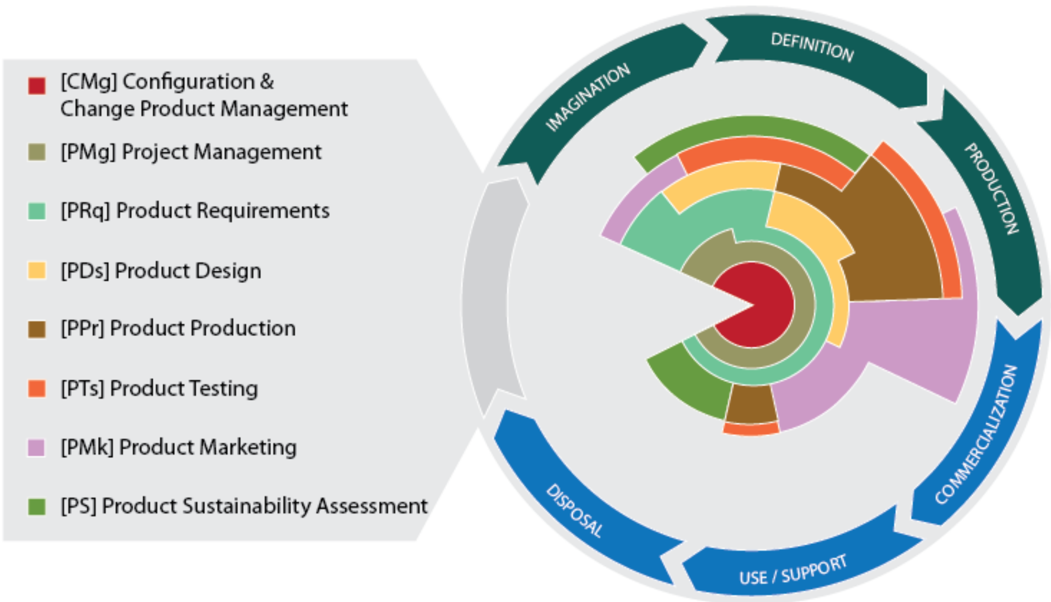


Fig. 17 – Process Areas

3.2.3. Definition phase

- PA Product Design: The objective is to define the product based on the conceptual design and product requirements. Sketches are transformed into more detailed drawings and 3D models with the support of computer aided design (CAD).

3.2.4. Production

- PA Production: The purpose of this process area is to produce parts and to assemble the product from the product components. It ensures that the product, as a whole, works properly and is responsible for the final delivery.
- PA Testing: The objective of this process area is to ensure product quality, to guarantee that the product meets client requirements (verification) and to demonstrate that a product

or product component fulfills its intended use, when placed in its intended environment (validation) [5].

3.2.5. Commercialization

- PA Marketing: This area is responsible for marketing the product and putting it on the market in the shortest time possible, for defining advertising and promotion strategies. It is responsible for conducting surveys to hear customers' voice, for knowing the product perceived value and for estimating the price that the market is willing to pay for it.

Use-support phase

- PA Support and maintenance: It seeks to ensure optimal support for the user in order to have a satisfactory experience with the product. It offers use guidance and precautions as well as maintenance information.

3.2.6. Disposal

- PA Product Sustainability assessment: According to the ISO 14000 standard [8], the three aspects to be considered in this phase are: the inventory of consumed energy, the inventory of emissions and the impact on environment and human health.

3.3 Model Foundations

A process is well described if it is clear who is doing what, how, and when. The Rational Unified Process (RUP) uses four primary modeling elements [9] to represent processes:

- Workflows or the 'when'
- Activities or the 'how'
- Roles[1] or the 'who'
- Items[2] or the 'what'

For the model presented here, workflow representation is based on UML as defined by the Object Management Group [10]. UML can be considered as a relevant and efficient notation enabling the modeling, specification, and implementation of PDM systems especially concerning the product structure and workflows [11].

Graphical representation of activities, roles and items have been modeled through schemes based on Rational Unified Process (RUP) [12]. RUP is a comprehensive process framework that provides industry-tested practices for software and systems delivery and implementation and for effective project management. RUP has been applied successfully over the years in software industry. J. Martinez [13] found the following advantages:

- Product Development time and cost reduction;
- Failure diminishing (less non-conform products);
- Better document control.

RUP has been applied successfully in software industry that lead us to think that RUP can also be implemented effectively to represent processes in the manufacturing industry. PLM manages Configuration Management a discipline that has also its origins in the software and that nowadays is topical in industry. The final model is presented in Fig. 14.

For an easy comprehension activities, roles and items are presented together in the decomposition diagram (DD).

[1] RUP definition for the "who" are called Workers. Workers are defines the behaviour and responsibilities of an individual, or a group of individuals working together as a team. In terms of PLM this is called roles.
[2] RUP definition for the "what" are called Artifacts. Artifacts are tangible products result or output of every activity. In terms of PLM this is called Item.

3.3.1. Workflow

A workflow is a sequence of activities that produces a result of observable value [9]. The UML representation offers a unified standard, suitable for complex processes. Fig. 18 shows an example of a UML workflow. UML is suitable for representing parallel activities, which cannot be represented in the same diagram with a classic flowchart.

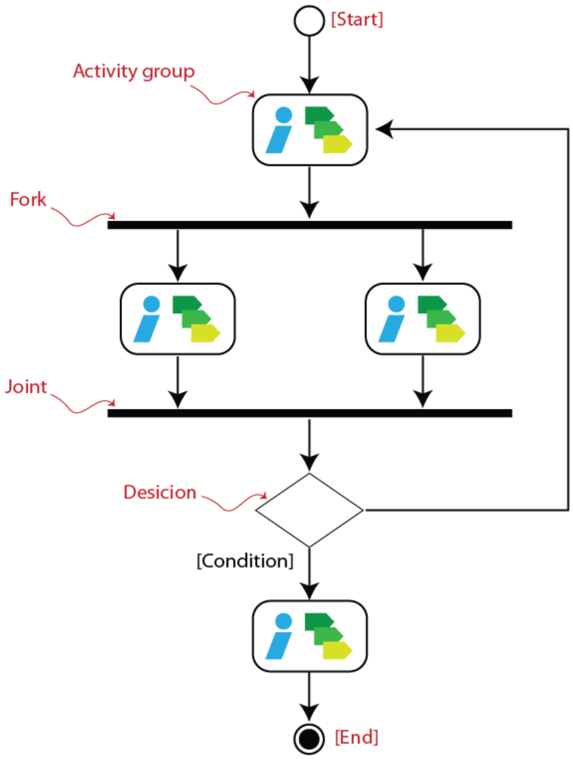
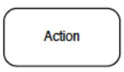
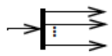
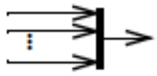
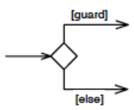
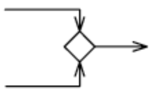


Fig. 18 – UML Workflow.

UML workflows are typically used for business process modeling, for modeling the logic captured by a single use case or usage scenario, or for modeling the detailed logic of a business rule. In many ways UML activity diagrams are the equivalent of flow charts and data flow diagrams (DFDs) from structured development. Basic notation of UML [14] :

Table 1 – Basic notation of UML

Symbol	Element	Meaning
	Initial node	The filled in circle is the starting point of the diagram. An initial node is not required although it does make the diagram significantly easier to read the diagram.
	Final node	The filled circle with a border is the ending point. An activity diagram can have zero or more activity final nodes.
	Action	The rounded rectangles represent activities that occur. An action may be physical, such as check lists, or electronic, such as files
	Flow	The arrows on the diagram that connects the actions

	Fork	A black bar with one flow going into it and several leaving it. This denotes the beginning of parallel activity.
	Join	A black bar with several flows entering it and one leaving it. All flows going into the join must reach it before processing may continue. This denotes the end of parallel processing.
[Condition]	Condition	Text in brackets [Condition] on a flow, defining a guard that must evaluated to true in order to cross the node.
	Decision	A diamond with one flow entering and several leaving. The flows leaving include conditions although some modellers will not indicate the conditions if it is obvious.
	Merge	A diamond with several flows entering and one leaving. The implication is that one or more incoming flows must reach this point until processing continues, based on any guards on the outgoing flow

3.3.2. Decomposition diagram (DD)

The DDs show more detailed components of operations. Workflow operations are broken down into activities that are easier to conceive and understand. The DD describes, in a graphic way, the interactions between activities, roles, items, tools and skills. Activities are performed by a single role of the organization that should have a range of skills and knowledge and may need some tools. The result of the activities is work products (items) that must be controlled by PLM software. DD permits system administrators, project managers and users to determine if all required information would be accounted for in the system. Fig. 19 highlights the main elements of a DD.

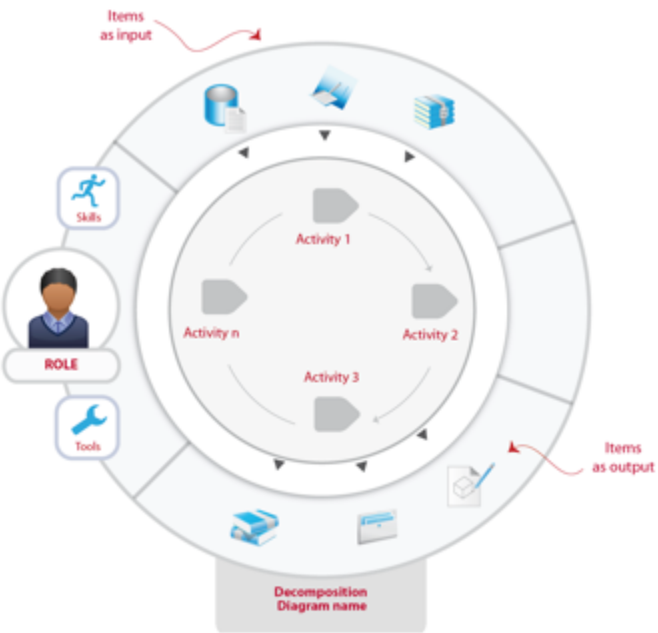


Fig. 19 – Example of Decomposition Diagram

3.3.3. Activities

Activities can be subdivided in a series of smaller and manageable tasks. A single individual will be responsible for each task. Each activity has an activity sheet (Table 2) where are defined: objective, target, input/output items and role. The activity sheet can contain also examples of document templates to help the responsible of the activity.

Table 2 – Example of an activity sheet

Activity Sheet	
Target: Specifies the content of the activity sheet	
Operation: Smaller steps explained to assure repeatability of operations	
Input items: •	**Output items:** • .
Role: Designer	

3.3.4. Roles

A role is not necessarily a single person; it can be a workgroup that is responsible of an activity. A role diagram shows all activities done and the items produced by a specific role during the whole product lifecycle and not only for a single activity (which is the case of the DD). The Role diagrams (Fig. 20) are a derivation of the DD but here are presented just the activities made by a single role all along the product lifecycle. It is a clear way to show the tasks of a role for a single product.

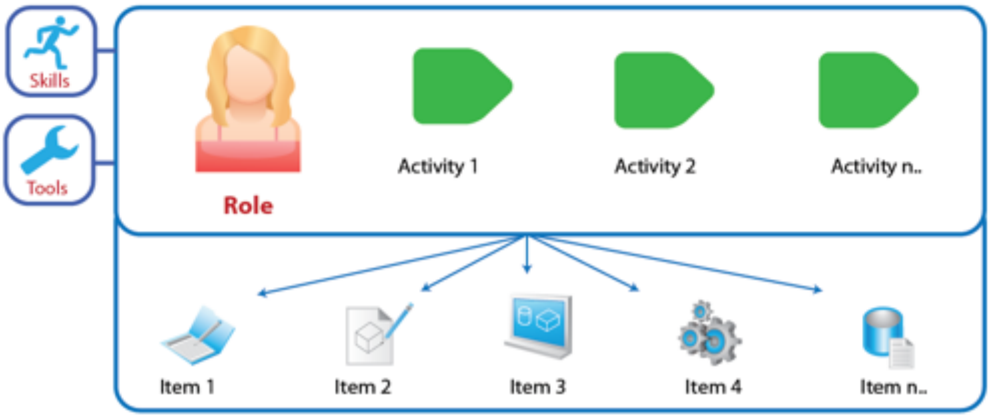


Fig. 20 – Example of Role diagram.

3.3.5. Item

Items are work products obtained after an activity is completed. An item can be a document, a 3D model, a standard, a Gantt chart, a guideline, document plans, etc. The visualization model allows also the representation of the Item Network Overview (Fig. 21), where the relationships and evolutions between items are shown all along the product lifecycle.

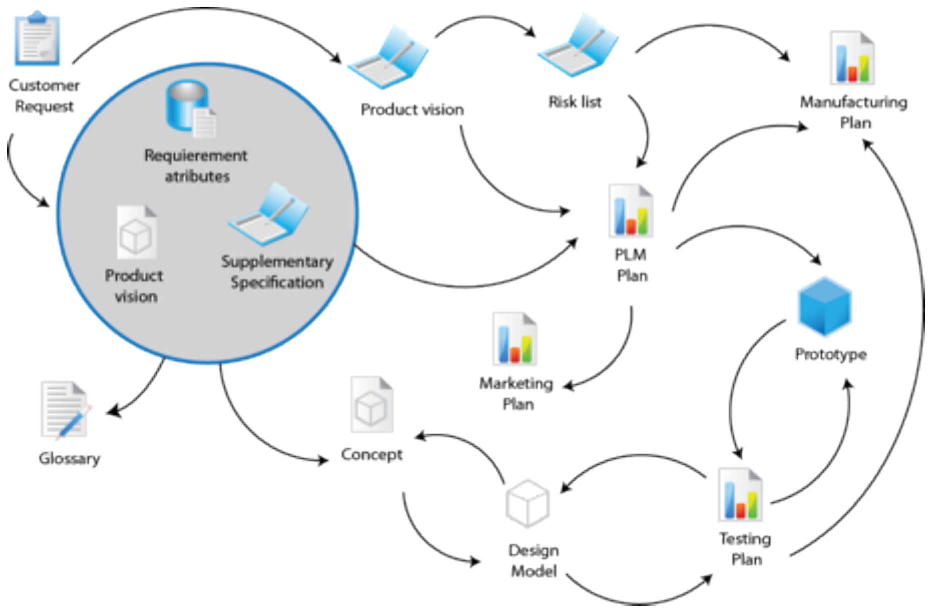


Fig. 21 – Item network overview

3.3.6. Tools and Skills

Once tasks have been clarified, people can be assigned to carry them out as a function of their skills, knowledge and competence [15]. Companies can identify the needs of training for every role participating in the product lifecycle. Roles executing activities must need a set of tools that automate the application of that activity. These tools can be specialized software, a marketing technique, a particular application developed by the company, etc.

3.4 PLM Integration

Once the product lifecycle is understood, activities and tasks are defined, responsibilities are established and information needs are identified; then implementation of product lifecycle in PLM or PDM software can be easily carried out.

PDM systems aim at managing and storing the product data together with the information generated along its entire lifecycle[16]. PDM software needs:

- Organization structure (Roles).
- Activities sequence (Workflow and decomposition diagrams).
- Documentation to be administrated by the system (items).

With the implementation of this model the adaptation is done in the direction of the product lifecycle to the PDM software and not the opposite. The framework also permits the establishment of Configuration Management process. Using the graphic representation of DD, Roles and items it is possible to determine the item owner and the effects of changes and revisions of the released versions (Fig. 22).

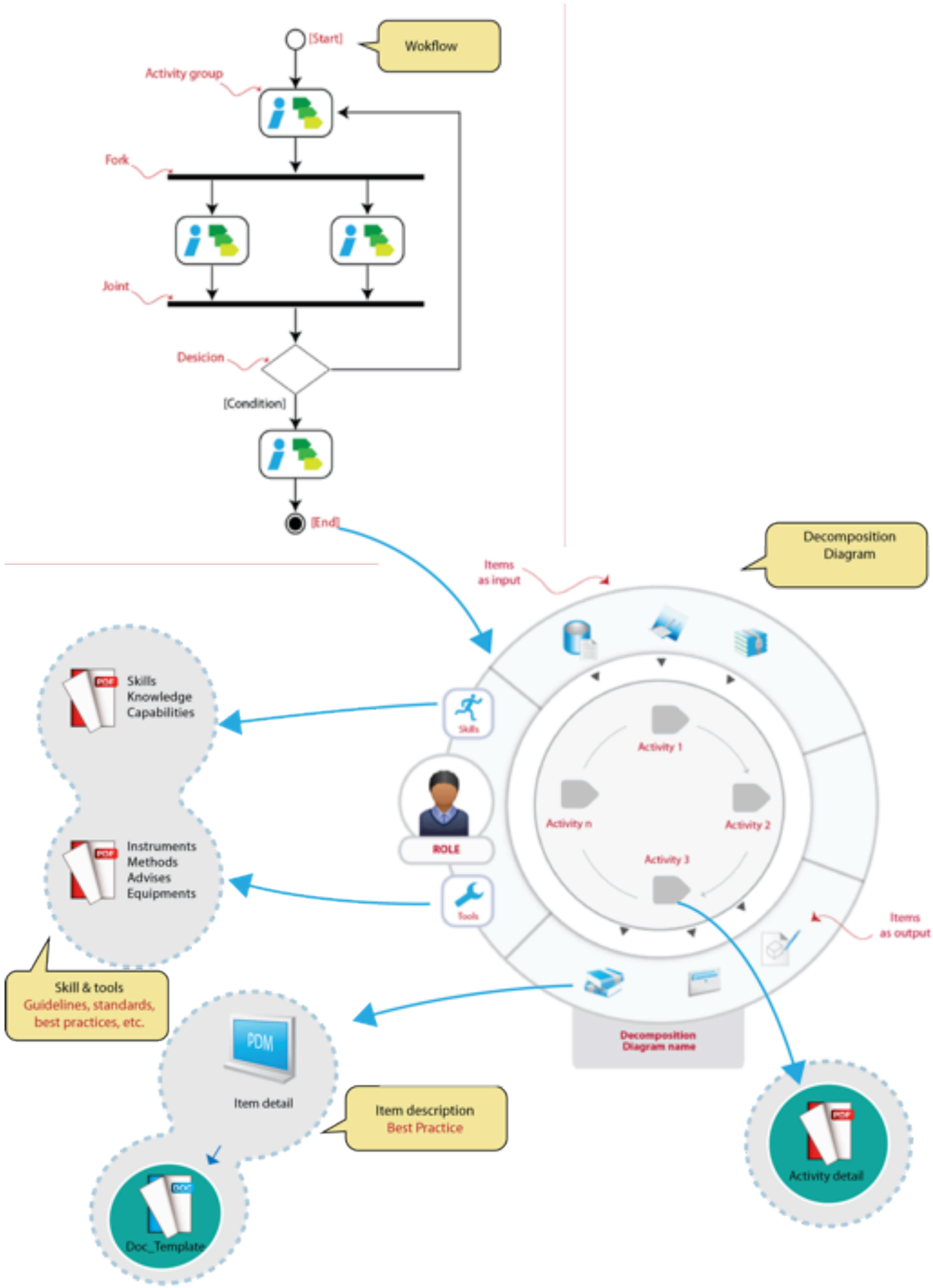


Fig. 22 – Visualization Model

3.5 References

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Chapter 4. GPS Implementation on a PLM Business

The aim of the job carried out in the framework of GREAT 2020-Ecoprolab3 project is to transfer the concepts indicated by GPS to the industry by means of a PLM based protocol. For this purpose, it was necessary to examine “product definition and verification” processes of project partners and to define a general model able to describe the resulting process. The analysis includes a reengineering process; improvements were identified, evaluated and (eventually) implemented. According to the technical or economic impact each participant modified its process. Through a case study it was possible to study the chain of standard for the flatness tolerance.

4.1 Great 2020-Ecoprolab3

The project “GReen Engine for Air Transport in 2020 (Great 2020)” aims at supporting the participation of Piedmont region in European projects, researching new environmental aeronautical engines entering service in 2020. The project led by Avio in joint with Politecnico di Torino and some SME’s (located in the region).

According to the European guidelines, the challenge is to lower fuel consumption, lower pollutants emissions and noise reduction of the new engines.

The Great project is focused mainly on 3 research topics: machining, non-conventional machining and measurement systems. It is made up of 7 parts, each of them treats and specific issue. The Ecoprolab part deals with environmental friendly manufacture technologies and in its part number 3 (OR3) looks forward the development of an application to assure the usability of the data from the 3D CAD model to the CMM according to the GPS standard.

Avio, Politecnico di Torino and APR integrated the Ecoprolab3.

4.2 Product definition and verification Processes

Project partners are part of the aerospace market. They design, produced and measure complex parts with tight tolerances. They use most advanced Computer Aided Design (CAD) and verification software. The use of the Coordinate Measuring Machine (CMM) is required due to the precision and accuracy needed for the inspection of these complex parts.

4.2.1. Base Line Process

At the beginning of this study, the current situation of project partner processes were signed by an uncompleted control of the information which led to an increment in the uncertainty of the operations.

Fig. 23 shows the base line of the definition and verification processes. The design process is presented as a series of two activities. The 3d modelling (a nominal representation of the part) and the subsequent drafting were tolerances are added. These two steps are connected taking advantage of the CAD technology. From the 3d model is possible to create, in an automatic way, the 2d views of the workpart. The resulting files are linked; a modification on the 3d model is recognized immediately in the drafting.

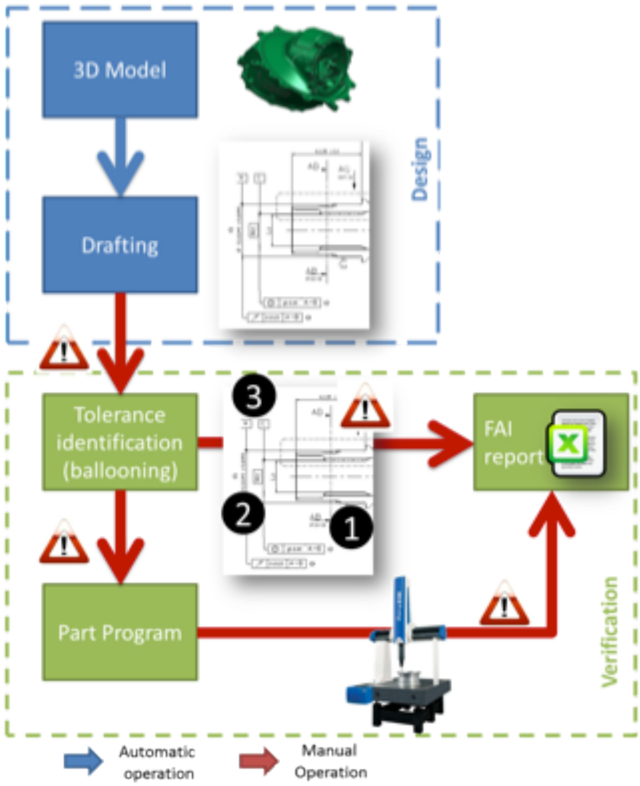


Fig. 23 – Base line of design and verification processes

The drafting file (and/or the 3d model) is then sent to the metrology department using different communication channels (e-mail, USB pen drive, PDM, printed drafting etc.). After receiving the information, the metrology department identifies the tolerances by adding a balloon with a number besides every tolerance. This is a manual process done on a printed drafting.

After the ballooning, a First Article Inspection (FAI) report is created. The FAI report contains the number identification of the ballooning with a description of the tolerance (type of tolerance and value). The creation of the FAI report is also a manual procedure made on a spreadsheet.

Next, a measurement program is generated. In the case of Politecnico and APR this procedure is made in the so-called blind programming (or off-line programming), which means that the measurement program is tested directly to the part without any virtual simulation. The identification of the tolerances is made also manual.

Finally, after the measurement of the real part, measurement results are transferred to the FAI report. The CMM operator copy the values from the measurement software to the FAI report by hand.

Fig. 24 shows how this practice generate looses of product information along the product lifecycle. During the design and verification phases the bad identification of the tolerances create an increase of uncertainties. Among the factors that increase uncertainty, there are specially three that are critical: the ballooning, the creation of the FAI report and the blind programming. All the information in these processes is generated using different technologies and the result is managed in terms of electronic files. However, these three operations are detached to the rest of the flow of the information and they are executed manually. Therefore, the risk of losing information is too high.

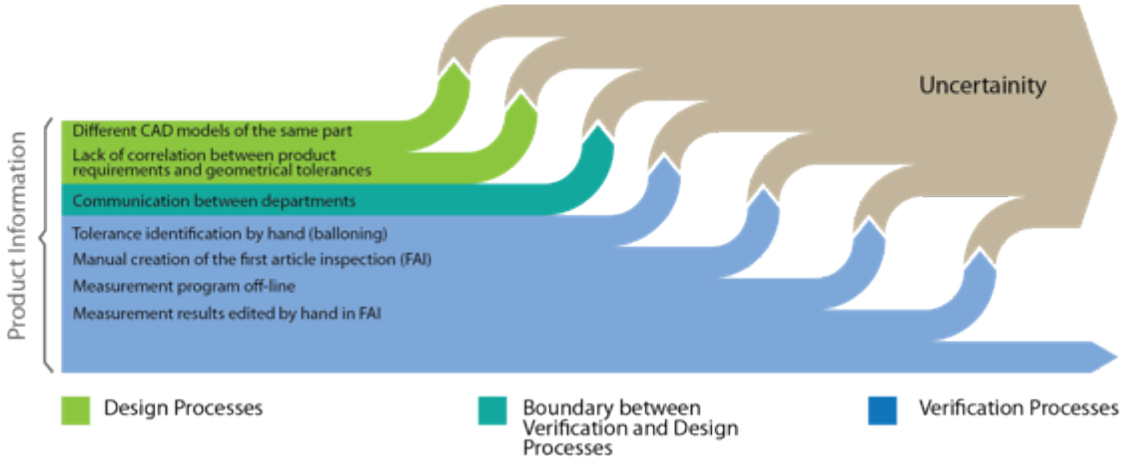


Fig. 24 – Uncertainty in design and verification processes

The tolerancing practice looked like more than artisanal job than a technological one. Tolerances were given according to the knowledge and experience of every designer without any solid foundation. Using knowledge and experience is a good practice only if all the company shares the same principles, stated for example in a company Best Practices. If any single designer uses his own experience, tolerancing practice becomes a non-standard process.

The selection of number of measurement points when using a CMM machine was defined without a demonstrable consistency. Again the experience of the responsible role (metrologist) played a major role. The same part given to different persons (executing the metrologist role) gave as a result different number of points.

CMM software normally uses the Least Square (LS) association method to calculate features. However, there are any references about the mathematic algorithm employed to do this calculus. Metrologist trusted blindly on the software and they never analysed the results by their own. Just the same, they did not analyse the same results according to other association method.

All project partners calculated measurement uncertainties only as the contribution of the MPE of the CMM. As seen on section 2.1.2, the MPE is only one of the contributors (implementation uncertainty) of the total uncertainty.

4.2.2. Process Improvements

Once the process was studied and significant factors were found, improvements were necessary. Actions taken were focused to reduce uncertainty by assuring a best control of the information and to introduce GPS principles in the technological flow.

Since some of these improvements required an investment, not all project participants decided to apply them.

To avoid manual ballooning of tolerances, Politecnico preferred to use Product Manufacturing Information (PMI). PMI solution facilitates a comprehensive 3D annotation environment that allows product teams to capture and associate a component's manufacturing requirements directly to the 3D model, as well as convey this information to downstream manufacturing applications. The tolerance is identified the design phase and the same identification is transfer to drafting, manufacturing and inspection.

Using the PMI, the final measurement result can be directly related to the tolerance made in the design phase.

Avio decided to buy specialized software for the ballooning activity. BCT inspector[1] permits an automatic drawing identification and revision comparison with graphical and spreadsheet display of the engineering changes. It was easily integrated in the actual information flow of its processes.

Politecnico decided also to abandon the CMM software Tutor for the on-line programming software PC-DMIS [2].

The new resulting process is depicted in Fig. 25. The new process eliminates the need of a printed draft, and thus the need of manual operations. All the information about the product remains in the 3d model (Master model) using the PMI technology.

The use of the PMI also allows the automatic identification of tolerances and the creation of automatic measurement part program. In order to transmit the measurement program to the CMM the Dimensional Measuring Interface Standard (DMIS) [3] is used. DMIS is an execution language for measurement part programs and provides an exchange format for metrology data such as features, tolerances, and measurement results.

Improvements made lead to a better control of the information and a reduction of process time. Specially, there was a significant reduction during the verification phase from 20 to 4 hours. The use of the DMIS standard and the on-line programming permits less errors and rework.

However, to solve the technological problems GPS principles are needed. Nevertheless, in literature there are any examples of a complete application of a whole GPS chain of standards for a tolerance. For this reason, it was decided the use of a case study. The use of the Visualization Model (described in Chapter 3) helps to better understand the processes and to translate them the into PLM systems.

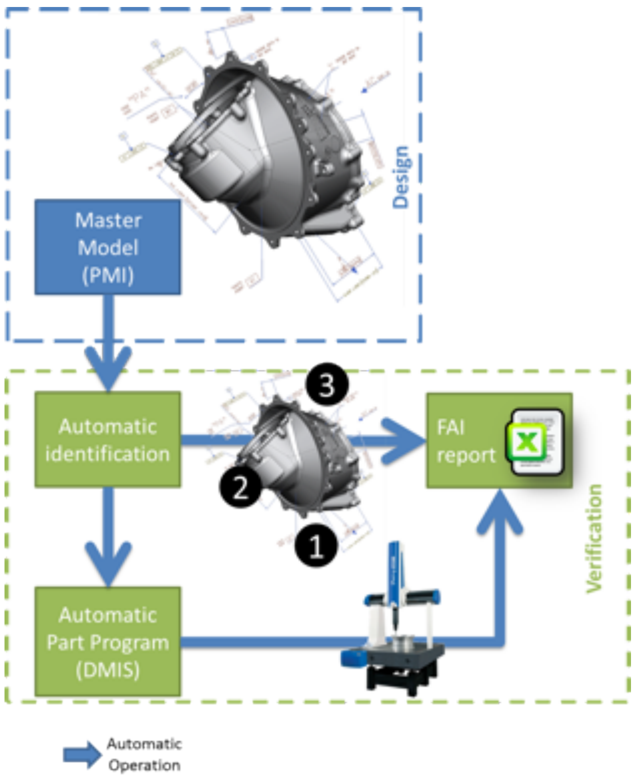


Fig. 25 – Process improvements

4.3 GPS Model

The resulting model is a mixed of the GPS principles and the actual improved industrial practices. The model is based in the belief that it must be software independent (Fig. 26). The model must be cleat enough to use in different PDM software.

It must be also general (Fig. 27) in order to be applied by different industries (whether participants to the project or not) that want to apply GPS principles.

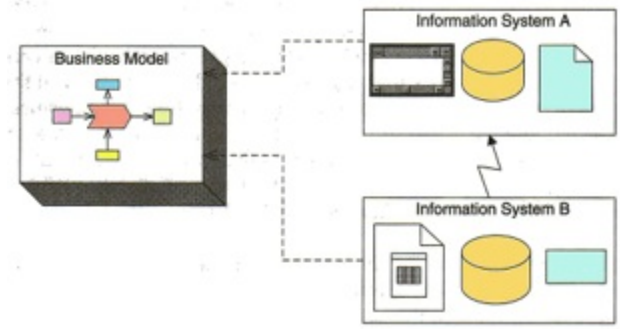


Fig. 26 – Business model - information system requirements relation [4]

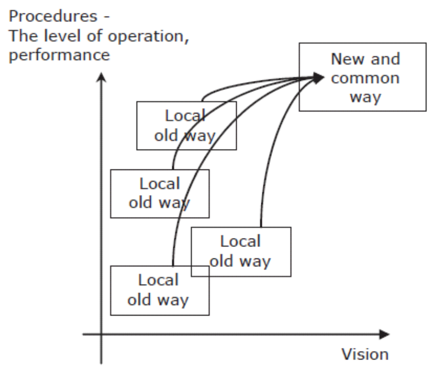


Fig. 27 – General model

4.3.1. Implementation Methodology

In order to define the GPS model, the methodology follows the next progressive steps [5]:

1. Understanding the product lifecycle: The first step for PLM implementation is the clear identification of the company's business within the product lifecycle. Usually companies operates on particular areas only, and do not follow products from the cradle to the grave. It is therefore important they have the maturity to clearly declare the objectives to be achieved and define the strategies to pursuit them.
2. Understanding the processes across the lifecycle: Only if processes are clear the deployment of a PLM software can be effective. In the VM, processes are organized into PAs that need to be clearly identified.
3. Describing the workflow: The company operations within each PA are described by means of workflows to grasp the actual concatenation or sequence of activities.
4. Decomposition Diagrams: Each step of the workflow is detailed, in a graphical way, to highlight activities, roles, skills, tools, and Items.
5. Product Data Management Software: According to the goals and the organization capability, the PDM is customized for allowing the integration of all the information sources involved in the process.
6. Training people: People need to be trained to work effectively in a PLM environment.

4.3.2. Understanding the product lifecycle

GPS standards regard in particular the product development process. The product lifecycle phases it covers (highlighted in Fig. 28) are: product requirements, product design, and testing.

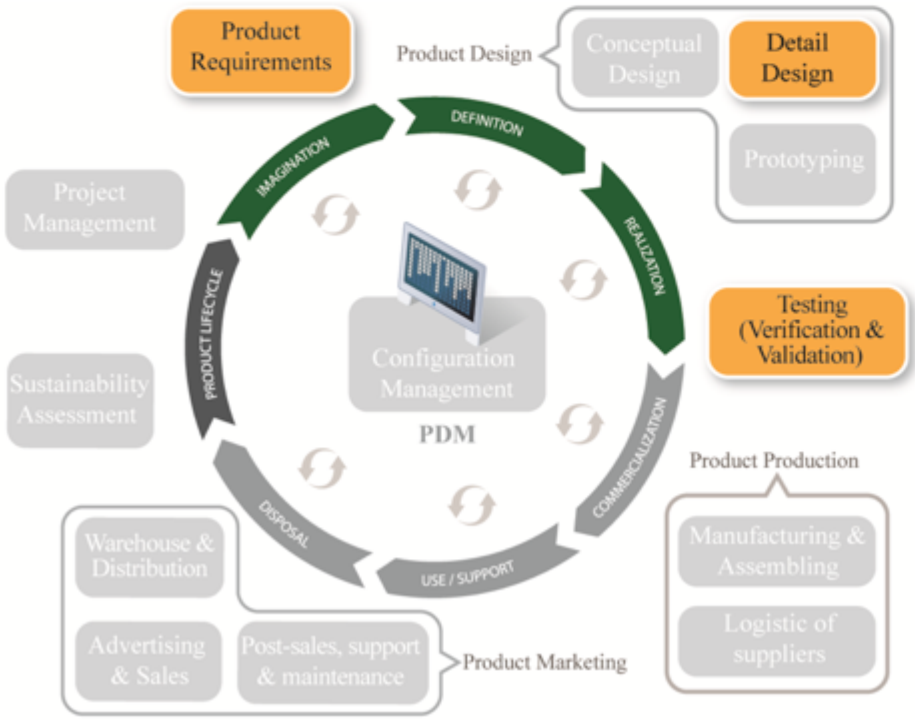


Fig. 28 – Process Areas involved in the study.

4.3.3. Understanding the processes across the lifecycle

Within the GPS approach, during the Product Requirement phase, the designer determines the geometrical functional requirements of the mechanism, according to a function analysis. Tolerancing takes place during detailed design phase to set the geometrical tolerances for the product realization. After manufacturing, tolerance verification permits to close the process loop, checking the product conformity and to verifying the assumptions made by designers [6].

4.3.4. Describing the workflow

GPS has 5 principal steps that are:

1. Functional Specification (nominal model)
2. Geometrical specification (skin model)
3. Measurement planning (skin model)
4. Measurement (real part)
5. Comparison for conformance

The process starts from the functional requirements of the part. The designer must accommodate the required functional performance of the workpiece by defining a functional specification. This step is executed on a nominal model that is a perfect representation of a part with only nominal values, impossible to produce or inspect.

Geometrical specifications (tolerancing) define the allowable variation for the form and possibly the size of individual features, and the allowable variation in orientation and location between features. The geometrical specifications applied to the part detailed drawings must express without ambiguities what are the target of functional requirements [7]. In this step, the designer imagines an imperfect part (skin model) and envisages which are the tolerances values that he must state in order to assure product functionality.

The verification process starts as soon as the metrologist receives the CAD model of the part with the tolerances to be verified. Then, for each tolerance, a specific measurement plan is created that will be executed on the real part upon receipt.

Once the measurement is complete, the results are compared against the tolerance value to establish whether the workpiece is conforming or not. All the information generated along this process consists of electronic files of different natures (CAD models, text documents, spreadsheets, etc.)

Fig. 29 presents the GPS process workflow with a UML diagram consisting of the five major steps. The workflow describes the sequence of activities but does not provide timing: measurement cannot start if its planning is not released and comparison waits until the measurement is finished. At a first look, the verification process seems linear, still the concurrency can be assured by the documents access rules. These rules can allow the members of a team to control the actual progress of documents before their official release.

Configuration & Change Management plays in parallel with the sequence of definition and verification activities, being the controller of all the information. According to the UML language, this means that all the information generated on the left stream is continuously managed through the Configuration & Change Management activity, which is therefore responsible for controlling changes and maintaining the integrity of product Items [8].

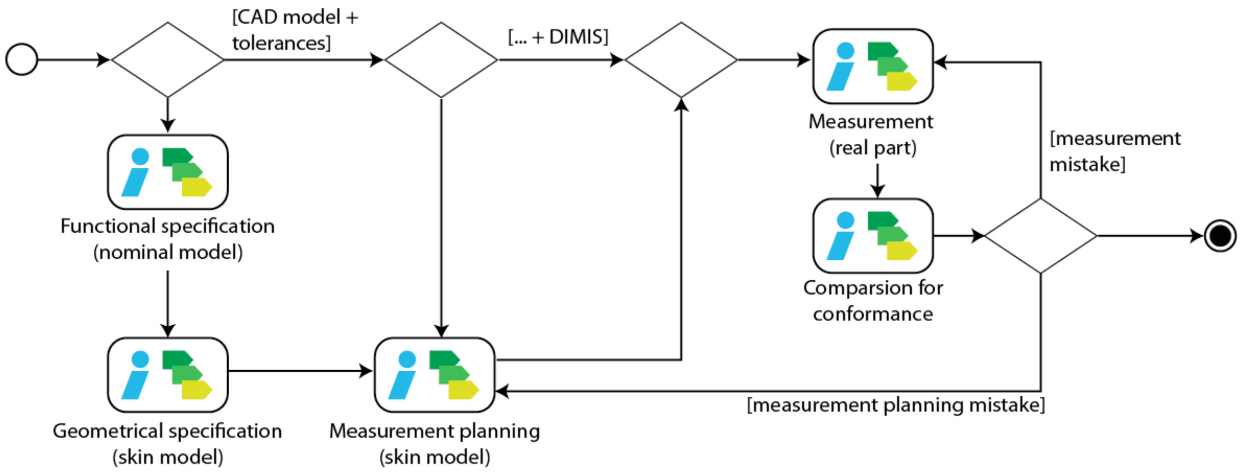


Fig. 29 – Workflow of GPS process.

4.3.5. Decomposition Diagrams

At this point the GPS process is not clear yet. Further effort is necessary to understand the activities and define the roles involved. For this reason it is essential to break down the workflow into smaller activities and describe them by means of DDs.

The DD of the functional specification has only one activity (Fig. 30). The definition of the functional operator has an objective the identification of functional surfaces of the product and its features.

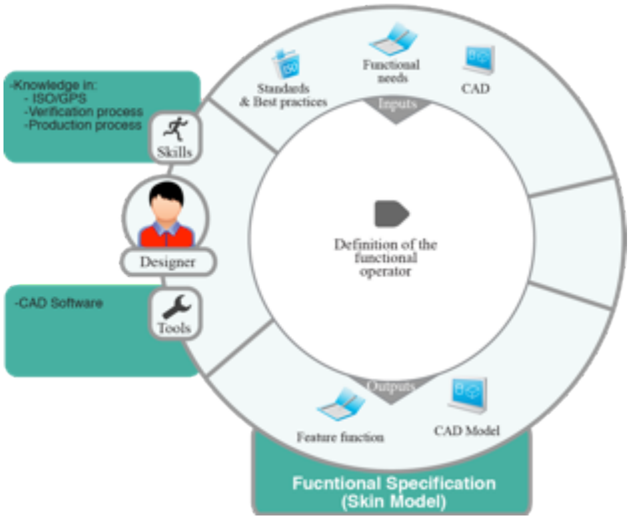


Fig. 30 – DD of “Functional Specification”

The Geometrical specification is made of 4 activities (Fig. 31). The specification operator identifies the functional features and applies the seven operations (partition, extraction, filtration, association, collection, construction and evaluation) to define a tolerance. The correlation uncertainty evaluates the performance of the geometrical specification while the estimation of the specification uncertainty evaluates the completeness of the tolerancing. Finally the designer identifies the geometrical specification with an electronic ballooning

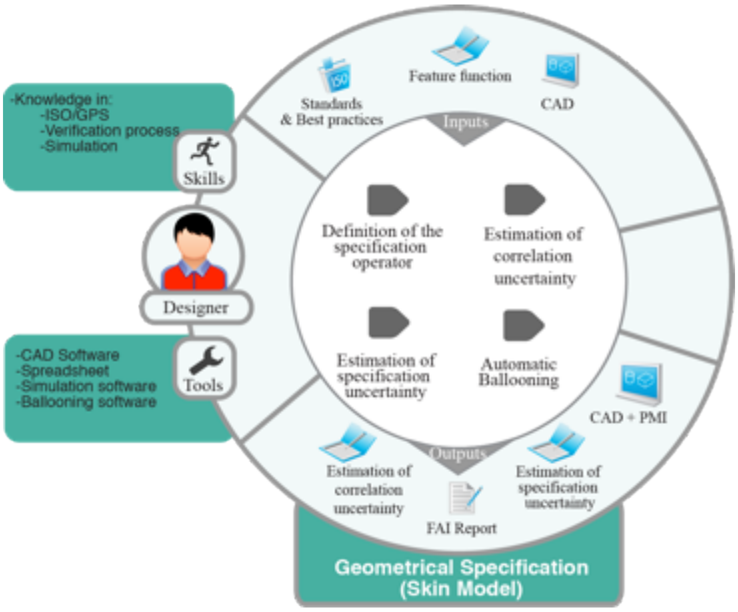


Fig. 31 – DD of “Geometrical specification”

As Fig. 32 shows that Measurement Planning can be partitioned into five activities. First, ballooning identifies each tolerance with an identification number (if the electronic ballooning has not been executed). Then an actual verification operator is defined, which includes all measurement parameters according to GPS standards, and a prior estimation of its measurement uncertainty is performed with a special tool developed by the company. A forecast of verification costs is then accomplished, which takes into account also the predicted measurement uncertainty, and, if costs are within the budget, the measurement path is defined and set-up. These activities are performed by the metrologist role. He should have a solid knowledge of the GPS standards (skill) and will be given some measurement software plus a spreadsheet to accomplish these activities (tools).

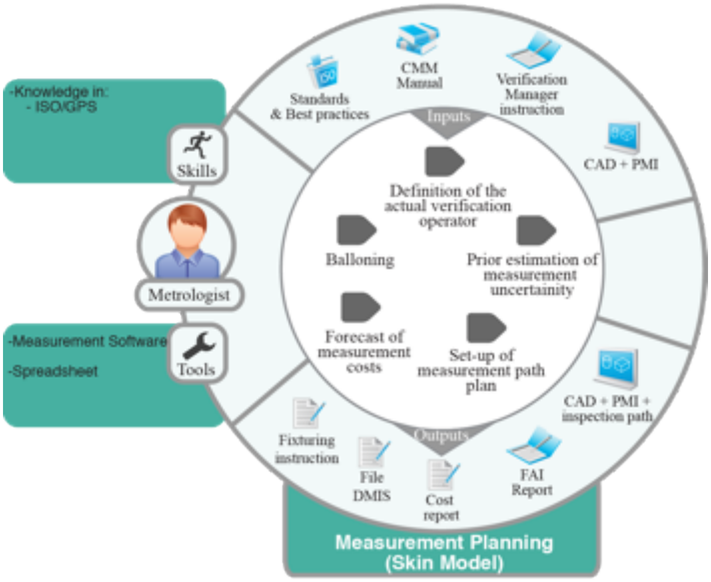


Fig. 32 – DD of "Measurement Planning"

The core activity of the process is represented by the “Measurement” DD in Fig. 33. The use of a CMM naturally brings two different activities, the machine set-up (probe calibration) and the measurement operation itself (physical sampling of measurement points). The measurement operation itself should be compliant with the GPS specification, otherwise some measurement uncertainty arises that shall be estimated in the following phase of measurement analysis and conformance test.

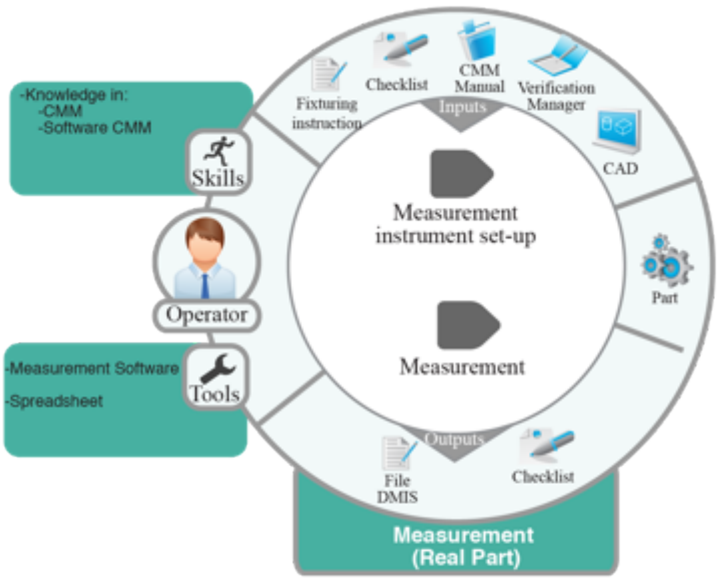


Fig. 33 – DD of "Measurement".

The DD of “Comparison for Conformance” (see Fig. 34) closes the verification process with the analysis of measurement data. Special attention is devoted, at this stage, to the measurement uncertainty and the costs it can introduce. Finally a deliverable document states the conformance or non-conformance resulting from the comparison of the measurement result (plus its measurement uncertainty) against the tolerance limit.

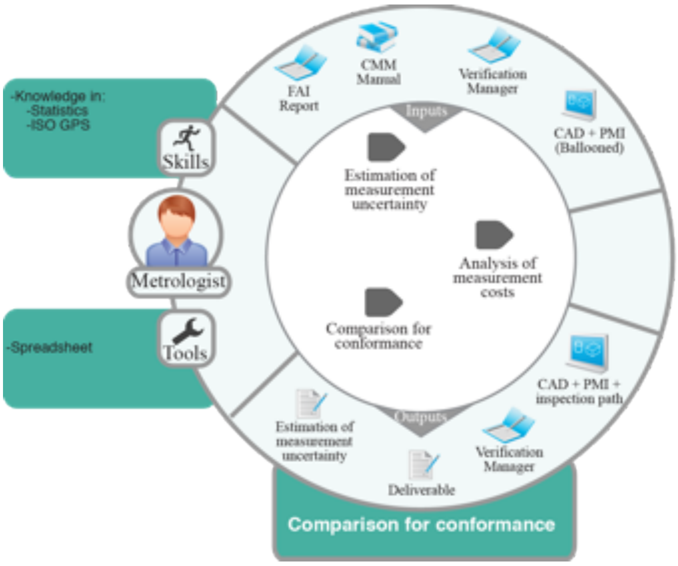


Fig. 34 – DD of "Comparison for conformance".

From the DD's is possible to create an item overview to see how the information evolves during the product lifecycle (Fig. 35).

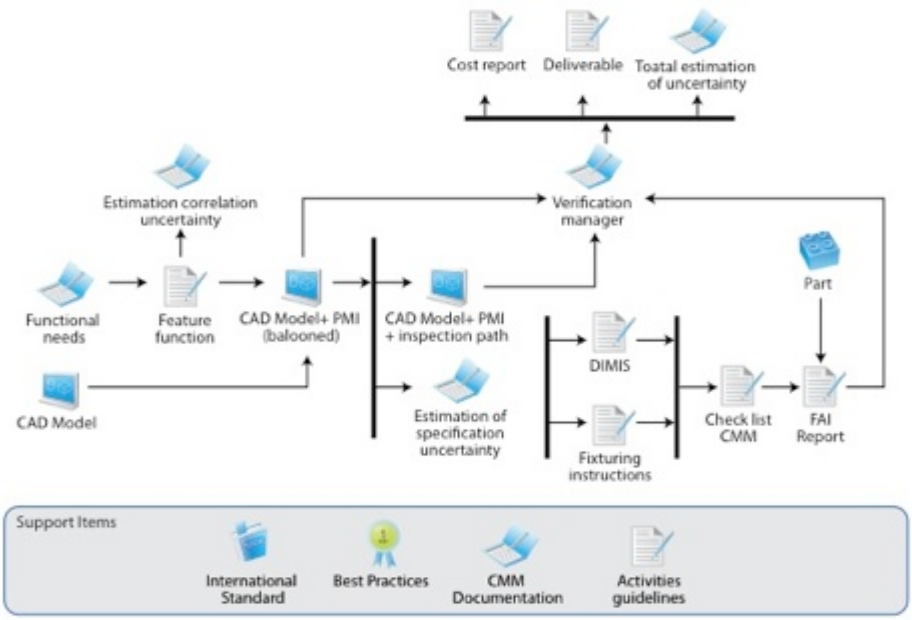


Fig. 35 – GPS Item overview

It is also possible to create a Role diagram to see clearly which are the activities that the designer executes during product definition and verification and its responsibilities

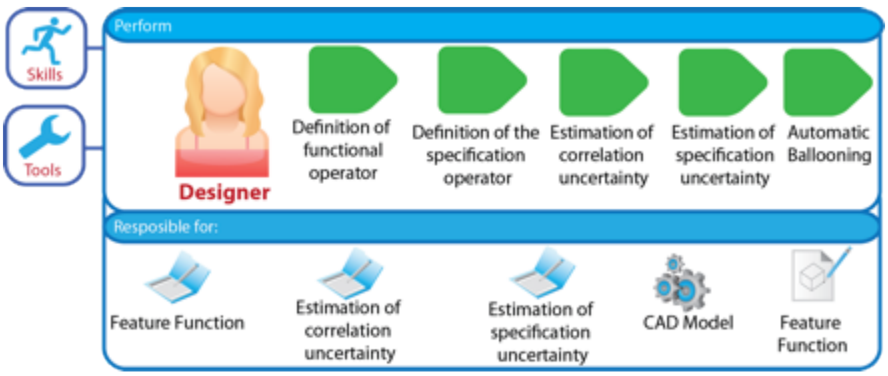


Fig. 36 – Designer Role diagram

4.3.6. Product Data Management Software

It was decided to use an open source PDM software to test the principles of GPS. By doing so, licensing costs were avoided and every project partner could afford it.

4.3.7. Training

Due to the novelty of terms, training on PLM is recognized as a fundamental step for a successful implementation. Training has been divided into two sections: general terms and principles of PLM and the use of the PDM software.

4.4 Case Study

The selected component is used to close the ends of an air cushion guide (other functions are not considered) and it is presented in a simplified form. There were not contemplated all technological features (chamfers, fillets, etc.) which in real work conditions are used to improve the ease of assembly, part duration, machinability and to minimize production costs. This choice is made to focus the attention on the main geometrical features involved in the definition of the functional requirements. From here on the part is called Flange.

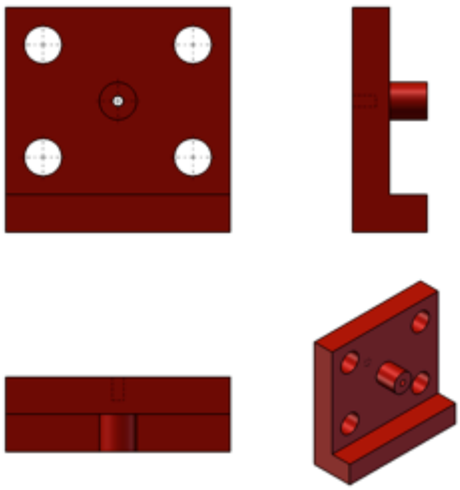


Fig. 37 – Case study: Flange

4.5.1. Functional Requirements

The flange (part 2 in Fig. 38) has the function to correctly position the air cushion guide into the chassis of the machine. It also acts as limit stop for the pallet that slides on the guide.

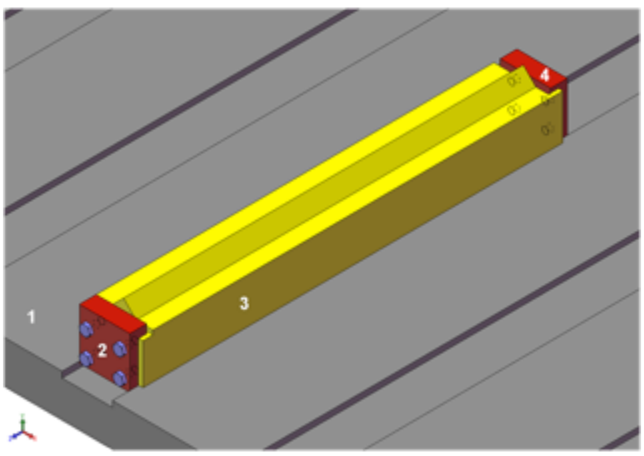


Fig. 38 – Positioning of the air cushion guide on the workplane of the machine

However, its principal function is to maintain the air pressure inside the air cushion guide. The flange allows the air supply through a drill in the central shaft. This shaft engages the hole located at the end of the guide. The supply conduit is connected to the flange via a threaded hole. The position tolerance for the hole on the guide can be quite large, because the hole diameter Ø11mm is coupled with a shaft of Ø10 mm.

A gasket interposed between the flange and the end of the guide performs the sealing function is by. The gasket is made of an elastic material, it has a nominal thickness of 1 mm plus a dimensional tolerance of ± 0.05 mm of thickness and coefficient of compressibility CR = 30-35%. The gasket, imposes a control over the shape of the surface, due to its compression the gasket fills the defects of shape surface.

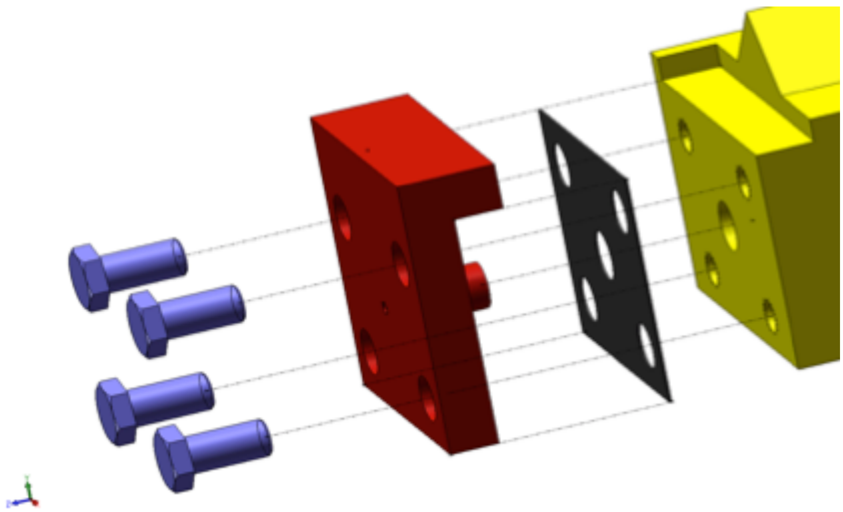


Fig. 39 – Flange positioning

4.5 GPS model Validation

The model application follow the workflow defined in section 4.3 and it is applied to the case study. The result of such modeling activity, based on Visualization Model, covers 1 workflow of activities; 5 decomposition diagrams of the workflow; 3 roles diagram; 15 activity sheets; and 1 item network overview. The complete model is located on Appendix A.

4.5.1. Functional Specification

The model does not have a tolerance so it is necessary to define the functional specification. According to the GPS workflow the first activity is the definition of the functional operator.

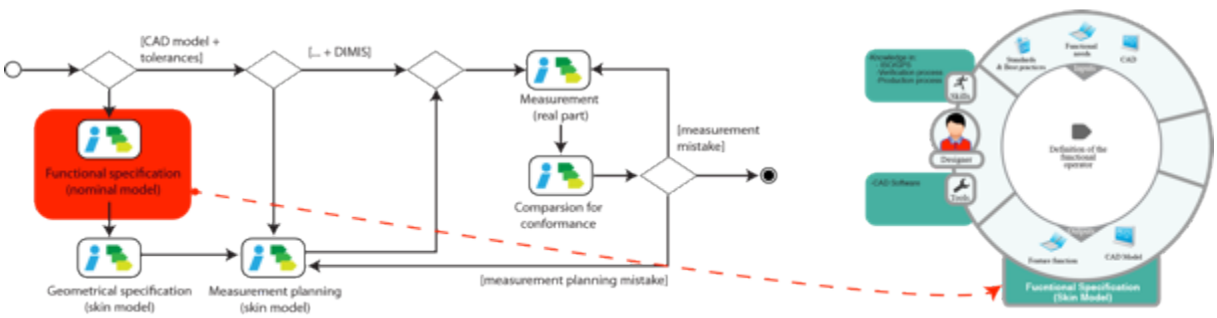


Fig. 40 – GPS workflow follow-up

4.5.1.1 Definition of functional operator

According to the functional requirements (defined in section 4.5.1), the designer must guarantee the performance of the part in the assembly. This activity is executed over the nominal model and it establishes the nominal requirements (Fig. 3).

For the flange, the designer must control the shape of a surface that has to be flat. The only operation needed is the partition of the plane surface (with respect to the other elements of the flange) that is highlighted in Fig. 41. This is normally an activity that designers do mentally still GPS asks for a clear definition of the passage from the nominal model to the skin model.

In order to assure operation repeatability, the steps needed to perform the activity are synthetized in Table 10 – Definition of functional operator. The activity sheet contains more detailed information with respect to the DD. In states the target of the activity, the needed steps to perform the activity, input and output items and the role responsible of the activity.

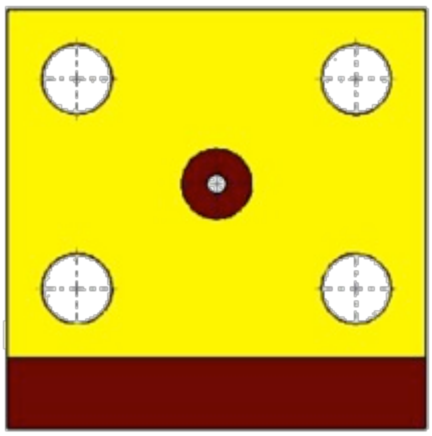


Fig. 41 – Identification of the functional surface

4.5.2. Geometrical Specification

The first step of the workflow has been completed, no the workflow moves to the geometrical specification (Fig. 42).

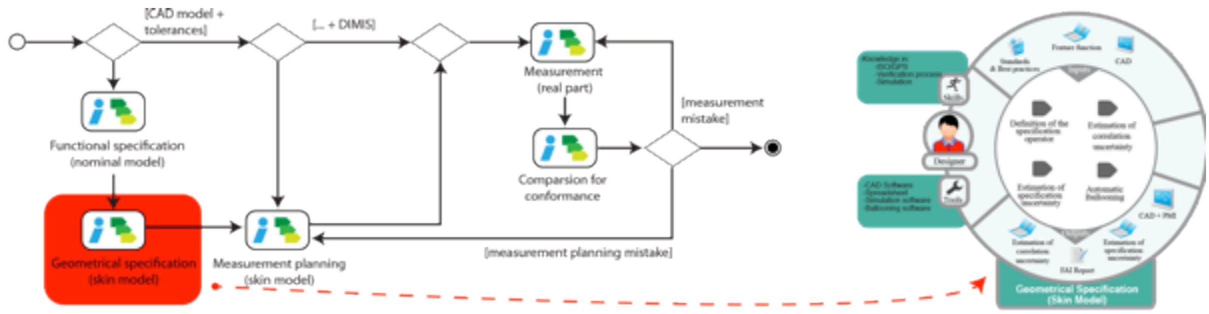


Fig. 42 – Workflow follow-up Geometrical specification

4.5.2.1 Definition of functional operator

From this activity on, the designer imagines the part as a real part with some imperfections (skin model). The definition of the functional operator consists in the identification of the nominal surface (result of the activity 4.5.1.1) and the statement of the tolerance.

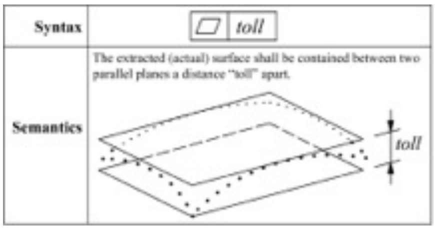


Fig. 43 – Flatness definition in GD&T

The classical definition of the GD&T includes only the tolerance symbol and value (Fig. 43). However, in the GPS framework this information is not enough to assure product definition. In addition to the symbol and value the tolerance must contain the filtration method (cut-off length value) and the association method (least square or minimum zone for the flatness).

The parameter Δ that extent the functionality of the gasket is the difference between the minimum thickness of the gasket HLmin in the free state (decreased for example of 0.1 mm to ensure, however, a slight compression of the gasket in the empty areas that need to be filled) and the maximum HCmax thickness of the gasket to the collapsed state. We have:

$$H_{Cmax} = H_{Lmax}(1 - CR_{min}) = 1{,}05\ (1 - 0{,}3) = 0{,}735$$

$$\Delta = \ (H_{Lmin} - 0{,}1) - H_{Cmax} = (0{,}95 - 0{,}1) - 0{,}735 = 0{,}115$$

It was decided to allocate the flatness errors on the two components. Consequently, a flatness tolerance of 0.05 mm was assigned to the flange and 0.06 mm on the end of the guide. The flatness tolerances are specified at design only if they are not already implicitly guaranteed by other tolerances of orientation (perpendicularity).

In particular, given the material of the flat gasket, the flatness tolerance must be defined with a cut-off length value of 2.5 mm. All the components of the error shape having a wavelength greater than 2.5 mm will be considered as flatness error.

Regarding the association criterion, it is decided to use the Minimum Zone (MZ), which allows minimizing the error of estimated shape with the verification process. The tolerance is inserted in the CAD Model using the PMI. It is possible to create automatically the First Article Inspection (FAI) report. The model with the complete functional operator is presented in (Fig. 44).

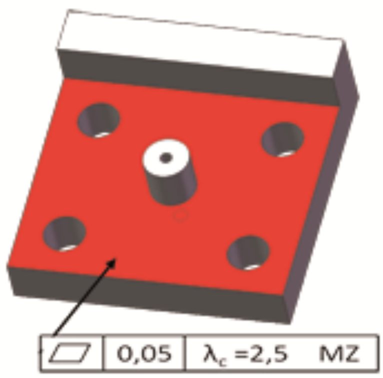


Fig. 44 – Flatness tolerance according GPS

4.5.2.2 Estimation of correlation uncertainty

The correlation uncertainty is not estimated in actual industrial practices. Yet the lack of correlation between user requirements and product function is one of the main factors of product malfunctioning.

Correlation uncertainty cannot be completely eliminated, it can be only reduced. The formulas used for calculating the flatness are part of a consolidated engineering practice. Therefore, there is the security that the geometric requirement is adequate to ensure the functional requirement specified in section 4.4.2. The uncertainty of correlation is reduced to its minimum. No simulations (i.e. Finite Element Analysis) were needed but for other products it may be indispensable.

4.5.2.3 Estimation of specification uncertainty

Since the specification is complete (Fig. 45) according to GPS, there are all the necessary elements to define a complete specification operator. The specification uncertainty is zero.

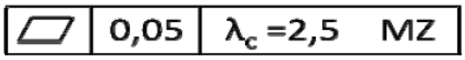


Fig. 45 – Geometrical specification for the flatness tolerance

4.5.2.4 Automatic Ballooning

The automatic ballooning allows the unique identification of the tolerance all along product lifecycle. PMI's of NX were used to associate automatically the flatness tolerance to the surface in the design. The tolerance value was assigned in the activity 4.5.2.1 (Fig. 44) and it is not necessary to do a specific task here. However, other software can be used to manage the tolerance ballooning (i.e. BCT).

4.5.3. Measurement Planning

The measurement planning is a responsibility of a metrologist (Fig. 46). He must define the verification operator and to forecast the measurement uncertainty and costs.

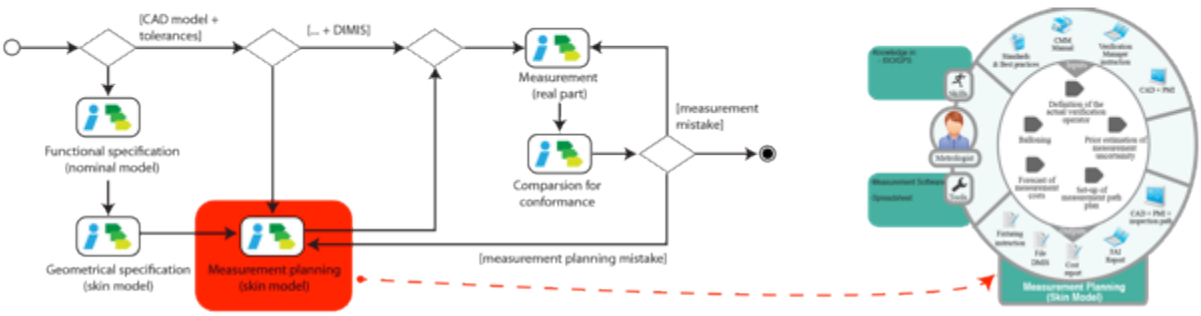


Fig. 46 – Workflow follow up Measurement planning

4.5.3.1 Verification/Implementation of manual ballooning

This activity is optional in case the company does not count with the CAD software with PMI's or the specialized software for automatic ballooning. In the case at study the ballooning was executed in section 4.5.2.1 (Fig. 44).

4.5.3.2 Definition of the actual verification operator

The actual verification operator can be perfect, if it respects the specification operator, or simplified, if some changes are introduce. The metrologist decides this time to use an actual (simplified) verification operator. This choice introduces uncertainties to the processes and they must be quantified. To do so the Verification Manager (VeM) was employed.

The VeM is a tool developed by Francesco Ricci [9]. The VeM is a novel categorical model able to manage the processes of specification and verification of a flatness tolerance. It also evaluates the uncertainty and cost of the whole verification process. This instrument is used here (and in some other activities) as a tool and full credits and recognizing are giving to its author. For further details about the VeM (statistical approach, cost model, etc.) refer to chapter 5 of the cited work.

Before defining the verification operator, the metrologist must give the information about the specification operator in the “Specification Operator” sheet of the VeM (Fig. 47). The flange has a flatness surface that does not present rotational symmetry and it has a surface of 60x50 mm. Then the VeM asks for the information about the tolerance value, cut-off length and association method. With this information the VeM estimates the number of points to be measured in order to suit GPS standards. Using these values the program estimates 23520 points to be measured with a CMM. Nevertheless, VeM considers a rectangular perfect grill and it cannot eliminate points locates on holes or pins (like in the case of the flange). Yet more than 20000 points are necessary to measure the part.

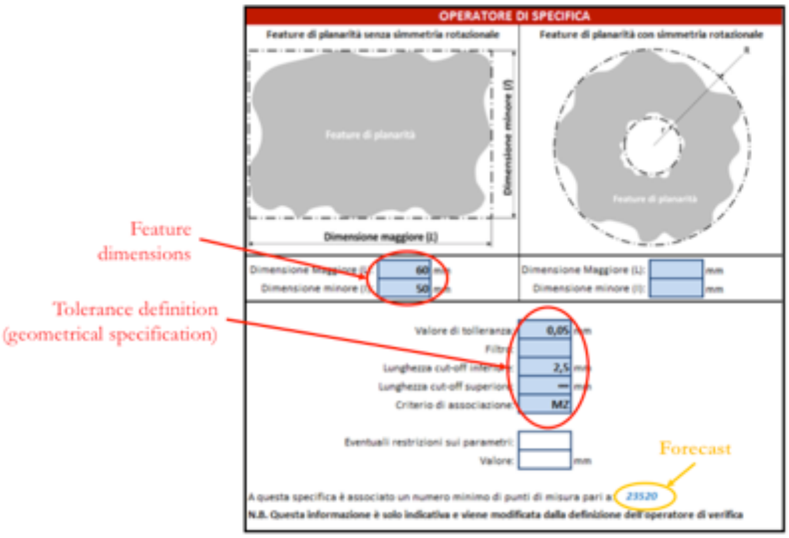


Fig. 47 – Verification Manager sheet “Specification operator”

According to the GPS standard, the maximum distance between points for a perfect rectangular grill with a cut-off wavelength is 0.35 mm. For the case study, the metrologist decides to use a simplified verification operator. He decides to change the distance between points in both directions to 2.5 mm instead of 0.35 mm; this will reduced the number of points (and measurement time) while introducing uncertainties (method uncertainty). The metrologist chooses also to use the Least Square association method instead of the MZ.

In the VeM sheet Verification Operator; the metrologist must introduce the values of the simplified verification operator. From this point on, the VeM will use the simplified operator to calculate the uncertainties (Fig. 48).

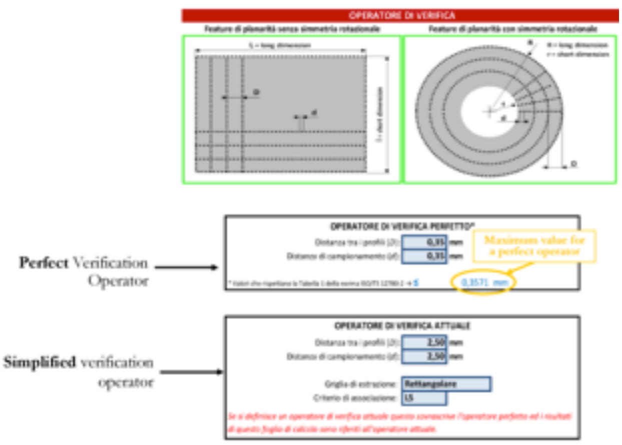


Fig. 48 – Verification Manager sheet “Verification Operator”

The metrologist creates the measurement path program that respects the actual verification operator. The ballooned CAD will be transformed in a part program that contains the measurement and travel points. To communicate with the CMM the resulting program will be saved in the Dimensional Measuring Interface Standard (DMIS) extension (Fig. 49).

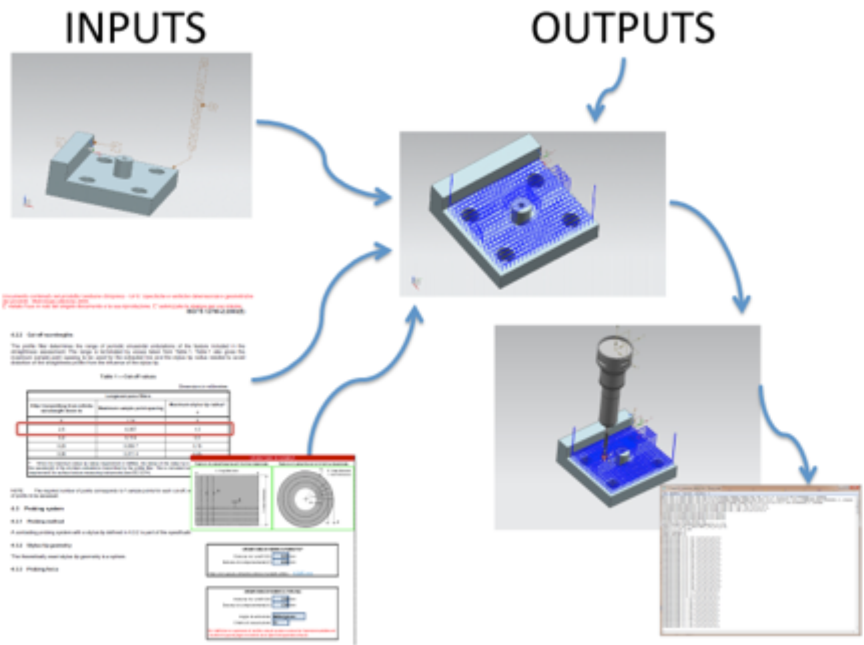


Fig. 49 – Definition of the actual verification operator activity

4.5.3.3 Prior estimation of measurement uncertainty

In order to calculate the method uncertainty, the VeM needs the information about the selected measurement instrument. A contact Coordinate Measuring Machine (CMM) was selected. Its parameters of measurement speed and travel, Maximum Permissible Error (MPE), probe diameter are stated in the sheet "Measurement set-up" (Fig. 50). The cost of the operation is also specified here and will be used to calculate the measurement cost.

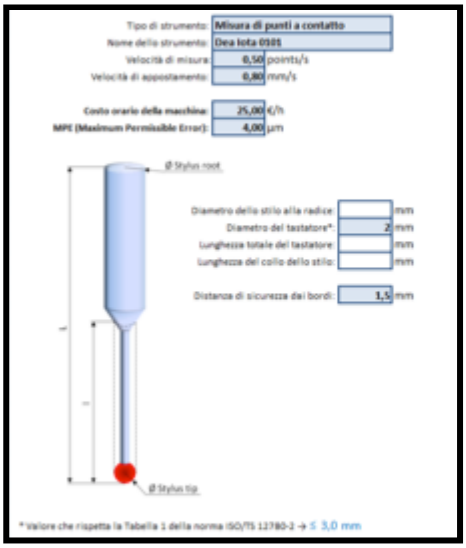
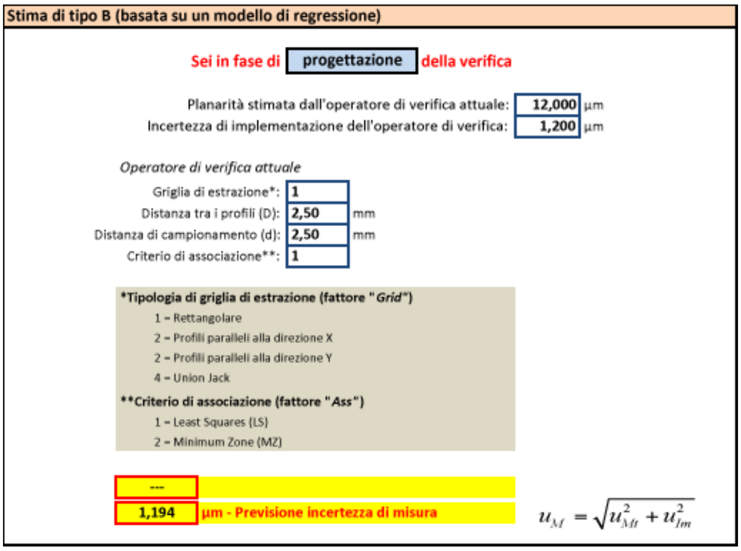


Fig. 50 – Verification Manager sheet "Measurement instrument parameters"

With the information about the Verification operator and measurement set-up, the VeM can finally estimate the uncertainty of the measurement process (Fig. 51).



Stima di tipo B (basata su un modello di regressione)

Sei in fase di **progettazione** della verifica

Planarità stimata dall'operatore di verifica attuale: 12,000 µm
Incertezza di implementazione dell'operatore di verifica: 1,200 µm

Operatore di verifica attuale

Griglia di estrazione*: 1
Distanza tra i profili (D): 2,50 mm
Distanza di campionamento (d): 2,50 mm
Criterio di associazione**: 1

***Tipologia di griglia di estrazione (fattore "*Grid*")**
1 – Rettangolare
2 – Profili paralleli alla direzione X
2 – Profili paralleli alla direzione Y
4 – Union Jack

****Criterio di associazione (fattore "*Ass*")**
1 – Least Squares (LS)
2 – Minimum Zone (MZ)

1,194 µm - Previsione incertezza di misura

$$u_M = \sqrt{u_{Mt}^2 + u_{Im}^2}$$

Fig. 51 – Verification management sheet "Measurement Uncertainty"

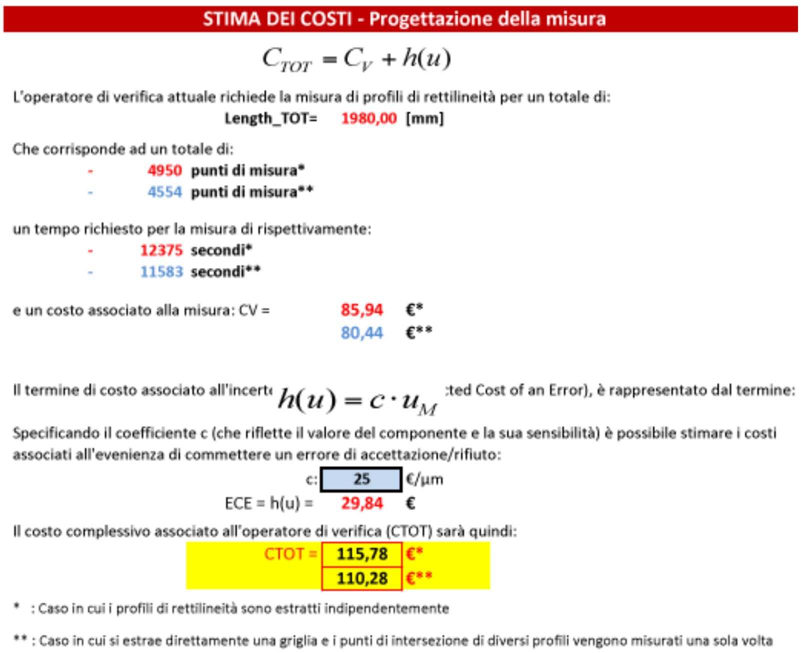
With these actions the metrologist forecast the uncertainty that a simplified verification operator introduced to the process. The VeM permits to simulate different verification operators and consequently to find the verification operator that optimizes the relation time-cost-uncertainty. The VeM is a powerful tool to drive the actions of designers and metrologist.

4.5.3.4 Forecast of measurement costs

The use of a simplified operator will reduce operation costs (machine usage + operator time) yet it will increase the risk to accept a wrong part (or to reject a good part). This is why it is essential to translate these possible mistakes into monetary units. The VeM makes two cost estimations:

1. It considers that all sampling points are taking once;
2. It considers that intersection points are measured only once.

The VeM gives an estimation of the time that it takes to the CMM to take the sampling points and the cost associated to it.



STIMA DEI COSTI - Progettazione della misura

$$C_{TOT} = C_V + h(u)$$

L'operatore di verifica attuale richiede la misura di profili di rettilineità per un totale di:
Length_TOT= 1980,00 **[mm]**

Che corrisponde ad un totale di:
- 4950 **punti di misura***
- 4554 **punti di misura****

un tempo richiesto per la misura di rispettivamente:
- 12375 **secondi***
- 11583 **secondi****

e un costo associato alla misura: CV = 85,94 €*
80,44 €**

Il termine di costo associato all'incert $h(u) = c \cdot u_M$:ted Cost of an Error), è rappresentato dal termine:

Specificando il coefficiente c (che riflette il valore del componente e la sua sensibilità) è possibile stimare i costi associati all'evenienza di commettere un errore di accettazione/rifiuto:

c: 25 €/µm
ECE = h(u) = 29,84 €

Il costo complessivo associato all'operatore di verifica (CTOT) sarà quindi:
CTOT = 115,78 €*
110,28 €**

* : Caso in cui i profili di rettilineità sono estratti indipendentemente

** : Caso in cui si estrae direttamente una griglia e i punti di intersezione di diversi profili vengono misurati una sola volta

Fig. 52 – Verification Management sheet "Measurement costs"

4.5.3.5 Set-up of measurement path plan

The measurement path plan of section 4.6.3.2 is not yet complete. It contains only the measurement points on the part but it lacks of the fixturing instructions of the part on the machine. No special fixturing is needed for the case study. It was decided to use plasticine to fix the part on the CMM.

4.5.4. Measurement

The measurement process (physical extraction according to the GPS definition) is executed by a CMM operator. He is responsible of preparing the CMM and of executing the measurement program on the real part Fig. 53.

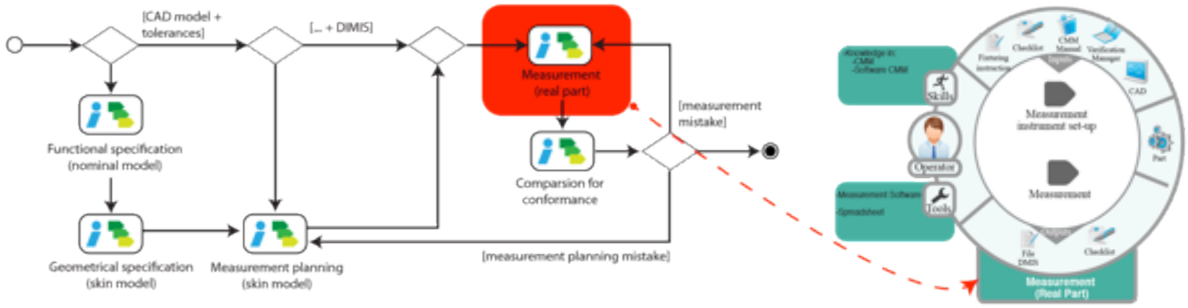


Fig. 53 – Workflow follow up Measurement

4.5.4.1 Measurement instrument set-up

During the CMM set-up, the probe calibration is an indispensable action. If probe calibration is not well executed, it will introduce measurement uncertainty. The instructions must contain the quantity of points to be measured in a metrological referenced sphere. These instructions are normally transmitted in a checklist.

4.5.4.2 Measurement

The CMM operator executes the resulting DMIS of section 4.6.3.2 on the real part (result of the manufacturing process) (Fig. 54). The result of the measurement operation is written in the FAI report.

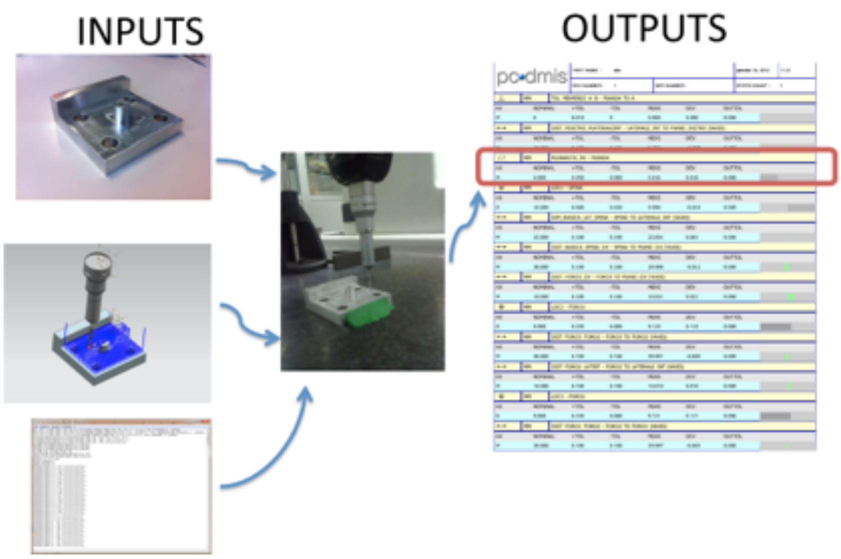


Fig. 54 – Measurement on the real part

4.5.5. Comparison for conformance

Finally, measuring results are comparing against the geometrical specification. This is the last step of the GPS workflow (Fig. 55).

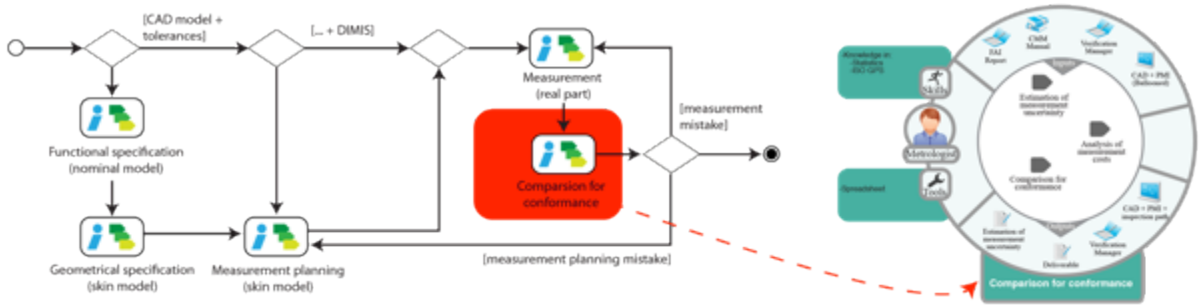
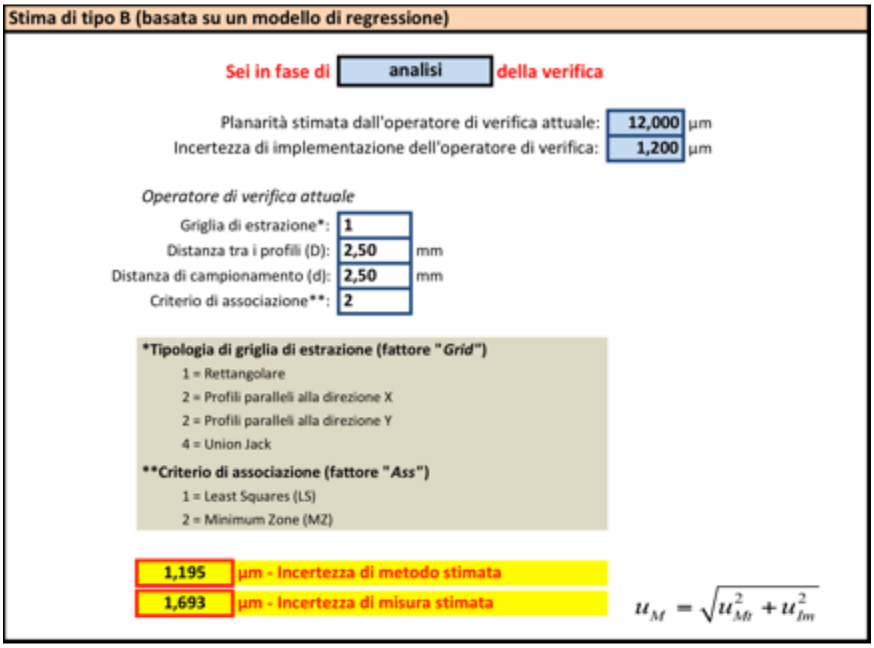


Fig. 55 – Workflow follow up Comparison for conformance

4.5.5.1 Estimation of measurement uncertainty

Every measurement process introduces uncertainties. Even if all parameters were contemplated and referred, the process must consider the MPE of the selected measurement instrument, the temperature of the room, etc.

Since the measurement was executed now is possible to estimate the uncertainties introduce by the measurement process. It includes the method and implementation uncertainties.



Stima di tipo B (basata su un modello di regressione)

Sei in fase di **analisi** della verifica

Planarità stimata dall'operatore di verifica attuale: 12,000 µm
Incertezza di implementazione dell'operatore di verifica: 1,200 µm

Operatore di verifica attuale

Griglia di estrazione*: 1
Distanza tra i profili (D): 2,50 mm
Distanza di campionamento (d): 2,50 mm
Criterio di associazione**: 2

***Tipologia di griglia di estrazione (fattore "*Grid*")**
1 = Rettangolare
2 = Profili paralleli alla direzione X
2 = Profili paralleli alla direzione Y
4 = Union Jack

****Criterio di associazione (fattore "*Ass*")**
1 = Least Squares (LS)
2 = Minimum Zone (MZ)

1,195 µm - Incertezza di metodo stimata
1,693 µm - Incertezza di misura stimata

$$u_M = \sqrt{u_{Mt}^2 + u_{Im}^2}$$

Fig. 56 – Verification Management sheet “Measurement uncertainty”

4.5.5.2 Estimation of measurement costs

In cases of instruments performing profiles extractions with contact probes the sampling time is given by the time necessary to extract the points plus the time for positioning the probe along the measurement path. This time is then considered as machine employment and can be quantified according to the machine use cost.

To this cost is also associated the possibility of committing a mistake in the acceptance of a non-conformance part.

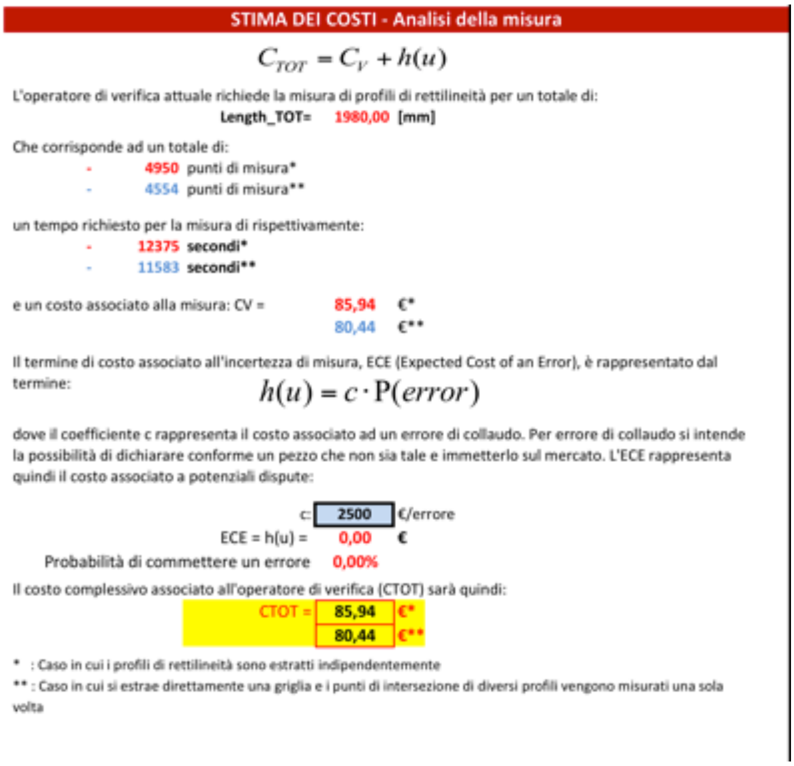


Fig. 57 – Verification Manager sheet “Estimation of measurement costs”

4.5.5.3 Comparison for conformance

The objective is to compare the defined specifications (skin model) with the results of the measurement (real surface). The comparison must include the estimated uncertainty of section 4.5.5.1. The final deliverable must indicate if the part is conformance to the specification (and thus to its function) Fig. 58.

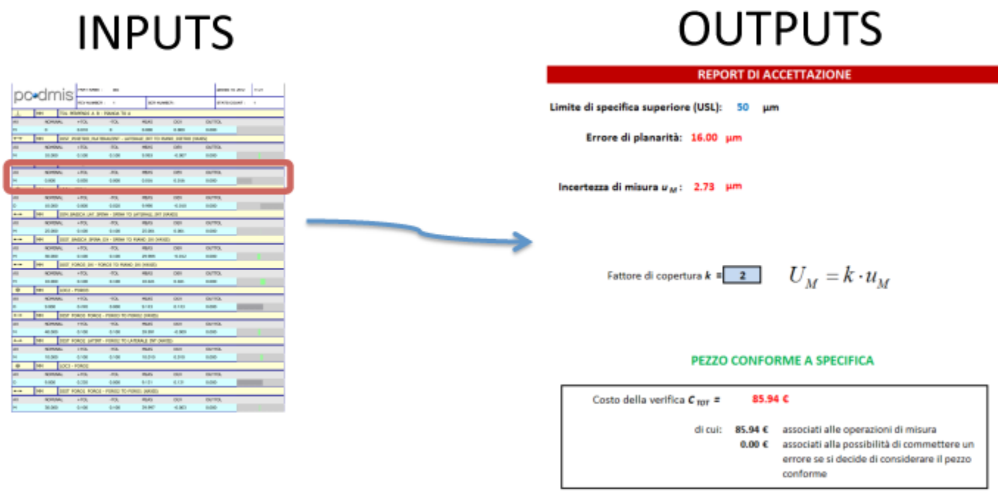


Fig. 58 – Comparison for conformance inputs and outputs

4.6 GPS in a PLM system

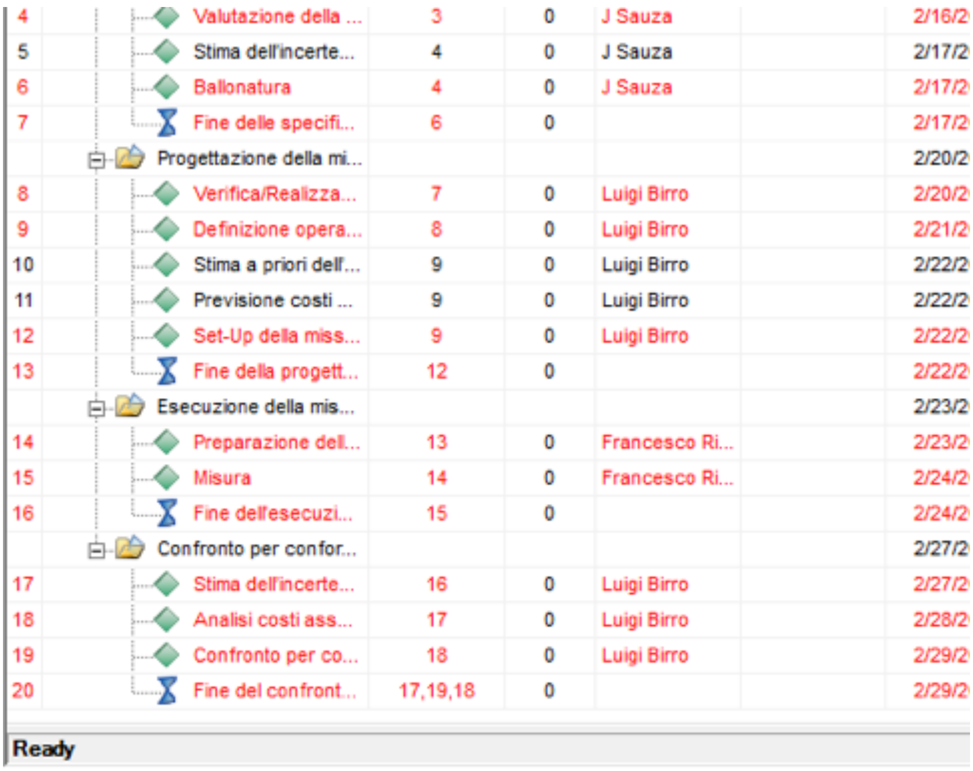
PLM is not just a technology, but rather an approach in which processes are as important as, or more important than, data [10]. The PDM software remains useless until the information needs and process behaviours are not defined. However, once the company's activity has been represented through the visualization model, the deployment of the model into the PDM is rather easy.

A PDM software requires some equipment to be deployed. For a small company it is necessary a server (hardware and software), a database, and client machines. The estimated cost for 1 server and 10 clients machines (including all operating system licenses but not the PDM software) is about 20,000 Euros.

On the market there are several PDM solutions for SME's. Most of them require the acquisition of server and client licenses. This would increment consistently the budget and represents an obstacle for PLM implementation. For this reason a PDM open source software (Aras innovator [11]) has been selected whose download is free and server license is provided just upon registration to the company's website. The open source software takes advantage of HTTP/HTTPS, XML, and SOAP protocols to deliver its functionality through a standard web browser (Explorer). No client licenses are needed though a small browser configuration is compulsory. An informatics technician can easily perform the installation of the PDM software and client configuration.

PLM activities are based on the definition of business objects suitable for representing the company operations. Normally, the definition of business objects requires the customization of PDM software, and a high level of expertise that usually belongs to consulting companies only. However, the business objects required by the case study's company were amongst those already available on the standard installation of the software, and no customization was needed.

Workflows and DDs can be implemented in the PDM software using different strategies: a project structure, an automatic workflow, or a combination of both. The open source software offers a project structure similar to Microsoft Project, that is very popular amongst designers, but with all the functionalities characteristic of PLM. Hence its selection came almost natural. The UML workflow of the visualization model has been translated into a project deploying the scheme graphically presented by the DDs (Fig. 59).



4	Valutazione della ...	3	0	J Sauza	2/16/2
5	Stima dell'incerte...	4	0	J Sauza	2/17/2
6	Ballonatura	4	0	J Sauza	2/17/2
7	Fine delle specifi...	6	0		2/17/2
	Progettazione della mi...				2/20/2
8	Verifica/Realizza...	7	0	Luigi Birro	2/20/2
9	Definizione opera...	8	0	Luigi Birro	2/21/2
10	Stima a priori dell'...	9	0	Luigi Birro	2/22/2
11	Previsione costi ...	9	0	Luigi Birro	2/22/2
12	Set-Up della miss...	9	0	Luigi Birro	2/22/2
13	Fine della progett...	12	0		2/22/2
	Esecuzione della mis...				2/23/2
14	Preparazione dell...	13	0	Francesco Ri...	2/23/2
15	Misura	14	0	Francesco Ri...	2/24/2
16	Fine dell'esecuzi...	15	0		2/24/2
	Confronto per confor...				2/27/2
17	Stima dell'incerte...	16	0	Luigi Birro	2/27/2
18	Analisi costi ass...	17	0	Luigi Birro	2/28/2
19	Confronto per co...	18	0	Luigi Birro	2/29/2
20	Fine del confront...	17,19,18	0		2/29/2

Ready

Fig. 59 – Project structure in Aras

The five-folder structure represents the five major steps of the workflow. The 15 activities are the 15 activities represented in the DD and in section 4.5. Moreover, every activity has an Activity completion form (Fig. 60) where it is stated the Project Manager, the leader (responsible) of the activity and activity information. The reproducibility of every activity is guaranteed by the use of checklists where every role working on the project states the accomplishment his tasks. Support information has been loaded on the system and identified in order to allow each person to access the file.

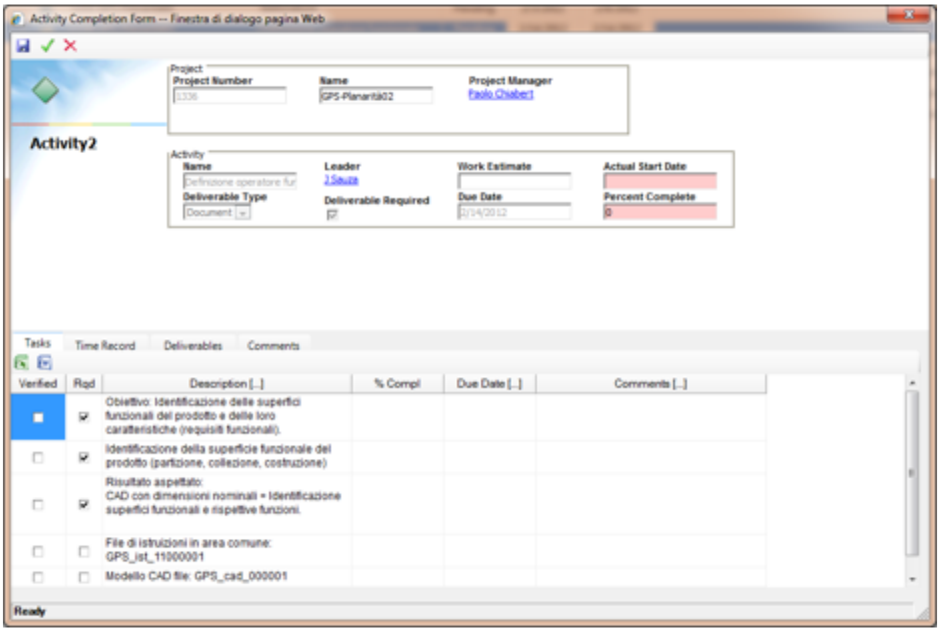


Fig. 60 – Activity Completion Form

For an easy control of information, every activity ends with a deliverable file (or Item) as work-product. Every document must be identified (document number); it must have a creator and an intended user (Fig. 60).

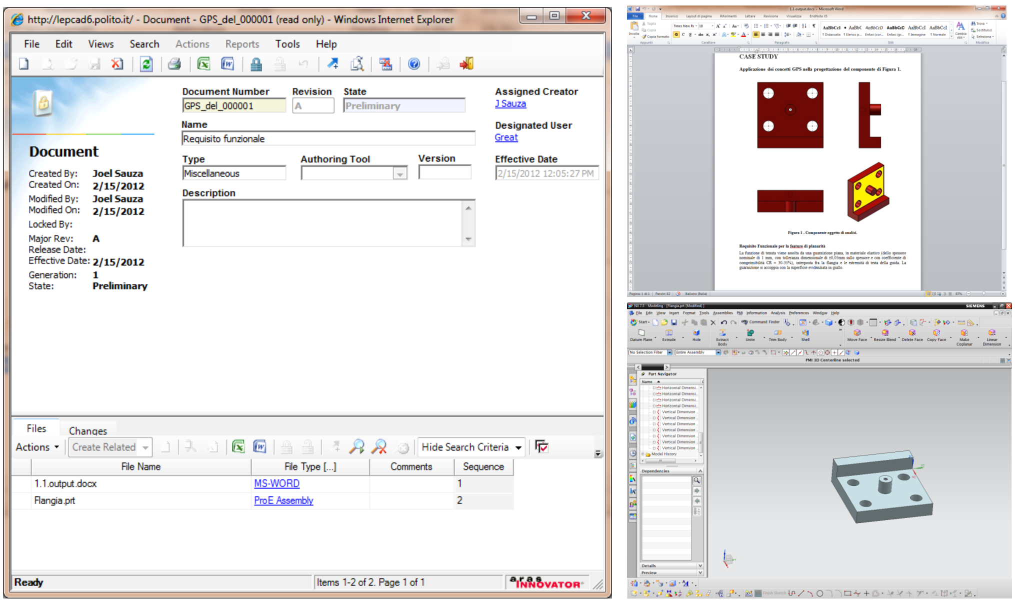


Fig. 61 - Deliverable

The PDM open source software uses a standard (CMII) for Configuration and Change Management. Engineering Change Notice (ECN), Engineering Change Request (ECR) and

Problem Reports (PR) are at the core of this process and are implemented by automatic workflows.

Aras uses a color codification to rapidly evaluate the progress of the project (Fig. 62). If preferred, it possible to see the project in a Gantt structure (Fig. 63). The project structure assures access to the information to all project participants. With the project ending it is possible to evaluate the individual and general performance of the project team.

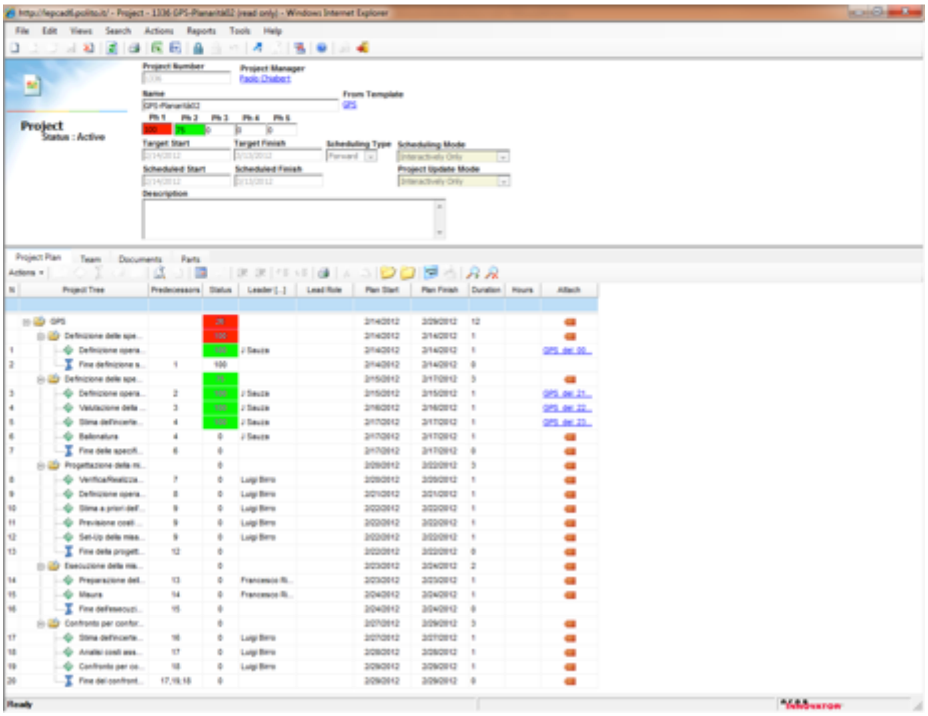


Fig. 62 – Project follow-up

The concurrency of activities is assured since it is possible to define relationships between activities. For example, the activities “prior estimation of measurement uncertainty” and “forecast of measurement costs” are not directly related and can be done in parallel, therefore this action will reduce process time.

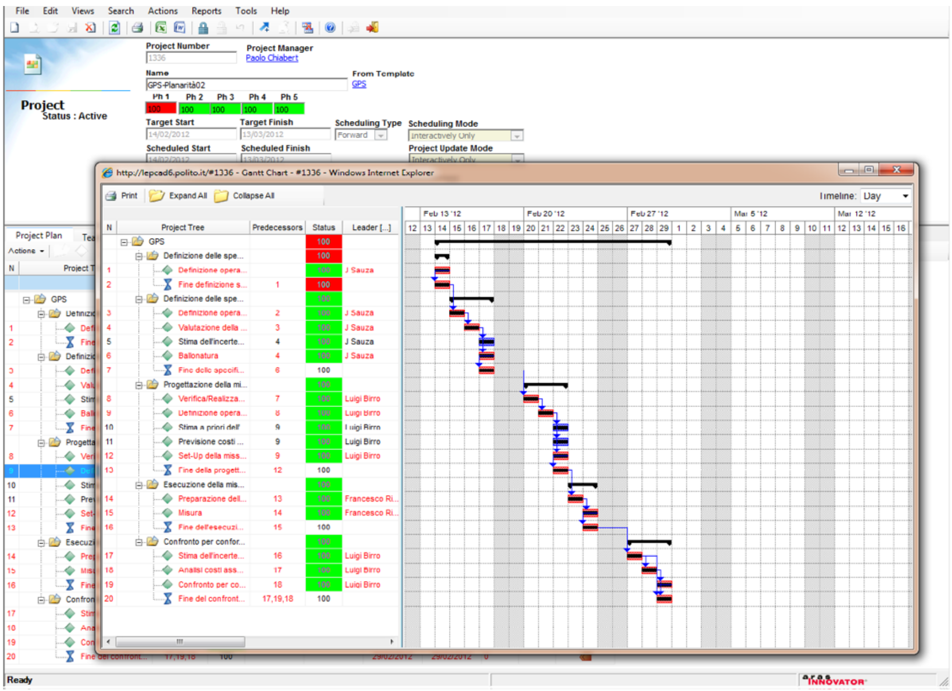


Fig. 63 – Project Ending

4.7 Chapter Conclusions

The visualization model proposed in chapter 3 helps understanding, modeling and improving industrial processes and provides a clear platform for PLM deployment. It addresses the actions and choices of designers, engineers, and metrologists, providing the right information to the right people at the right time. However, it goes some way beyond the original aim of enhancing the understanding of PLM and fostering its implementation in SMEs.

The visualization model is a powerful tool for information management; it shows the evolution of data along the project and the interaction between roles. The analysis of partners' product development processes is a complex task where the visualization model has provided a better understanding of processes and a clarification of the embedded hierarchy in people roles.

The visualization model simplifies the development of PLM applications to support people involved in the product development process. It reduces the gap between the tasks supported by PLM software and the real activities managed by designers, engineers and metrologists.

The GPS model can be employed by any company willing to shift to the innovative principles of GPS. Whether they want to do it in a PLM system or not, the model has quantified the need for information and has clarifies the activities and roles involved during product definition and verification.

The installation, configuration and use of the open source PDM were successfully deployed during the development of this project. The software proved efficiently its functioning.

GPS implementation in a PLM environment allows for a better information control and thus reducing uncertainties. The use of instruments, as the Verification Manager, helps in the assessments of uncertainties and cost that in actual industrial practices are not considered.

4.8 References

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Chapter 5. PLM solution as a support for industry

Over the last decade PLM has become one of the key technological and organizational approaches and enablers for the effective management of product development and product creation processes [1]. The past years have seen growing investments in the area of PLM.

Until now, PLM has been taught on isolated aspects without the necessary holistic approach. There is no educational curriculum for PLM that has examined integrated engineering processes [2]. In recent years industry and research has focused its attention to the innovative principles of PLM. However, PLM implementation stage at most organizations still does not apply the lifecycle management thoroughly [3]. Industry needs a new profile of engineers being able to work in a PLM environment. This means new engineers need to know the principles of PLM and they must know how to use the tools they will find at the time of joining the industry. These are some of the reasons why a PLM solution to support companies is necessary.

Centro Ricerca Fiat (CRF), an enabler of innovation inside FIAT Automobile Group, aims at developing new working methods and systems to ensure factory efficiency and flexibility and to meet market challenges. CRF became aware that the correct use of PLM technologies requires knowledge of the PDM instrument functionality and the methodology of use. Consequently, CRF decides to invest in the development of new students of automotive engineering at Politecnico di Torino through the project PLM@Poli. The main objective is to reproduce FIAT working method in an academic environment, in order to introduce students in the use of PLM technology. This will reduce the adaption time of new engineers in FIAT and this will help also its supply chain.

Business integration and collaboration is applied to all phases of the product lifecycle but it is particular challenging during product design and development, where unrestrained user-directed initiatives meet a boundary of business constraints establish under inter/intra enterprise integration [4]. As stated before PLM goes far beyond CAD integration. However, CAD integration is, normally, the first step that all enterprises take in order to implement PLM. The present solution deals with the definition of the rules for using PDM software within the scope of the CAD designing activity.

The course of Fundamentals of Machining Design and Drawing of Automotive Engineering at Politecnico di Torino aims to develop technicians with an in depth knowledge of building features and technologies for motor vehicles. Especially, the main objective of the course to give students the basic knowledge of the technologies used in the mechanical design aided systems. This course offered perfect conditions to test the PLM solution.

5.1 Case Study

A case study, an industrial clamp fixture (Fig. 64), was carefully chosen among other proposals. The clamp has a relative easy geometry but at the same time it presents technological difficulties as other complex parts.

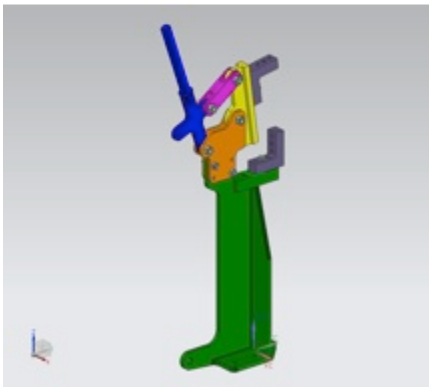


Fig. 64 – Industrial Clamp Fixture

Even though the clamp fixture is not a car component, it is used also in the car production. It is employed in the automotive industry to assemble and weld the car body in the production line (Fig. 65).

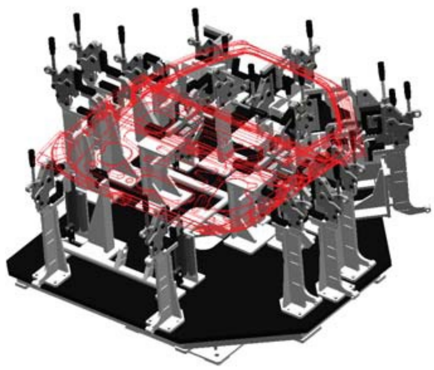


Fig. 65 – Automatically dressed fixture for production [5]

5.2 FIAT Requirements

FIAT internal processes more and more integrate information systems and communication technologies to manage process data. Since 2001, FIAT uses Siemens Teamcenter as PDM software in almost all its processes. Therefore the use of Teamcenter (TC) for preparing this course is a mandatory requirement.

Some requirements were established together with FIAT to structure a complete exercise using the CAD integrated methodology. Using the clamp exercise every student execute the following operations:

1. Create a Bill of Materials (BOM) with functional groups.
2. Design the 6 principal parts of the clamp.
3. Create a product variant (Actuator: Manual lever or piston).
4. The releasing of every part (Releasing part workflow).
5. Assembly the main parts and standard fasteners.
6. The releasing of the assembly (Assembly releasing workflow).
7. Perform a change on a part.

Fiat uses CODEP (an internal tool develop on FIAT) to create the BOM of its products. Since Politecnico could not have this tool, it is decided that the BOM will be created instead inside TC.

A car can be divided into functional groups that represent the various functions of the car: motor, chassis, break system, power train, etc. This situation can also be characterized with the clamp (see Fig. 66) and a structure is agreed. The clamp is divided into the functional groups: frame, kinematics, actuator and grips.

Moreover, a car has several configurations: 3 doors and 2.0 L motor or 5 doors and 2.5 L motor, etc. In the case of the clamps is decided to create a variant on the actuator of the clamp. Two possible configurations are proposed: manual lever and piston.

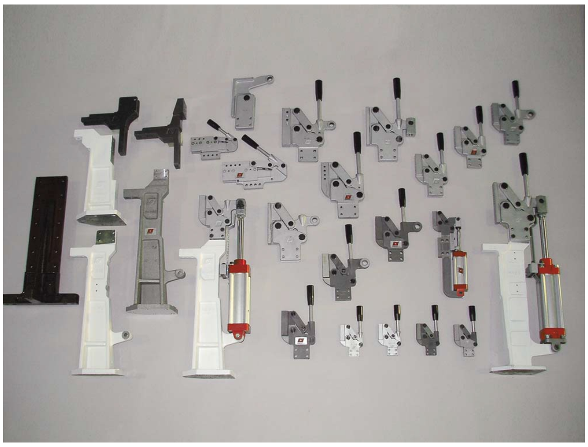


Fig. 66 – Clamp family parts (SIMPRO)

The design of the parts is performed using the integrated work method. This means that the operations of loading and saving the parts in the CAD NX must be transferred and managed in TC. Part and assembly releasing are done through the use of automatic workflows.

A design error is introduced intentionally in one of the parts in order to permit a change on a second moment.

5.3 Pilot Group

Politecnico di Torino is part of the PACE program and thanks to this international collaboration TC and NX are available at Politecntico.

The course of fundamentals of machine design and drawing until the year 2011 used the CAD software Solidworks as a tool for the lectures. The course expected to reach more than 100 students in the period September 2012-February 2013. To test a new tool, as complex as a PDM software and a new CAD system, with too many students was too risky. For this reason it was decided to test the contents within a Pilot Group.

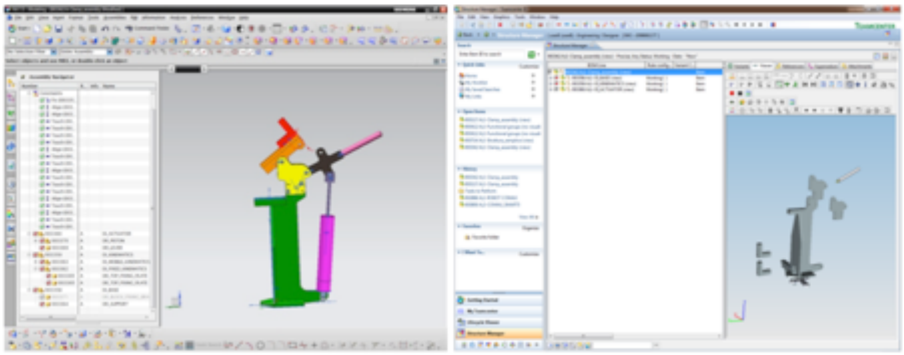
A small group of students from automotive engineering volunteered to test the contents of the course but with its new focus on mechanical design integrated in a PLM framework. The Voluntary Educational Program (VEP) PLM in automotive industry was held from March to July 2012. During this course, it was tested the introduction of TC and the change of CAD software from Solidworks to NX.

Within a controlled environment it was possible to test the PLM concepts, to define the structure of the case study, to study and to solve different organizational problems.

During the development of the VEP pilot course some important issues arose. As a consequence some of the established requirements could not be satisfied due to technical difficulties and to specific contents of the course.

TC has integrated to its functions the CAD software NX and a viewer for lightweight version of the 3D model (JT file). The JT is a high-performance, compact, persistent storage format for product data; used for product visualization, collaboration, and CAD data sharing. The JT files are automatically updated and syncrhonized to the PDM system during

CAD saving. The use of functional groups creates a completely unaligned situation between the CAD and the JT viewer. The parts in the viewer are at different positions with respect to the original 3d model (Fig. 67).



a) NX b) TC JT viewer

Fig. 67 – Visualization difficulties

In FIAT products are organized in functional groups, as described earlier. To assemble the parts, assembly constraints are employed but before releasing them, assembly constraints are eliminated. In this way, parts are not constrained to one another but in its perfect location. This condition creates a perfect alignment between the JT viewer and the CAD.

A functional group structure works as an empty box where all parts of a group are placed without any relationship. The final location of the part is given when all components are assembled. Nevertheless, the CAD system translates this empty box as a sub-assembly and it assumes that constraints are given to the parts. When parts are constrained at general assembly level, the JT file takes the position of the sub-assembly level (not part at final position in the assembly) and this situation creates the non-alignment between the CAD and JT.

The clamp exercise involves a kinematic test of the assembly (the clamp must open and close), thus assembly constraints are necessary. For this reason, functional groups could not be used instead a single level BOM was preferred. In a single level BOM, all parts are constrained at the same level and CAD and JT are synchronized.

In addition, the product variant was eliminated since the definition of a variant implied several steps of difficult reproduction. In FIAT, neither the creation of functional groups nor the definition of product variants are tasks executed by designers.

The results of the evaluation made to the pilot group demonstrated the need of a customization of the PDM software. The direct use of existing features of TC did not guarantee the correct representation of the desired design process.

Moreover, it was recognized the need for a model that accounts for the principal concepts of PLM while simultaneously serve as a guide for students. The visualization model (presented in Chapter 3) meets both characteristics and it was decided its used as a tool during the course.

5.4 PDM set-up

TC is a complex software capable of controlling all processes of an international company as FIAT. Nevertheless, training is necessary to understand and to manage the software. The cost of an 80 hours training must be considered by any enterprise willing to use TC as PDM software.

TC installation requires a deep knowledge on the software, server, database and network communications. Siemens training for server and client installation was necessary.

The PDM installation was held on July 2011 and had as a principal objective to define the TC two-tier architecture (communication client-database), the four-tier architecture (communication client - web application - server manager - database), and File Management System.

Server installation was firstly deployed on the lephv2 server of LEP laboratory and then reproduced in the server PLM of automotive engineering. TC client installation is available in more than 200 computers in different informatics laboratories.

On October 2011, user training on TC was accomplished at LEP laboratory. The user training was focused on TC engineering and covered all basics aspects of PLM: data management, basic user tasks, item and item revisions, product structure, CAD integration, product variants, embedded viewer and workflow design.

Finally, server administrative tasks were considered on the last training on September 2012. The overall purpose of the course was to extend the data model by creating business objects, classes, options, list of values, constants, access rules and to configure the application for use by creating business data and processes.

PDM server and client installation, user training and server administration activities were recorded and they are available, together with all Siemens manuals, at Laboratorio di Economia e Produzione (LEP) of Politecnico di Torino.

5.5 PDM customization

The customization activity is far the most complicated and difficult activity while creating a PLM solution. Over a seven months period different modifications were made to TC at different levels (client options, site variables, access rules, TC administrator, server manager).

The customization of PDM software implies the use of resources and thus costs. Costs optimization and time for solution deployment will depend on the degree of customization that the company needs.

The customization is by nature an information system project where product information and processes are tailored in a server.

5.5.1. Server Customization

In PLM, A business object is the fundamental entity to represent business model data. In short, business objects are all the things created in TC. Besides simply defining what values can be stored (storage classes), it is possible to outline the behaviour of business objects consequently it is possible to customizing it.

Some examples of business objects are: dataset, folder, form, item, item revision. Business objects are setting in the environment Business Modeller IDE (BMIDE) in TC database. In the BMIDE is possible to define the name of the business object (display names), to state the rules to configure its name (naming rules), to establish the values that it can take (list of values, LOVs), to describe the events to be done while copying or saving it (deep copy rules), to determine the necessary conditions needed before its creation (Pre-conditions) or the actions required after its creation (Post-actions).

Fig. 68 shows the structure of the BMIDE. On the upper left side there is the list of all business objects and on the right the properties of the selected business object.

The desired business object for the clamp exercise has the configuration shown in Fig. 69. The CORP_PART item is needed to have a naming rule made of 6 numbers, the identification of revisions with letters (A,B,C) and a free space for naming it.

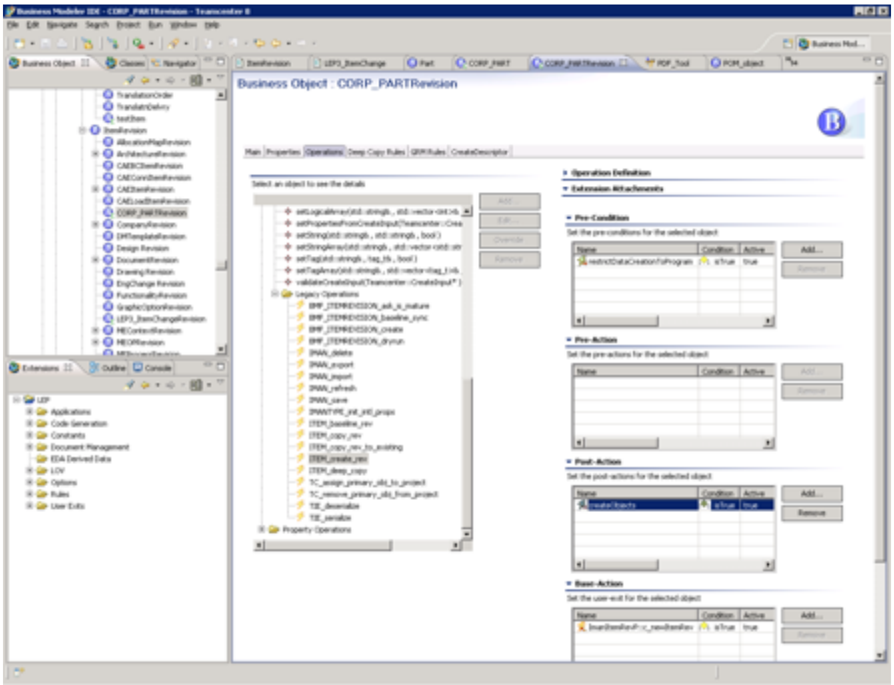


Fig. 68 – Business Modeler IDE

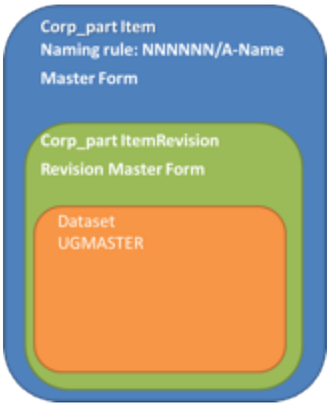


Fig. 69 – Item CORP_PART

When non-TC applications are launched, TC upholds the files generated. The objects used to manage these files are called datasets. In TC there are different kinds of datasets (Fig. 70) and they are typically linked to item revisions. When the item CORP_PART is created, it is desired that it must contain a dataset type UGMASTER. This dataset will contain the file .prt of the 3d model made in NX CAD software. The structure Item - Master form and ItemRevision - Revision Master Form is the standard structure for every item.

Symbol	Type	File	Purpose
	Text	.txt	Text document
	MSWord	.doc	MSWord document
	MSExcel	.xls	MSXExcel spreadsheet
	DirectModel	.jt	3D visualization model
	UGMASTER	.prt	NX part file

Fig. 70 – Datasets in TC.

To create the Item CORP_PART a copy of the Item type *Item* (which comes with standard installation of TC) was made. Then a series of modification were made to the display rules, deep copy rules and post-actions. Fig. 68 shows the change made to the post action to include the dataset UGMASTER after the creation of the item revision. The item CORP_PARTRevision was selected and in the operation (right side of the screen) ITEM_create_rev a post action (CreateObject→Dataset→Type UGMASTER) was inserted.

5.5.2. Client customization

Client customization is made with TC administrator privileges. Mainly, the customization of the client involves the definition of some variables values of some business objects. These variables can affect the whole installation (site variables) or just defined clients (client variables).

There are 1984 variables on TC, each of them controlling a specific behaviour of a business object on the system. Altering the value of one of these variables may affect the correct function of other parts of the system.

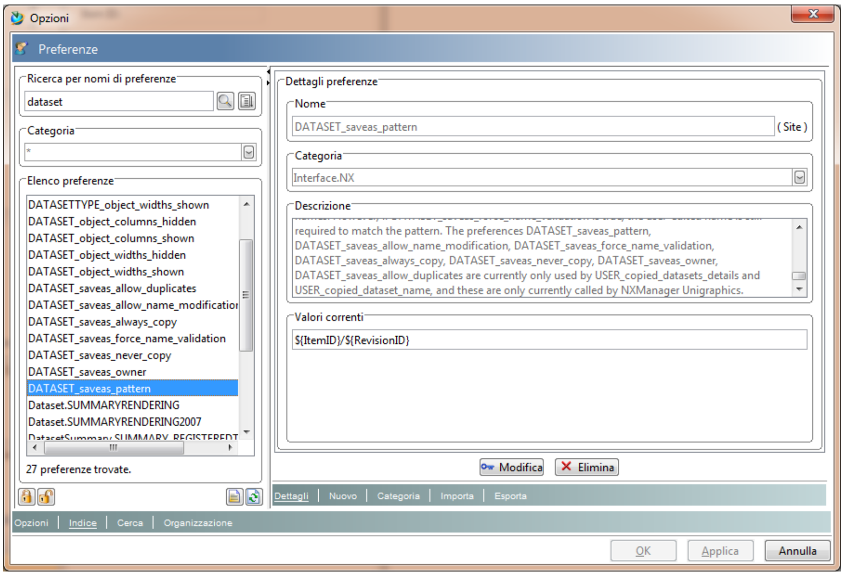


Fig. 71 – Variables definition

In Fig. 71, it is presented the Options menu of TC where variables are defined. In this case, the variable DATASET_saveas_pattern controls the comportment of the dataset UGMASTER of a NX file. While saving a new revision of an item, the dataset maintained the original revision A name (Fig. 72). In PLM, every Item and dataset must be identified uniquely in the server and this situation created two different dataset having the same name. By changing the value of the variable the problem was solve. The variable is a site variable and it affects the performance of the whole system.

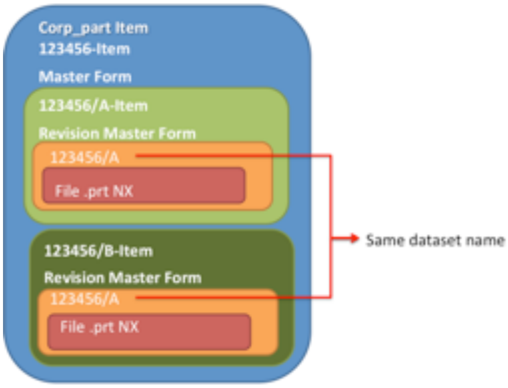


Fig. 72 – Dataset identification problem

5.5.3. Organization structure definition

An organization is a group of people structured and managed that will exchange information to reach goals. In the real world, an organization is made of departments (Design, Marketing, Production, etc), roles, responsibilities and authorities. The structure of the organization determines relationships between different activities and the members.

This complexity must be represented in TC in order to work in a PLM framework. A group (department) can be formed by subgroups that at the same time are composed by users. A real person must be associated to the TC user. One user can perform different roles in an organization.

The structure selected for the course has the structure of Fig. 73. The course is divided in two subgroups: professors and students. In this way, professors can share information about the course and all students have the same rules.

In the student subgroup every student is placed under a subgroup and a role. This decision was made to avoid unintended exchange of material. However, students may change some information during the development of the course. To solve this, there were needed some access rules to grant access information.

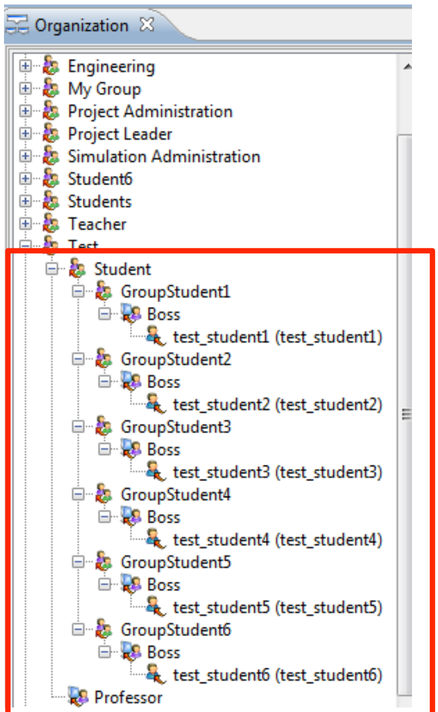


Fig. 73 – Organization for the course of fundamentals machine design and drawing.

5.5.4. Access rules

In this section user access to data and objects is defined. To do so, the configuration of the access control lists (ACL) was necessary. The ACL are located in the Access Manager menu of TC. The rules are structured in a tree (left side of Fig. 74). Rules are defined by a definition of conditions, a value for that condition and an ACL.

The desired behaviour of the CORP_PART consisted in the visibility to all members of the course of the items but the no visibility of the dataset UGMASTER between users of different groups.

In order to do so, a new rule (testACLNoRead) was created under the UGMASTER type class. It was associated to it an ACL (right side of Fig. 74). With this ACL, it was given permission to the owner of the dataset to modify the part while it was denied to members of other groups.

Rules are easy to configure but a modification on an ACL on one item can have an undesired behavior in another item. Many tests are necessary before reaching the perfect solution.

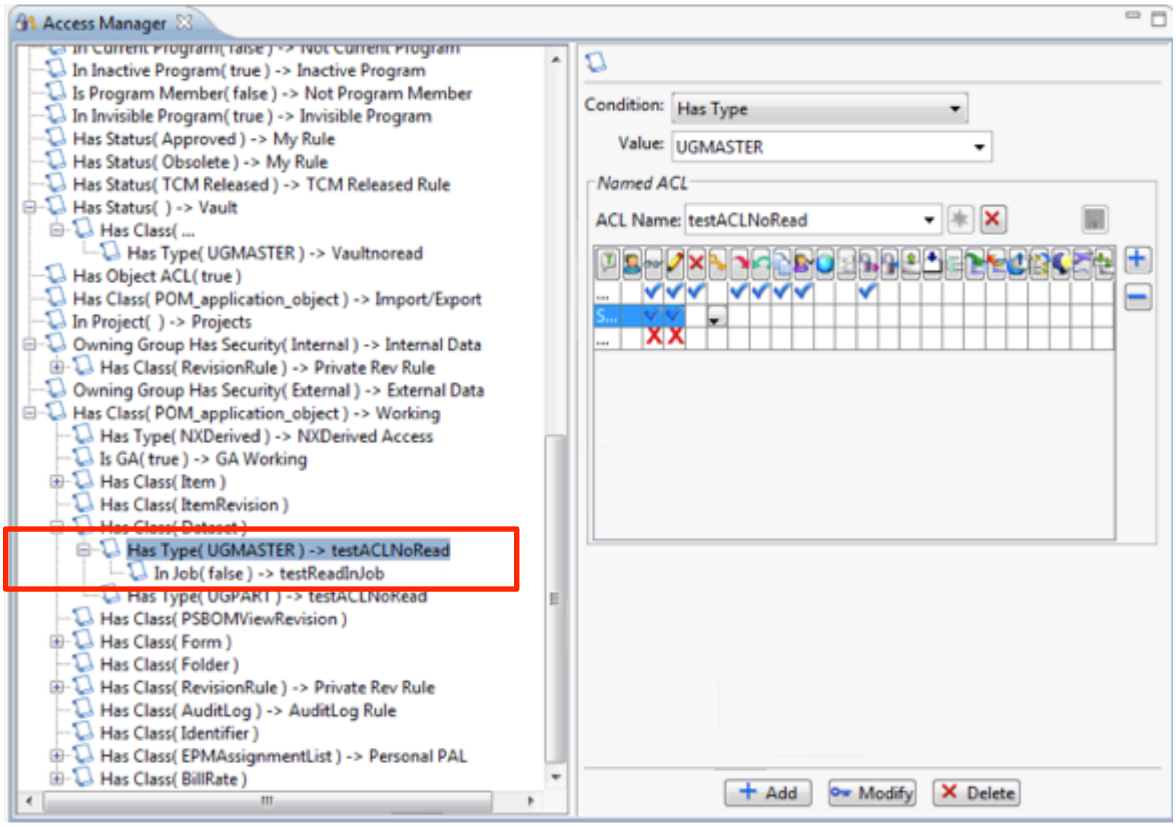


Fig. 74 – Access rules tree

5.5.5. Workflow designer

Looking forward to automate the operation in the Workflow Designer menu of TC it is possible to create workflows that represent the real work conditions of an enterprise. In Fig. 75 is presented a workflow example. After the workflow starting, the item enters into a decision activity. Activities can be directed to a specific role of the company or can be left open to decide each time to who address the request. After the decision is made there are two possibilities. If the decision is yes the item will take a released status (configuration management) and will be saved in the vault. If not the item will leave the workflow without any status. Three workflows were created for this exercise: Release part, release assembly and team release part.

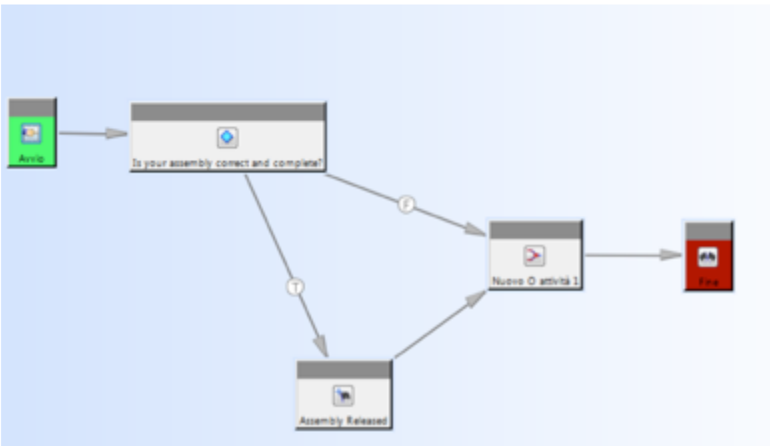


Fig. 75 – Workflow example

5.6 Course definition

General Course Aim:

- To give students the basic knowledge on the computer based systems used in the product development process (PDP) in order to support the enterprise decision process in very complex businesses

Knowledge and skills students will acquire:

- Work method independent of a specific CAD system
- Being familiar with the technologies used in mechanical CAD systems.
- To understand and evaluate the impact of new technologies on the working procedures.
- PLM general concepts
- Customers' needs that pushed enterprises to adopt PLM
- Concepts for integrating data in a complex enterprise
- To understand the connection with the technologies supporting the automotive product and manufacturing engineering

Prerequisites:

- Be familiar with the contents of Mechanical Drawing and Computer Aided Design

Structure:

- Lecture 24h; Exercise 24h;

During the lectures, students will learn all concepts of PLM in automotive industry. The use of TC is programmed to use 18 of the 24 hours of laboratory exercise.

It was decided to split the clamp exercise in two sections. In a first phase, every student works alone (creating the parts and making the assembly). In a second stage teams of 6 people work together exchanging information. Consequently from the 18 hours, 9 are considered for single user exercise and the rest hours for teamwork. Laboratory sessions are 3 hours each; which means that each part of the exercise occupies 3 lab sessions.

Both exercises are based on the use of the clamp assembly. Every student repeats the assembly twice yet different purposes are assessed. During the single user exercise, energies are focused to acquaint confidence with TC environment, to design the parts and to make GD&T tables of each component. Every student will be asked to design 6 principal parts of he clamp (Table 3) and to assemble them through the use of some standard fasteners (Table 4).

On the other hand, during the teamwork, students reuse the parts created in the single user exercise and focused their attention to the information exchange (principal use of TC). Using the resulting teamwork assembly, every student will simulate the motion and then detect any modification useful for correct its functioning.

The visualization model is used to transmit the concepts of the course. The methodology is based again on the concepts presented in section 4.3.1.

5.7 Visualization Model for fundamentals machine design and drawing

The resulting models were uploaded to the course webpage and all students had access to them. In addition to the model, parts drafting were also uploaded and referred to the model. The model is completed with 18 videos as a support of the operations.

Table 3 – Clamp parts

Part name	Quantity	Part Model
Support	1	
Rotary support	1	
Swinging transmission device	1	
Top fixing plate	2	
Operating lever	1	
Block fixing bracket	2	

Table 4 – Clamp standard fasteners

Part Name	Quantity
Hexagon head screw M8x34	2
Hexagon head screw M8x30	2
Hexagon head nut M8	2
Hexagon head screw M10x34	4
Hexagon head nut M10	4
Pin Ø6 x 24	2
Pin Ø6 x 30	4

In this section is presented only the complete single user model and partial representation of the teamwork model. The model is completed with activity sheets, which are located in Annex B, drafts of the parts in Annex C, Nx guide to model in annex D, drawing guide in annex E and the list of videos in Annex F.

5.7.1. Single User Model

In Fig. 76 is presented the workflow of activities for the single user exercise. The process starts with the creation of the Product Structure (or BOM) of the clamp. Then, every student creates the 3d models of the parts. After all parts are completed and released, the student assembles the parts together with the standard fasteners and finally releases the clamp assembly.

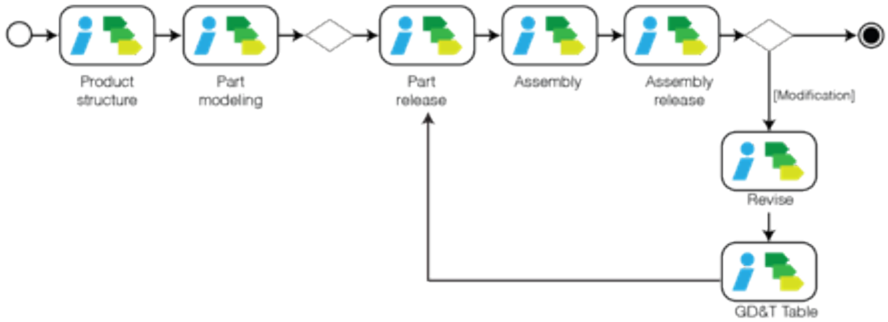


Fig. 76 – Single user Workflow

The part release and assembly release are part of the configuration management. Since students are new to the concepts in PLM it was decided to explicit these operations in the flow. The revision (also a part of the configuration management) and the GD&T table were place in that way as a direct request of the associated professor of the course in case time for the exercise was not enough.

For every module of the workflow, a decomposition diagram is needed in order to better understand the operations.

The product structure is created in the structure manager of TC. However, the resulting BOM is recognized only in TC. The integrated CAD NX must be synchronized with the PDM. For this reason Fig. 77 presents two activities, the creation of the product structure and manage pending components, where issues between instruments are solved.

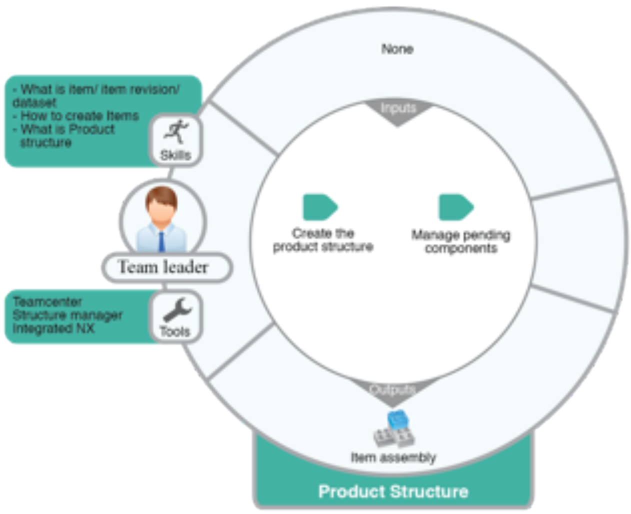


Fig. 77 – DD Product structure

The core of the exercise is the part modeling in the CAD system (Fig. 78). Students receive the drafts of every part (Annex C) and subsequently they execute the necessary steps for 3d modeling (and associated JT file) in integrated NX. Students are driven in one part creation during lessons and have as a support a PDF guide (Annex D).

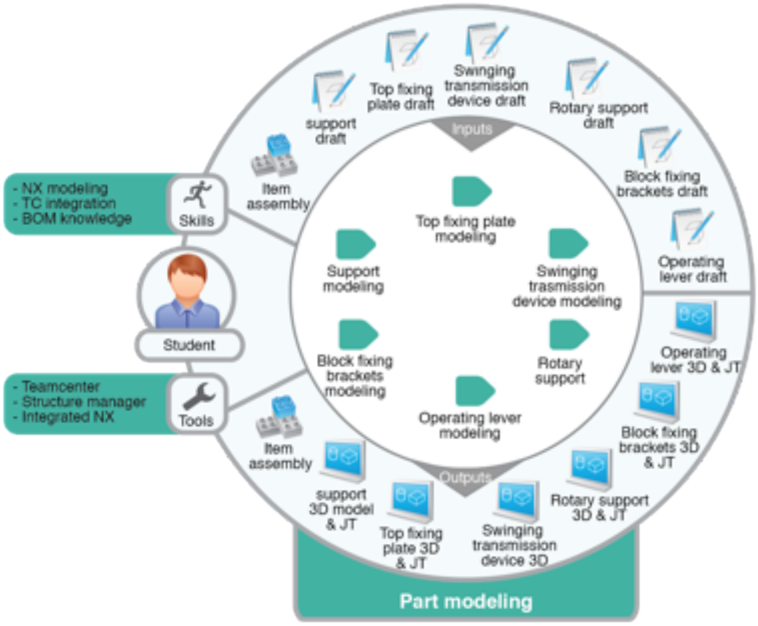


Fig. 78 – DD Part modeling

Once parts are completed, the next step is to release them using an automatic workflow (see Fig. 75) created during the customization of the PDM software. Every part is sent to the automatic workflow "Release Part". The student must operate the workflow (My Worklist) in TC in order to release the part. The release operation is repeated for every part (Fig. 79). The release of an item revision has the purpose of freezing the current status of the item, and then refers to it in the future. When a revision is released and submitted to a workflow, TC indicates the release status adding a flag.

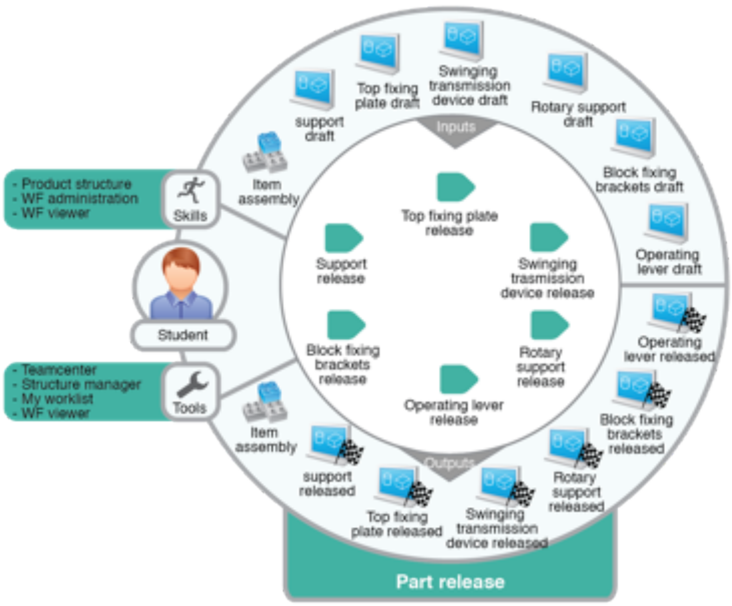


Fig. 79 – DD part release

The next step is to assemble the modeled parts together with some standard parts (screw, nuts and pins). Standard parts were loaded during customization of TC (Table 5). Through an item search students can load the standard parts to its own assembly.

Table 5 – Standard Fasteners ID

Part Name	Quantity	Item ID in TC
Hexagon head screw M8x34	2	001071
Hexagon head screw M8x30	2	001072
Hexagon head nut M8	2	001073
Hexagon head screw M10x34	4	001074
Hexagon head nut M10	4	001075
Pin Ø6 x 24	2	001076
Pin Ø6 x 30	4	001077

Subsequently, students duplicate the necessary parts in the structure manager of TC. Then, students constraints the assembly, mostly to the use of the touch align constraint. Finally, the assembly is set to a precise configuration. The five activities decomposition diagram is presented in Fig. 80.

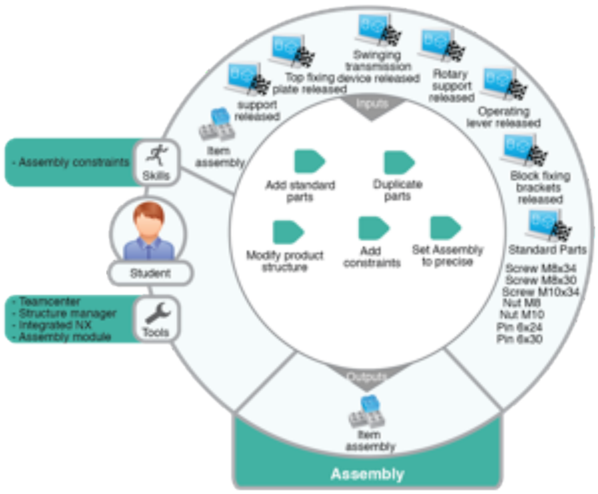


Fig. 80 – DD Assembly

The assembly is now complete and can be release (Fig. 81). To do so an automatic workflow "Release Assembly" is used. Again the student must operate the workflow in order to release it.

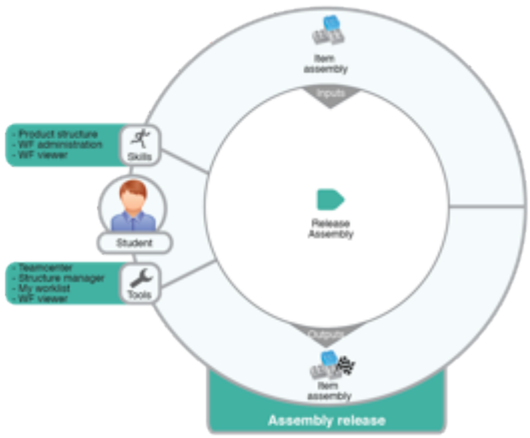


Fig. 81 – DD Assembly release

Once the assembly release is performed, to continue with work, a new revision must be created. The revision step considers the revision of the assembly and the revision of every part (Fig. 82).

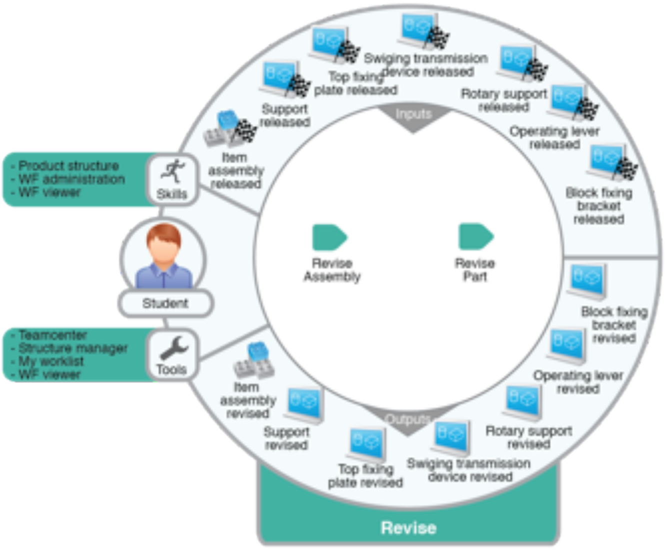


Fig. 82 – Revise

A draft must be associated to every part according to the GD&T standard (Fig. 83). To guide students to do it a drafting guide (Annex E) has been also prepared.

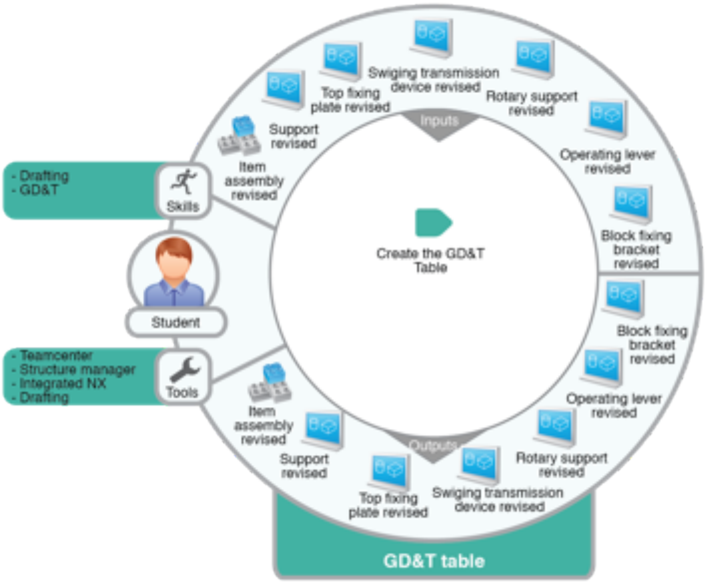


Fig. 83 – GD&T Table

Finally, after drafting completion, the flow goes back to release every part to set the assembly and to release it. The exercise is complete.

5.7.2. Teamwork

Every student during the teamwork will perform two roles: team leader and team member. As team leader the student is responsible of gathering parts from team members and to execute and release the assembly. As team member the student is asked to perform activities.

Groups of 6 students are formed and they exchange information between them according to the next design:

Table 6 – Part identification

ID number part	
N°	Item name
p1	Support
p2	Top fixing plate
p3	Rotary support
p4	Swinging transmission device
p5	Operating lever
p6	Block fixing bracket

Table 7 – Teamwork exchange matrix

Role	Team Mate							
Team leader			Do					
		USER	s1	s2	s3	s4	s5	s6
	Ask	s1	p1	p2	p3	p4	p5	p6
		s2	p6	p1	p2	p3	p4	p5
		s3	p5	p6	p1	p2	p3	p4
		s4	p4	p5	p6	p1	p2	p3
		s5	p3	p4	p5	p6	p1	p2
		s6	p2	p3	p4	p5	p6	p1

Each student shall act as a team leader asking his teammates to realize (do) the components of the assembly. For example, through a workflow, student s3 performing as a team leader asks:

- to s1 to realize the component p5
- to s2 to realize the component p6
- to s3 (himself) to realize the component p1
- to s4 to realize the component p2
- to s5 to realize the component p3
- to s6 to realize the component p4

In Fig. 84 is presented the workflow of activities for the team exercise. Since both exercises are very similar and to avoid content repetition it will be only presented the task assignment activity and the change to be done on the swinging transmission device.

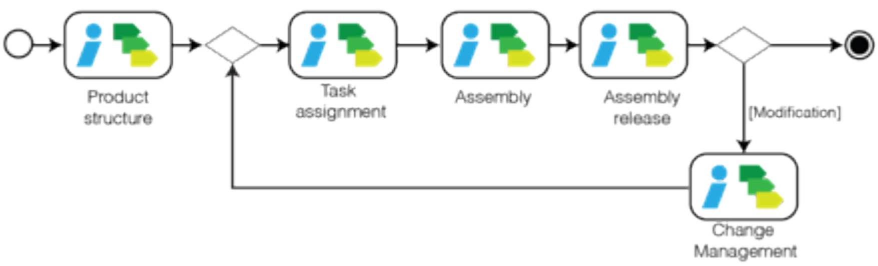


Fig. 84 – Teamwork Workflow

Every student performing as a team leader will ask 5 parts to other 5 team members. The remaining part is one of his own. The activity is performed through an automatic workflow "Release Team part" created during PDM customization. Every Team member will receive the task to perform and he must deliver the part. At the end of the workflow execution the part is released. The workflow assignment is made 6 times by the team leader, the workflow execution is an activity allocated to a team member and the workflow follow up is again responsibility of the team member (Fig. 85).

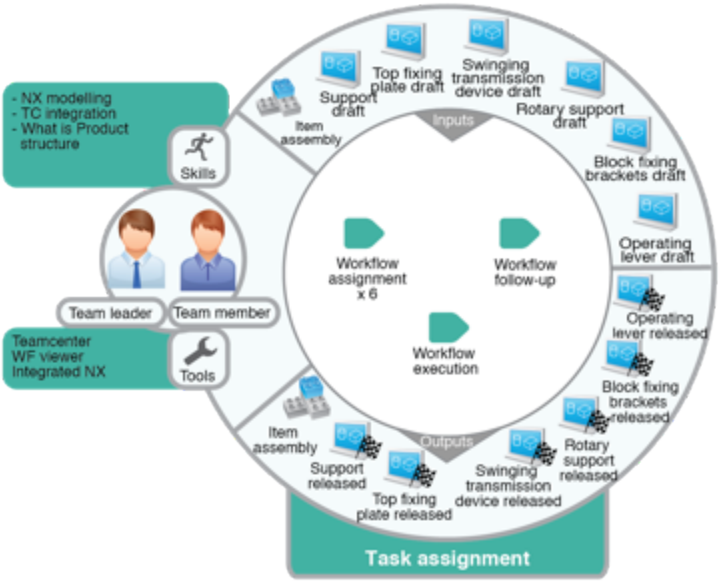


Fig. 85 – Task assignment

After the assembly completion, the team, analyze the mechanism. The "Top fixing Plate" is a critical part, because the two top fixing plates support all the others parts (not the support). In order to limit the deformations ant to achieve the full functionality of the clamp, the team Leader owner of the assembly has to:

a) Create a new working release of the assembly using TC,
b) Create a new item "TOP FIXING PLATE – new",
c) Model the new part in NX.
d) Modify the assembly by substituting the two "TOP FIXING PLATE" with the new one using TC structure manager.
e) Simulate the system motion to check.
f) Release the new part.
g) Release the assembly using TC.
h)

5.8 Results

102 students of different nationalities are using the visualization model and working with TC (Fig. 87). At the time of ending this thesis, all students completed successfully the single user exercise and teamwork. All activities were clear enough and the use of the videos as a support has simplified the explanations and the reduction of misguidance.

At the end of the course an anonymous questionnaire (Likert scale) was used for measuring perception of the VM model (10 questions) and the general contents of the course (further 10 questions). The complete questionnaire and analysis of all the variables can be found at Annex G. The more relevant aspects are listed below:

Positive Aspects:

- Students agree that the course achieved its objectives.
- Students have a fairly clear perception of the way product design is handled in a collaborative environment (Fig. 86a).
- Students found the VM a useful support for understanding PLM (Fig. 86b).

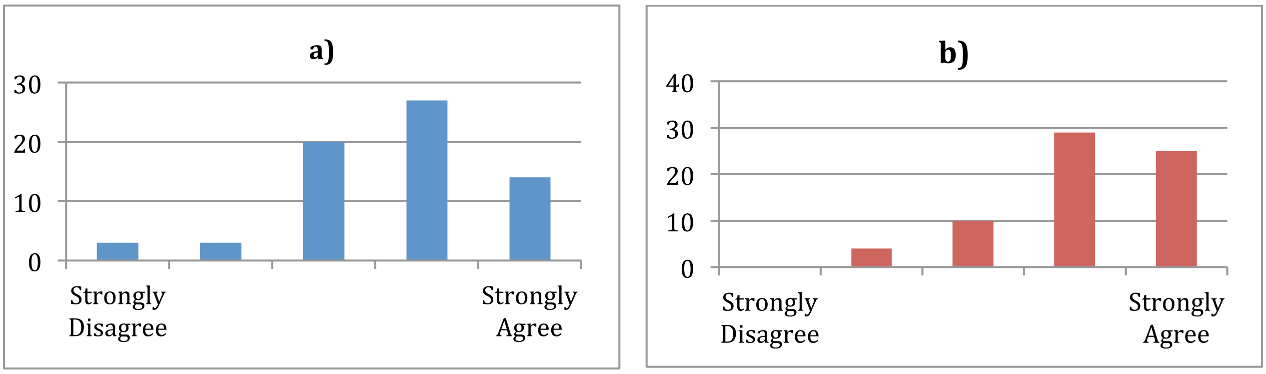


Fig. 86. Answers to questions: a) The PLM experience enlightened me on how product design is handled in a collaborative way by large companies b), I think the VM helps to understand PLM.

Negative Aspects:

- Too many interruptions due to Teamcenter crashes have been an obstacle for learning.
- The availability of informatics laboratories for exercising was insufficient.
- Students think that there was some inconsistency in the VM.

Several recommendations were outlined by students and are now being considering to improve next year course. Special attention has been given to Teamcenter for the several drawbacks that caused service interruption during the course. A cause-root analysis was performed and all problems were solved.

Fig. 87 – Fundamentals of machine design and drawing course

5.9 Conclusions

The FMDD course successfully integrated the CAD designing activity in a PLM system using a work methodology inspired by FIAT. A class of near 100 students of different nationalities used the VM as a guide for its work in the PLM environment. All students successfully completed the single and team exercise. All activities were fairly clear and the use of videos as a support has simplified the explanations and reduced the misinterpretations.

During this project, the PDM software Teamcenter has been effectively installed, customized and managed. The software is set up to grant access to 120 students.

The students of the course have been trained to work in a PLM environment. They have acquired the necessary skills to work in an integrated work method and they are able to understand and work in the PDM software Teamcenter. They are prepared to support industry to understand the holistic approach of PLM

The VM has proven to be an extremely effective training tool. It drove the actions of students, clarifying the activities at every step, and training them to work in a collaborative environment. Given the scarcity of PLM-specialized professionals on the work market, Politecnico di Torino is contributing to bridge the educational gap on PLM.

5.10 References

[1] Abramovici M., Future Trends in Product Lifecycle Management (PLM), in The Future of Product Development, F.-L. Krause, Editor 2007, Springer Berlin Heidelberg. p. 665-674.

[2] Kakehi M., Yamada T., and Watanabe I. (2009) PLM education in production design and engineering by e-Learning. Production Economics.

[3] Schuh G., et al. (2008) Process oriented framework to support PLM implementation. Computers in Industry, 59 210-218.

[4] Flaxer D., et al., Metrhod and apparatus for Product Lifecylce Management in a distributed environment enabled by dynamic business process composition and execution by rule inference, U.S.P.A. Publication, Editor 2004.

[5] SIMPRO. Design manufacturing and turnkey installation of equipment and plants. 2012; Available from: http://www.simpro.it/home.php?argid=51&pagid=15&lang=en.

Chapter 6. Conclusions

A content of novelty here is presented, as this work is the first complete application of GPS chain of standard to a product lifecycle. An experimental case study (flange) has been run to explore all the aspects ranging from the definition of geometrical specifications to the compliance verification of real workpieces, explaining the effort and highlighting the benefits.

The visualization model is a powerful tool to understand process and define the needs of information, roles, tools, knowledge and skills. The model answer to the questions who is doing what, when and how, thus clarifying every activity in a PLM process.

By applying the Visualization Model to understand the definition and verification process, the integration of GPS in a PLM business can be easily achieved. This integration allows a better information control and thus reducing uncertainties. The use of instruments, as the Verification Manager, helps in the assessments of uncertainties and cost that in actual industrial practices are not considered.

The GPS model can be employed by any company willing to shift to the innovative principles of GPS. Whether they want to do it in a PLM system or not, the model has quantified the need for information and has clarifies the activities and roles involved during product definition and verification.

The installation, configuration and use of an open source PDM and a market leader PDM were successfully deployed during the development of this thesis. Aras innovator has proven to be a useful tool particularly to SME’s due to simplicity of use and the free cost of the software. Teamcenter, instead, is appropriate for larger companies and requires a bigger effort to understand it and customize it.

The study has gone some way towards enhancing our understanding of PLM. The experience acquired from the development of the two case studies can be transmitted to the industry to help them to better understand GPS and PLM principles.

For being a visual tool, the visualization model has proven to be an extremely effective training tool. 102 students of automotive engineering from different countries are using the visualization model and working in a PLM environment.

The course of fundamentals machine design and drawing has successfully introduced the CAD designing activity integrated in a PLM system using (partially) FIAT work methodology.

Given the scarceness of PLM-specialized professionals on the work market, the visualization model is being used to educate the next generation engineers with very encouraging results, both in terms of students’ achievements and companies’ appreciation.

6.1. Results achieved by Specific Goals

SG. 1 - State of the art

- General overview of GPS and PLM.
- Identification of research opportunities.
- Review of 113 GPS standards.
- Review of 3 PLM books
- Review of 90 articles

- Identification of Journals 5 journals for publishing

SG. 2: Definition of a visual model representation of PLM

- Development of a tool to visualize PLM.
- It helps to understand and deploy PLM processes.

SG. 3: Implementation of the GPS principles in PLM

- Identification of improvements at Politecnico di Torino (CAD+PMI+DMIS).
- Process improvement: Verification process reduction on time → 40 to 8 hours.
- A complete implementation of a GPS chain of standard: Flatness.
- Identification of the process/tools/skills/roles/items/knowledge to successfully work GPS.
- «Dimostratore» procedurale del Controllo di Planarità nel quadro normativo ISO/GPS.
- 1-workflow/5 Decomposition diagram/15 activity sheets.
- Installation, customization and usage of ArasPDM software: Aras

SG. 4: PLM solution as a support for the industry

- PLM support for the course Fundamentals of machine design and drawing - Automotive Engineering.
- First real implementation of PLM in Politecnico di Torino (concepts / rules / instrument).
- 103 students (different countries) are using the model and using Teamcenter.
- Few examples in literature of a PLM solution as a training tool.
- Visualization Model for Fundamentals of Machine Design and Drawing
- Model deployment in Teamcenter LAIB Mirafiori
- Single: 1workflow/7 decomposition diagrams/ 23 activity sheets / 20 videos
- Team: 1 workflow/5 decomposition diagrams / 13 activity sheets / 20 videos

6.2. Dissemination

Table 8 – Conferences dissemination

Conference	Place
Visualization Model for Product Lifecyle Management	MOTSP 2012 Croatia
Implementazione GPS nel paradigma PLM	Avio - Rivalta
Implementazione GPS nel paradigma PLM	APR - Pinerolo
"Il GPS nell'industria aeronautica piemontese: l'esperienza del Progetto Great2020 ECOPROLAB OR3"	Unione Industriale Torino
Visualization Model for Fundamentals of machine design and Drawing	Politecnico di Torino

Table 9 – Paper dissemination

Paper	Journal
Visualization Model for Product Lifecyle Management	Annals of Faculty of Engineering Hunedoara
El proceso de Diseño en la Gestión del Ciclo de Vidad del Producto	ACTAS DE DISEÑO 14, Universidad de Palermo Argentina 2012.
A case study on the integration of GPS concepts into a PLM based industrial context.	Computer Aided Design

6.3. Limitations

The GPS model implementation was limited by the fact that industrial resources are restricted. Project partners evaluated positively the model and the complete test was performed at Politecnico di Torino. However, until the conclusion of this thesis the model have not been implemented in industrial practices. In the case of APR this is due to scarceness of economical resources. Avio is strongly motivated but before they can take the step modification to its organization structure (and consequently the PDM software) are needed.

Since this was the first application of a GPS chain of standard, the case study (flange) deals only with one type of tolerance. This choice was made to simplify the identification of the tolerance all along the lifecycle. However, in real conditions a complex part has several different kinds of tolerances.

The visualization model for fundamentals machines design and drawing could not satisfy FIAT requirements of functional groups and product variant due to technical difficulties and to specific contents of the course. The use of the clamp comprises a kinematics analysis and this creates a visualization problem in Teamcenter. If this situation wants to be solved another case study must be evaluated.

In Teamcenter, operations can be done in many ways. For example the product structure can be created in the structure manager or directly in the integrated CAD system NX. The use of the visualization model forces the selection of only one solution.

6.4. Recommendations for further work

The first steps have been taken in order to apply the complete chain of GPS standard. However, further effort must be done in future research to understand and incorporate to the GPS visualization model other kinds of tolerances.

Considerably more work will need to be done to illustrate the benefits of GPS and motivate industry to apply GPS principles.

This work deals with different stages of the product lifecycle. Nevertheless it has mainly focused its attention to the product information. From here it is possible to connect to other stages of product lifecycle: process information, supply chain, marketing, etc. Research on manufacturing process integration in PLM has already started and experimental investigations are needed to confirm its validity.

Appendices

Annex A. Activity sheets of the Visualization Model for GPS

Table 10 – Definition of functional operator

<table>
<tr><th colspan="2">Definition of functional operator</th></tr>
<tr><td colspan="2">Target:
Identification of functional surfaces of the product and its features (functional requirements).</td></tr>
<tr><td colspan="2">Operation:
Identification of the functional surface of the product (Partition, Collection, Construction)</td></tr>
<tr><td>Input items:
• International Standard
• Best practices
• CAD Model with nominal dimensions
• Functional requirements</td><td>Output items:
• CAD with nominal dimensions.</td></tr>
<tr><td colspan="2">Role:
Designer</td></tr>
</table>

Table 11 – Definition of the specification operator

<table>
<tr><th colspan="2">Definition of the specification operator</th></tr>
<tr><td colspan="2">Target:</td></tr>
<tr><td colspan="2">Definition of geometrical specification: flatness tolerance</td></tr>
<tr><td colspan="2">Operation:</td></tr>
<tr><td colspan="2">• Identification of the surface (Partition, Collections, Construction)
• Definition of the flatness tolerance:
o Symbol
o Tolerance value
o Cut-off value (Extraction – Filtering)
o Association method (Association)</td></tr>
<tr><td>Input items:</td><td>Output items:</td></tr>
<tr><td>• International Standard
• Best practices
• CAD Model
• Feature function</td><td>• CAD + PMI (Ballooning)</td></tr>
<tr><td colspan="2">Role:
Designer</td></tr>
</table>

Table 12 – Estimation of correlation uncertainty

Estimation of correlation uncertainty	
Target: Evaluate the performance of the geometrical specification / estimate the uncertainty of correlation	
Operation: • Import CAD model (+ PMI) • Functional simulation. • Analysis of simulation results. • Identification of the distance between the operator and specification operator and the functional operator. • Estimation of correlation uncertainty.	
Input items: • International Standard • Best practices • CAD Model + PMI • Feature function	**Output items:** • Correlation uncertainty
Role: Designer	

Table 13 – Estimation of specification uncertainty

Estimation of specification uncertainty	
Target: Performance evaluation of geometrical specification in terms of specification uncertainty.	
Operation: • Definition of the geometrical specification • Estimation of specification uncertainty	
Input items: • CAD Model + PMI	**Output items:** • Estimation of specification uncertainty
Role: Designer	

Table 14 – Automatic Ballooning

Automatic Ballooning	
Target: Identification of geometrical specification with electronic ballooning	
Operation: • Electronic ballooning of CAD Model	
Input items: • Best Practice • CAD Model + PMI	**Output items:** • FAI Report • CAD+PMI (Ballooned)
Role: Designer	

Table 15 – Verification/Implementation of manual ballooning

Verification / Implementation of manual ballooning	
Target: Review or definition of manual ballooning of geometrical specifications.	
Operation: • Manual Ballooning of CAD Model	
Input items: • Best Practices • CAD Model + PMI	**Output items:** • FAI Report • Design drafting ballooned
Role: Metrologist	

Table 16 – Definition of the actual verification operator

Definition of the actual verification operator	
Target: Optimization of measurement parameters	
Operation: • Feature identification (Partition, Collections, Construction) • Definition of number of points (Extraction and Filtering) • Definition of the coordinate of measurement and travel points • Selection of the Association Method (Association)	
Input items: • Best Practices • International Standard • CMM Manual • CAD Model +PMI (ballooned) • Verification Manager instructions	**Output items:** • File DMIS • CAD Model +PMI + Inspection path • Verification manager (sheet «Verification operator»)
Role: Metrologist	

Table 17 – Prior Estimation of measurement uncertainty

Prior estimation of measurement uncertainty	
Target: To have an indication about the performance of the measurement in terms of measurement uncertainty	
Operation: • Identification of the geometrical specification • Generation of artificial samples • Evaluation of uncertainty: o Associated to simulated samples o From a database of related evidence	
Input items: • Metrological characteristics of the measuring instrument • Metrological parameters • Experimental data (previous experience) • Part Characteristics (material, geometry, etc.) • Actual verification operator (File DMIS, CAD Model +PMI + Inspection Path) • Verification Management instructions • FAI Report	**Output items:** • Verification Manager (sheet «uncertainty estimation»)
Role: Metrologist	

Table 18 – Forecast of measurement costs

Forecast of measurement costs	
Target: Evaluation of the costs associated to the measurement taking into account the uncertainties introduced by the simplified verification operator (different from the perfect verification operator) and the set-up of the measuring instrument	
Operation: • Selection of the measuring instrument • Definition of measurement and travel speed • Calculation of costs associated to the: o Number of measurement and travel points o Uncertainty estimated for the measurement process	
Input items: • International Standard • Actual verification operator (File DMIS, CAD Model +PMI+ Inspection Path) • Estimation of measurement uncertainty (B type) • Verification manager instructions	**Output items:** • Cost Report • Verification Manager (sheet »Set-up measurement» and «Cost forecast»)
Role: Metrologist	

Table 19 – Set-up of measurement path plan

Set-Up of measurement path plan	
Target: Part positioning, clamping and creation of the reference system for the part measurement	
Operation: • Identification of the geometrical elements to be measured • Positioning of the piece on the machine • Selection of the probe / s • Definition of the reference system on the workpiece (alignment)	
Input items: • International Standard • Best practices • CMM Manual • CAD Model +PMI (Ballooned) • “Verification Manager”	**Output items:** • Fixturing instructions • File DMIS alignment
Role: Metrologist	

Table 20 – Measurement instrument set-up

Measurement instrument set-up	
Target: Probe calibration	
Operation: • Axis calibration • Selection of the calibration sphere • Probe calibration	
Input items: • Check list • CMM Manual	**Output items:** • Check list
Role: CMM operator	

Table 21 – Measurement

Measurement	
Target: Execution of measurement path plan	
Operation: • Clamping of the real part on the machine • Coordinate system definition on real part • Measurement execution DMIS file (Physical extraction)	
Input items: • Fixture instructions • FAI Report • CAD Model +PMI • File DMIS • Part • CMM Manual • Check list	**Output items:** • Check list • FAI Report
Role: CMM Operator	

Table 22 – Estimation of measurement uncertainty

Estimation of measurement uncertainty	
Target: Estimation of measurement uncertainty	
Operation: • Estimation of the form error and the implementation uncertainty • Estimation of Method uncertainty • Estimation of measurement uncertainty (+ method implementation) • Analysis FAI report	
Input items: • FAI Report	**Output items:** • Estimation of measurement uncertainty • Verification Manager (sheet «Uncertainty estimation»)
Role: Metrologist	

Table 23 – Estimation of measurement costs

Estimation of measurement costs	
Target: Evaluation of the costs associated to the measurement taking into account the uncertainties introduced by the simplified verification operations (different from the perfect verification operator) and the set-up of the measuring instrument	
Operation: • Measuring instrument selection • Calculation of costs associated with: o Number of measurement points and travel points o Estimated Measurement uncertainty	
Input items: • International Standard • Actual verification operator (File DMIS; CAD Model + PMI + Inspection path) • Estimation of measurement uncertainty • Verification manager instructions	**Output items:** • Cost report • Verification Manager (sheet »Set-up measurement» e «cost Analysis»)
Role: Metrologist	

Table 24 – Comparison for conformance

Comparison for conformance	
Target: To compare the defined specifications (skin model) with the results of the measurement (real surface)	
Operation: • Comparison between the FAI report output (geometric error estimated and measurement uncertainty) and the specification	
Input items: • Report FAI • CAD Model +PMI • Verification Manager	**Output items:** • Deliverable • Verification Manager (sheet «Acceptance report»)
Role: Metrologist	

Annex B. Activity sheets of the visualization model fundamentals of machine design and drawing.

Table 25 – Create the product structure

<table>
<tr><th colspan="2">Create the Product Structure</th></tr>
<tr><td colspan="2">Target:
To create the product structure (BOM) of the assembly.</td></tr>
<tr><td colspan="2">Operation:
• Create an Item CORP_PART: Assembly
• Select the Item Revision of the Assembly and Send To- Product Structure
• Create under the Assembly 6 Item CORP_PART:
    o Support,
    o Top_Fixing_Plate,
    o Swinging Transmission Device,
    o Rotary_support,
    o Block_Fixing_Bracket,
    o Operating_Lever
• Save the product structure</td></tr>
<tr><td>Input items:
• None</td><td>Output items:
• Product structure (Assembly + 6 parts)</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
Video: 01_How to create a product structure</td></tr>
</table>

Table 26 – Manage pending components

<table>
<tr><th colspan="2">Manage Pending Components</th></tr>
<tr><td colspan="2">Target:
To solve conflicts between Teamcenter and NX</td></tr>
<tr><td colspan="2">Operation:
• Open the UGMASTER dataset under the Item Revision of the Assembly
• In integrated NX select MODEL in the Template menu
• A warning will appear and you will be asked to go to Assemblies→ Components →Manage Pending Components
• Add the six parts as model under the assembly·
• Save the assembly</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)</td><td>Output items:
• Product structure (Assembly + 6 parts)</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
Video: 02_Manage pending components</td></tr>
</table>

Table 27 – Support Modelling

<table>
<tr><th colspan="2">Support Modelling</th></tr>
<tr><td colspan="2">Target:
Support modelling</td></tr>
<tr><td colspan="2">Operation:
• Open the dataset of Support in NX
• Open the PDF file of the Support Draft
• Model the part in NX
• Save the model
• Go to File→Options→Save Options →JT data</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)
• Support draft</td><td>Output items:
• Product structure (Assembly + 6 parts)
• Support 3d model + JT</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
Video: 03_Open support dataset
Video: 04_Save JT
PDF: Support draft
PDF: Rotary support operative guide</td></tr>
</table>

Table 28 – Top fixing plate modeling

<table>
<tr><th colspan="2">Top fixing plate Modelling</th></tr>
<tr><td colspan="2">Target:
Top fixing plate modelling</td></tr>
<tr><td colspan="2">Operation:
• Open the dataset of Top Fixing plate in NX
• Open the PDF file of the Top Fixing plate Draft
• Model the part in NX
• Save the model
• Go to File→Options→Save Options →JT data</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)
• Top fixing plate draft</td><td>Output items:
• Product structure (Assembly + 6 parts)
• Top fixing plate 3d model + JT</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
PDF: Top Fixing plate draft</td></tr>
</table>

Table 29 – Swinging transmission device modeling

<table>
<tr><th colspan="2">Swinging transmission device Modelling</th></tr>
<tr><td colspan="2">Target:
Swinging transmission device modelling</td></tr>
<tr><td colspan="2">Operation:
• Open the dataset of Swinging transmission device in NX
• Open the PDF file of the Swinging transmission device Draft
• Model the part in NX
• Save the model
• Go to File→Options→Save Options →JT data</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)
• Swinging transmission device draft</td><td>Output items:
• Product structure (Assembly + 6 parts)
• Swinging transmission device 3d model + JT</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
PDF: Swinging transmission device draft</td></tr>
</table>

Table 30 – Rotary support modelling

<table>
<tr><th colspan="2">Rotary support Modelling</th></tr>
<tr><td colspan="2">Target:
Rotary support modelling</td></tr>
<tr><td colspan="2">Operation:
• Open the dataset of Rotary support in NX
• Open the PDF file of the Rotary support Draft
• Model the part in NX
• Save the model
• Go to File→Options→Save Options →JT data</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)
• Rotary support draft</td><td>Output items:
• Product structure (Assembly + 6 parts)
• Rotary support 3d model + JT</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
PDF: Rotary support draft</td></tr>
</table>

Table 31 – Operating lever modelling

Operating lever Modelling	
Target: Operating lever modelling	
Operation: • Open the dataset of Operating lever in NX • Open the PDF file of the Operating lever Draft • Model the part in NX • Save the model • Go to File→Options→Save Options →JT data	
Input items: • Product structure (Assembly + 6 parts) • Operating lever draft	**Output items:** • Product structure (Assembly + 6 parts) • Operating lever 3d model + JT
Role: Student	
Attached information: PDF: Operating lever draft	

Table 32 – Block fixing brackets modelling

Block fixing brackets Modelling	
Target: Block fixing brackets modelling	
Operation: • Open the dataset of Block fixing brackets in NX • Open the PDF file of the Block fixing brackets Draft • Model the part in NX • Save the model • Go to File→Options→Save Options →JT data	
Input items: • Product structure (Assembly + 6 parts) • Block fixing brackets draft	**Output items:** • Product structure (Assembly + 6 parts) • Block fixing brackets 3d model + JT
Role: Student	
Attached information: PDF: Block fixing brackets draft	

Table 33 – Support release

Support Release	
Target: To check and give the state of release to the Support part.	
Operation: • Select the Item Revision of the Support • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Block fixing brackets 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Block fixing brackets 3d model + JT released
Role: Student	
Attached information: Video: 05_Workflow assignment Video: 06_Workflow running	

Table 34 – Top fixing plate release

Top fixing plate Release	
Target: To check and give the state of release to the Top fixing plate part.	
Operation: • Select the Item Revision of the Top fixing plate • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Top fixing plate 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Top fixing plate 3d model + JT released
Role: Student	
Attached information:	

Table 35 – Swinging transmission device release

Swinging transmission device Release	
Target: To check and give the state of release to the Swinging transmission device part.	
Operation: • Select the Item Revision of the Swinging transmission device • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Swinging transmission device 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Swinging transmission device 3d model + JT released
Role: Student	
Attached information:	

Table 36 – Rotary support release

Rotary support Release	
Target: To check and give the state of release to the Rotary support part.	
Operation: • Select the Item Revision of the Rotary support • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Rotary support 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Rotary support 3d model + JT released
Role: Student	
Attached information:	

Table 37 – Operating lever release

Operating lever Release	
Target: To check and give the state of release to the Operating lever part.	
Operation: • Select the Item Revision of the Operating lever • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Operating lever 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Operating lever 3d model + JT released
Role: Student	
Attached information:	

Table 38 – Block fixing bracket release

Block fixing bracket Release	
Target: To check and give the state of release to the Block fixing bracket part.	
Operation: • Select the Item Revision of the Block fixing bracket • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Part • Go to My Worklist • Answer the question • The part will be automatically released	
Input items: • Block fixing bracket 3d model + JT • Workflow release part • Product structure (Assembly + 6 parts)	**Output items:** • Product structure (Assembly + 6 parts) • Block fixing bracket 3d model + JT released
Role: Student	
Attached information:	

Table 39 – Add standard parts

<table>
<tr><th colspan="2">Add standard parts</th></tr>
<tr><td colspan="2">Target:
Add the Standard parts (screws and nuts) to the assembly.</td></tr>
<tr><td colspan="2">Operation:
• Go to my Teamcenter
• Open Search View
• Search the item number 001071 (Screw_M8x34)·
• Copy and paste it in your space·
• Repeat the procedure for the items:
o 001072 (Screw_M8x30)
o 001073 (Nut_M8 mm)
o 001074 (Screw_M10x34)
o 001075 (Nut_M10)
o 001076 (Pin 6x24mm)
o 001077 (Pin 6x30)
• Copy all the items and paste them into the product structure of the Assembly Clamp
• Save the product structure</td></tr>
<tr><td>Input items:
• Product structure (Assembly + 6 parts)
• Standard parts:
• 001072 (Screw_M8x30)
• 001073 (Nut_M8 mm)
• 001074 (Screw_M10x34)
• 001075 (Nut_M10)
• 001076 (Pin 6x24mm)
• 001077 (Pin 6x30)</td><td>Output items:
• Product structure (Assembly + 6 parts + 7 standard parts)</td></tr>
<tr><td colspan="2">Role:
Student</td></tr>
<tr><td colspan="2">Attached information:
Video: 07_Perform an item search</td></tr>
</table>

Table 40 – Duplicate parts

Duplicate parts	
Target: Add duplicate parts necessary for the assembly	

Operation:
• Open the Product Structure
• Copy the Top_Fixing_Plate item and paste it under the assembly
• Repeat the same operation for the following parts:
  o Block_Fixing_Bracket – 2 parts·
  o Screw_M8x34 – 2 parts;
  o Screw M8x30 – 4 parts;
  o Nut_M8 – 2 parts;
  o Screw_M10x34 -4 parts;
  o Nut_M10 – 4 parts,
  o Pin 6x24 – 2 parts;
  o Pin 6x30 – 4 parts;
• Save the product structure	

Input items: • Product structure (Assembly + 6 parts + 7 standard parts)	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts)
Role: Student	
Attached information: Video: 08_Duplicate parts	

Table 41 – Modify product structure

Modify product structure	
Target: To pack duplicated parts	
Operation: • Select the duplicate Items Top fixing plate • Look the Menu Bar Find No. • Both items must have the same Find No. • Select both items and go to View → Pack • Repeat these steps for all duplicated parts • Save the Product Structure· _ • Repeat the operation Manage Pending Components for the Standard Parts that you have added to the assembly	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts)	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts)
Role: Student	
Attached information: Video: 09_Modify product structure	

Table 42 – Add constraints

Add constraints	
Target: Add the constraints to the released parts in order to get the final assembly	
Operation: • Open the Assembly item • Add the constraint Fix to the Support part • Add the Touch align constraint to the other parts • Save the Assembly	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts)	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts)
Role: Student	
Attached information: Video: 10_Move a part Video: 11_Fix constraint Video: 12_Touch and align constraint	

Table 43 – Set assembly to precise

Set assembly to precise	
Target: Set to precise the final assembly	
Operation: • Open the Assembly item • Go to Edit→Toggle Precise/Imprecise (Ctrl+Shift+F) • Save the Assembly	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts)	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts)
Role: Student	
Attached information: Video: 13_Set to precise	

Table 44 – Assembly release

Assembly release	
Target: To check and release the assembly	
Operation: • Select the Item Revision of the Assembly • Select Edit/New/Workflow process or (Ctrl+P) • Select the Workflow Release Assembly • Go to My Worklist • Answer the question • The assembly will be automatically released	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts)	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts) released
Role: Student	
Attached information: Video: 14_Assembly release	

Table 45 – Revise assembly

Revise assembly	
Target: Create a Revision of the Item Assembly to perform a modification on the parts.	
Operation: • Select the Item Revision of the Assembly • Select Edit/Revise • Click Finish • You will find a Revision of the Item	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts) released	**Output items:** • Product structure (Assembly + 8 parts + 22 standard parts) revision
Role: Student	
Attached information: Video: 15_Revise assembly	

Table 46 – Revise part

Revise part	
Target: Create a Revision of the part to be modified	
Operation: • Select the assembly revision in the structure Manager • Untoggle Precise Assembly • Save the Assembly • Select the Item Revision of the Part to be modified • Select Edit/Revise· • Click finish • A revision of the Part will be created	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts) revision	**Output items:** • Product structure (Assembly revision + 8 parts + 22 standard parts) • Part revised
Role: Student	
Attached information: Video: 16_Revise part	

Table 47 – Create GD&T table

Create the GD&T table	
Target: Create the table of the part according to the GD&T standard	
Operation: • Select the Dataset UGMASTER of the part and open it on Integrated NX • Click File/New/Drawing. • This operation will create a Dataset UGPART in Teamcenter • Select A0 and click Ok • Create the views • Add the GD&T tolerance	
Input items: • Product structure (Assembly + 6 parts + 7 standard parts) revision • Parts revised	**Output items:** • Product structure (Assembly revision + 8 parts + 22 standard parts) • Part drawing
Role: Student	
Attached information: Video: 17_Create a drawing PDF: Drafting guide	

Annex C. Clamp Drafts

Support

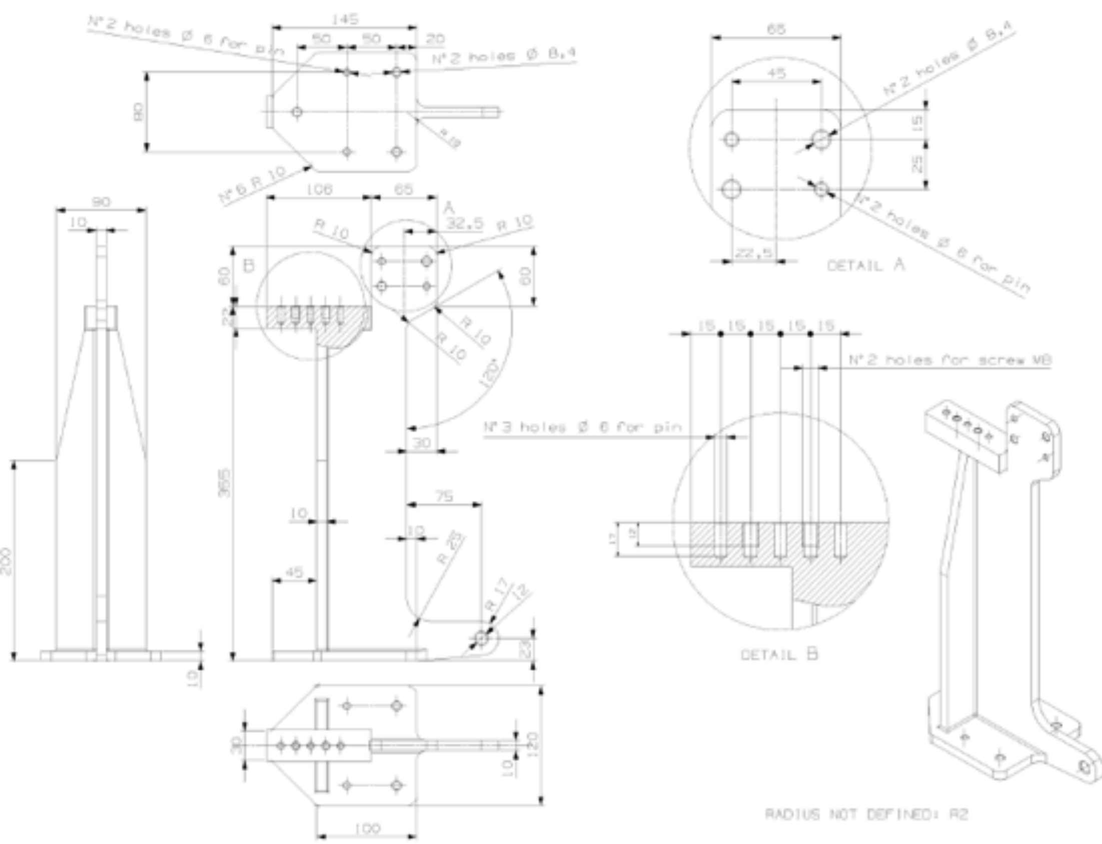


Fig. 88 – Support draft

Rotary support

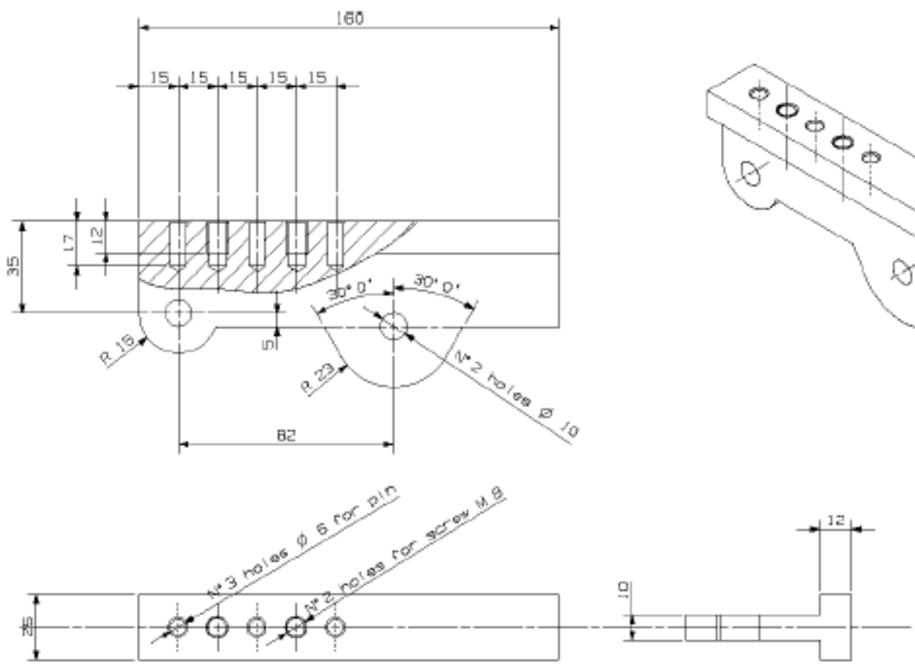


Fig. 89 – Rotary support draft

Swinging transmission device

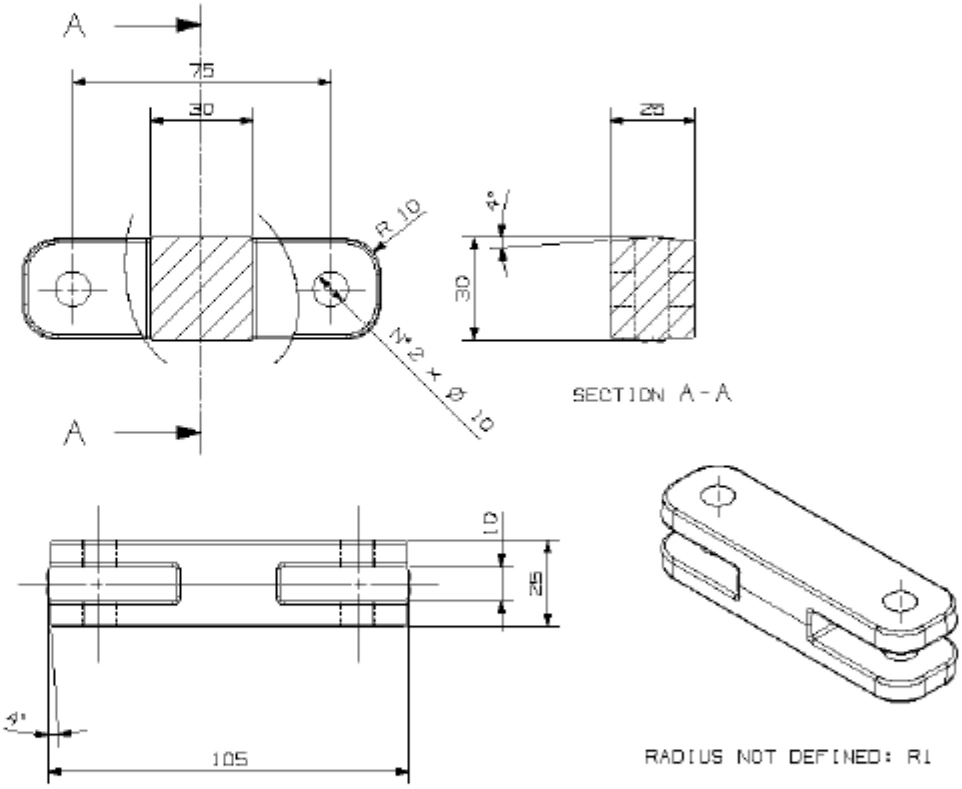


Fig. 90 – Swinging transmission device draft

Top fixing plate

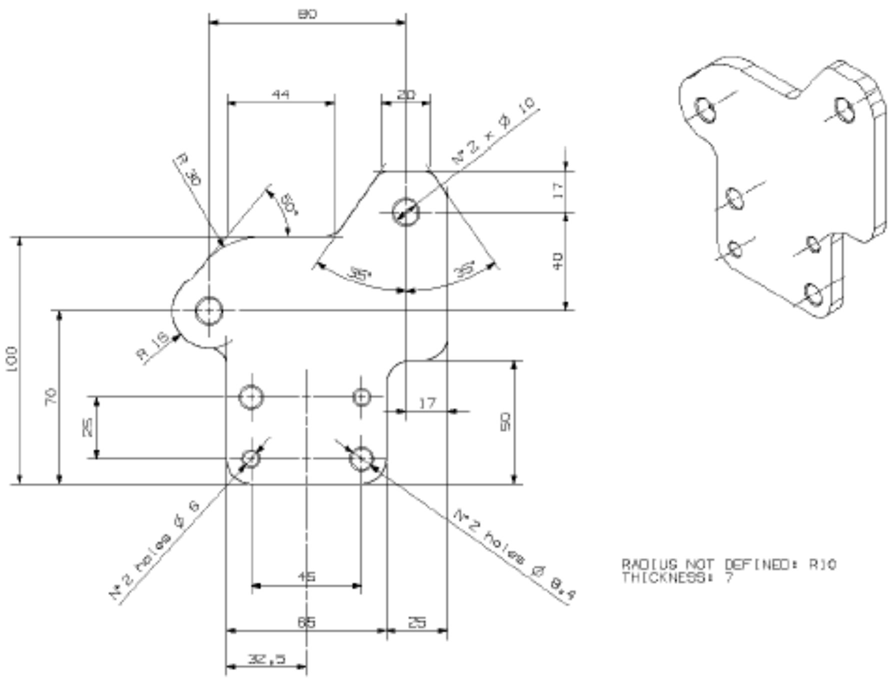


Fig. 91 – Top fixing plate draft

Operating Lever Assembly

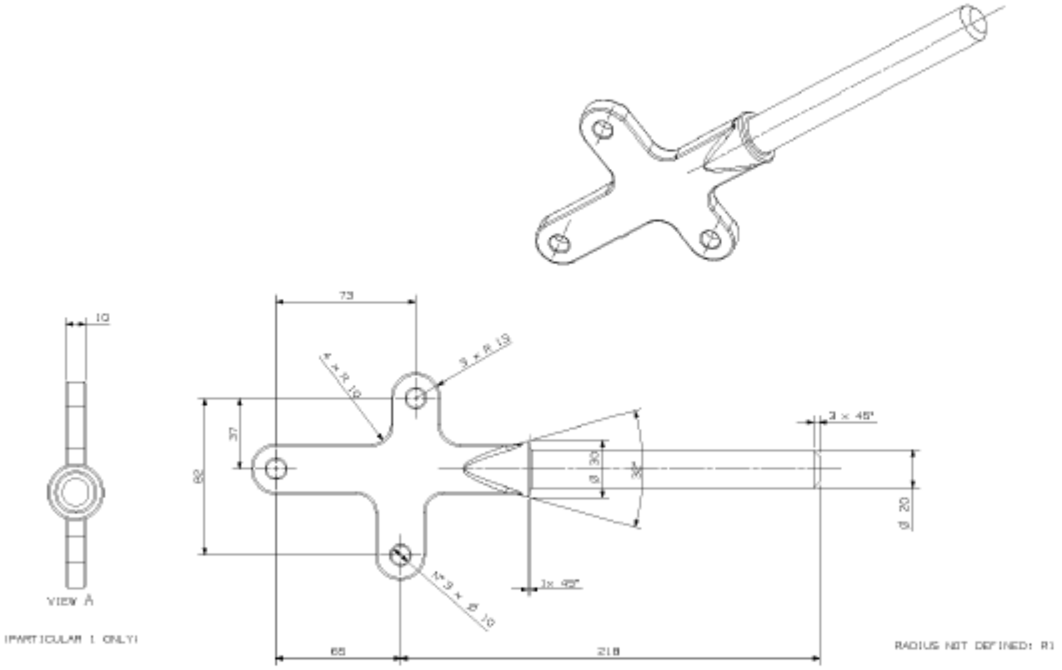


Fig.92 – Operating lever draft

Block fixing bracket

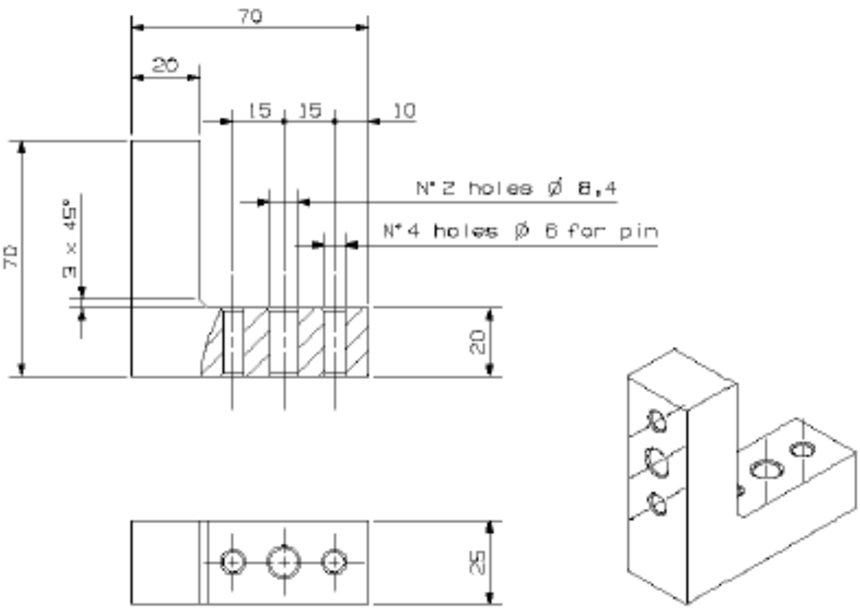
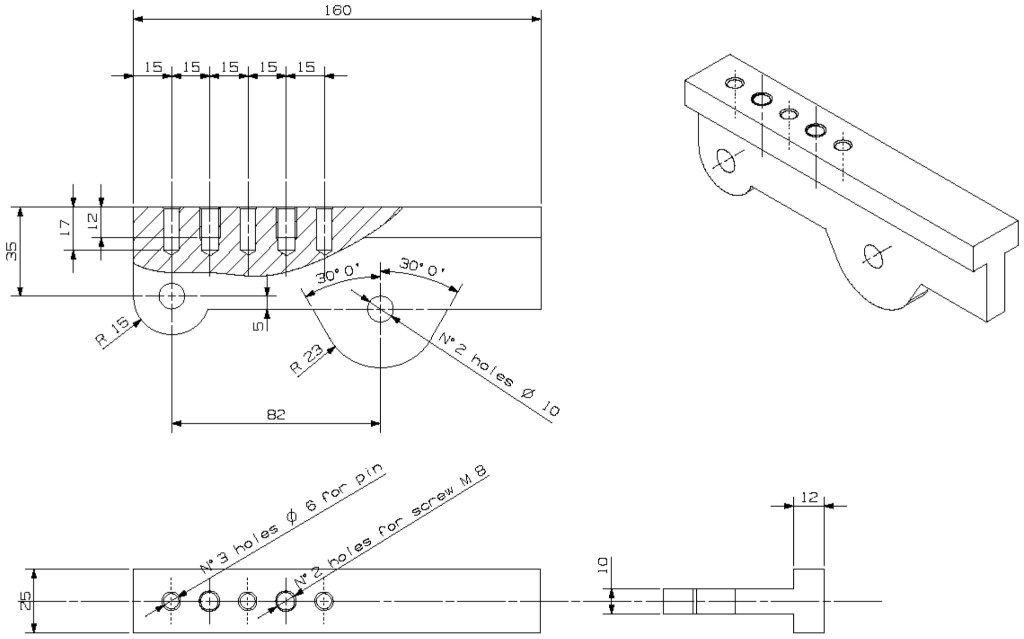


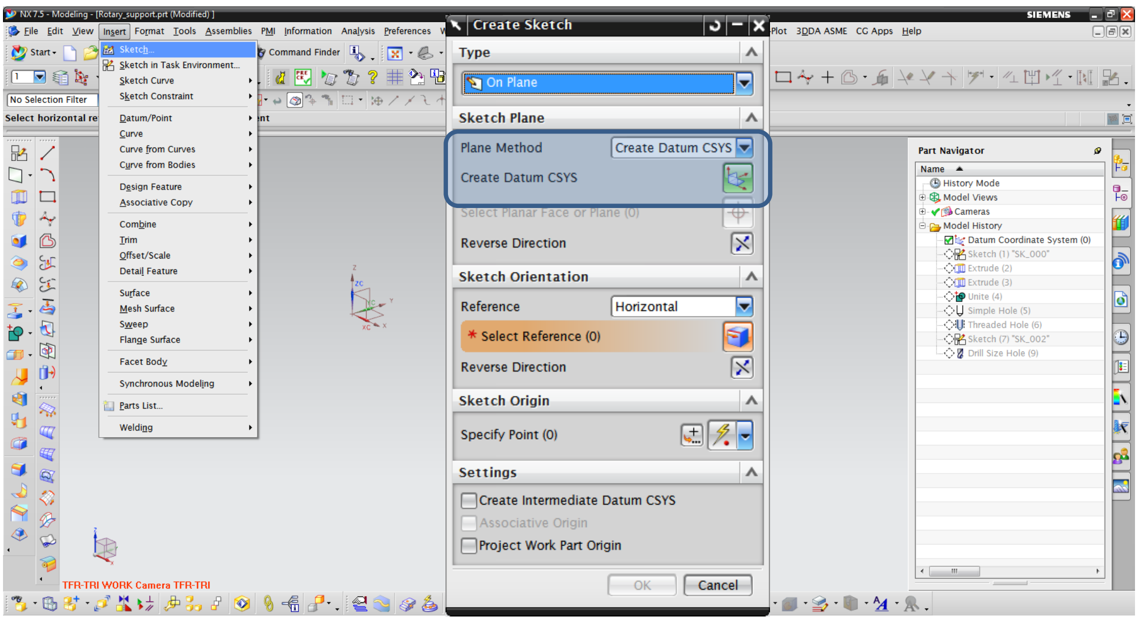
Fig. 93 – Block fixing bracket draft

Annex D. NX Guide to model the rotary support

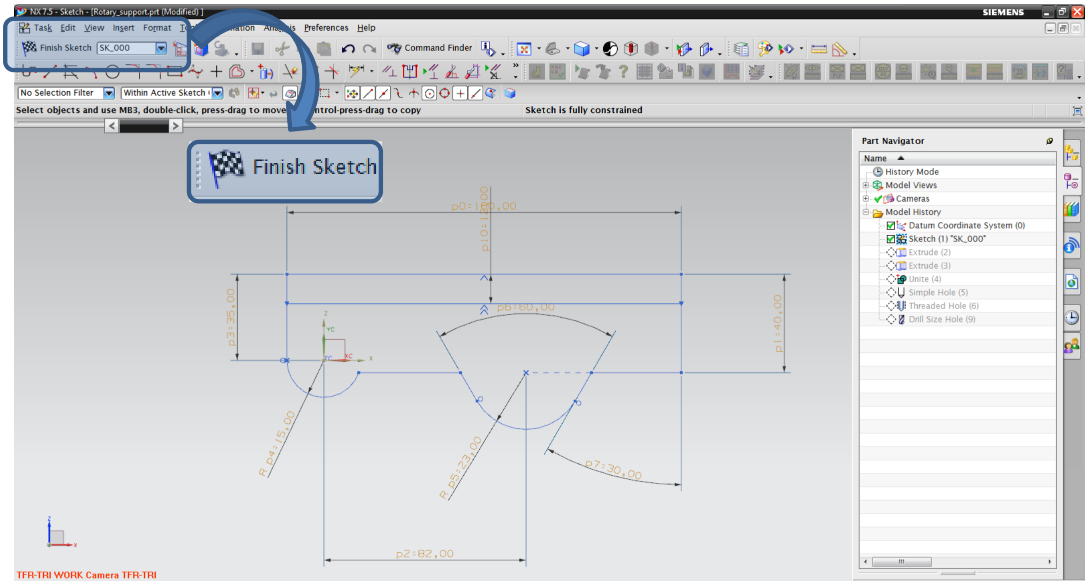
Rotary support



1. We create the main sketch : *Insert → Sketch (On plane)*

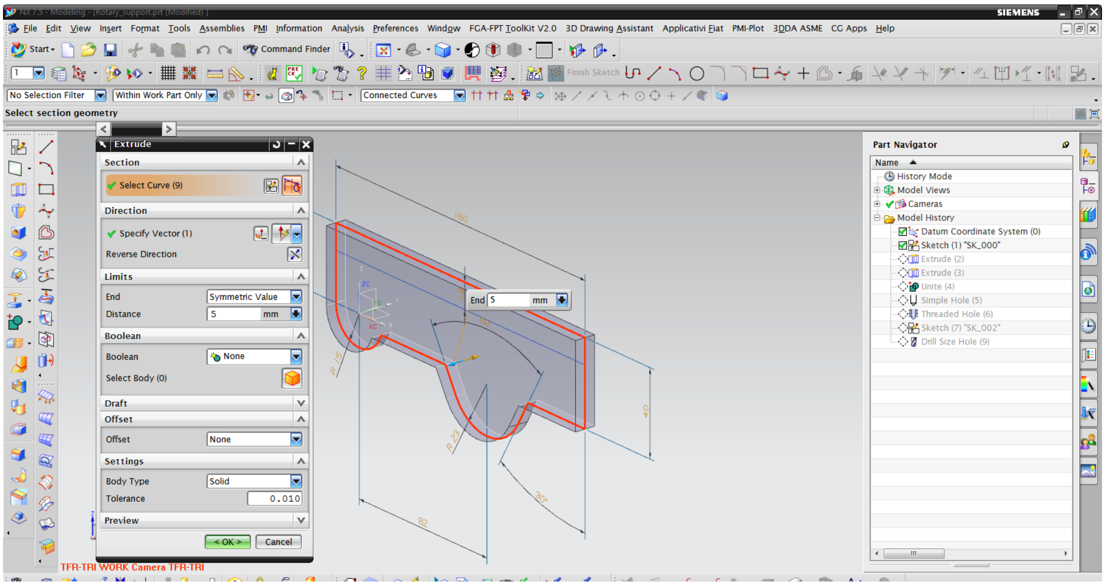


Choosing “Create Datum CSYS” we’ll create a complete reference system with three planes, three axis and the origin point. After that it’s easy choose one of the plane for starting the sketch

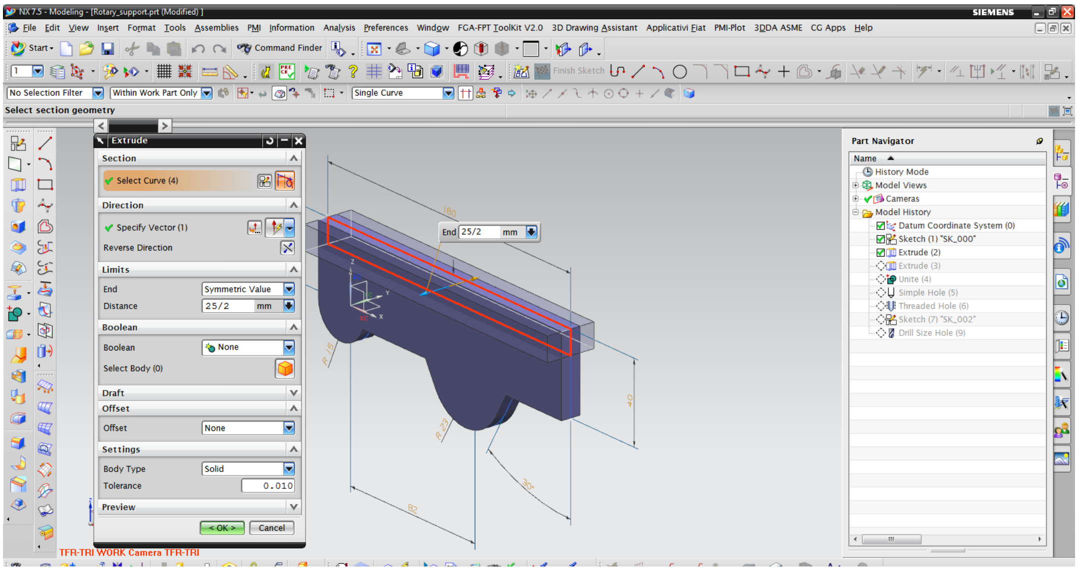


2. Exit from the sketch environment

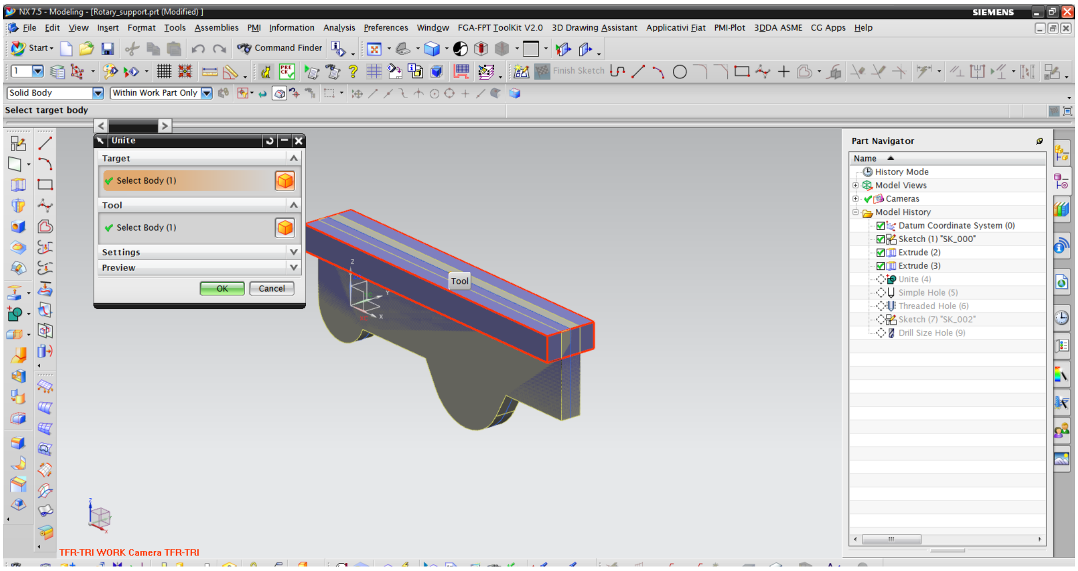
3. Extrude the external profile (*Insert → Design Feature → Extrude*)



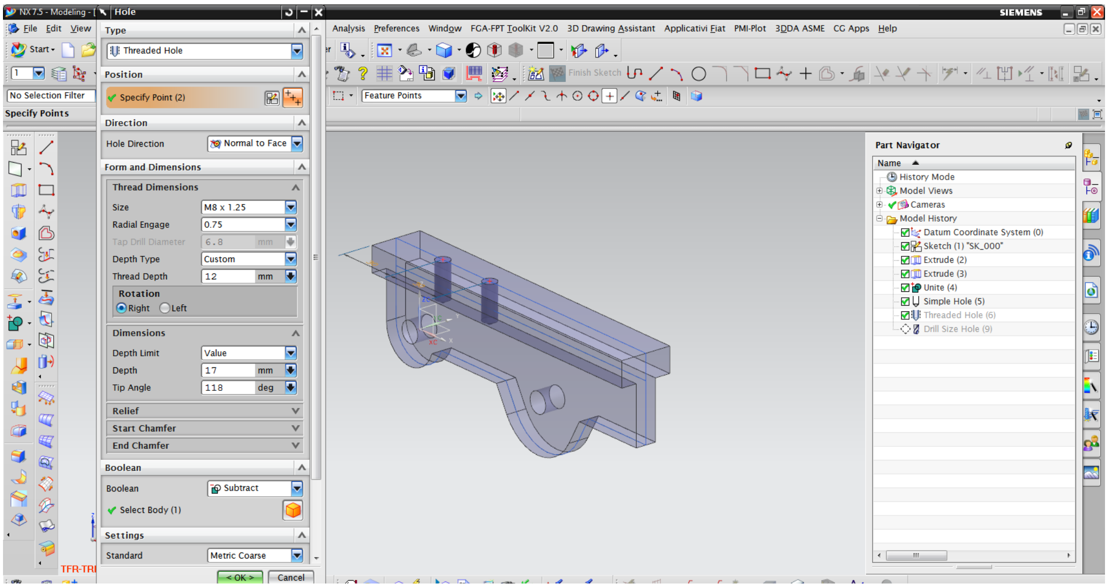
4. Extrude the upper profile



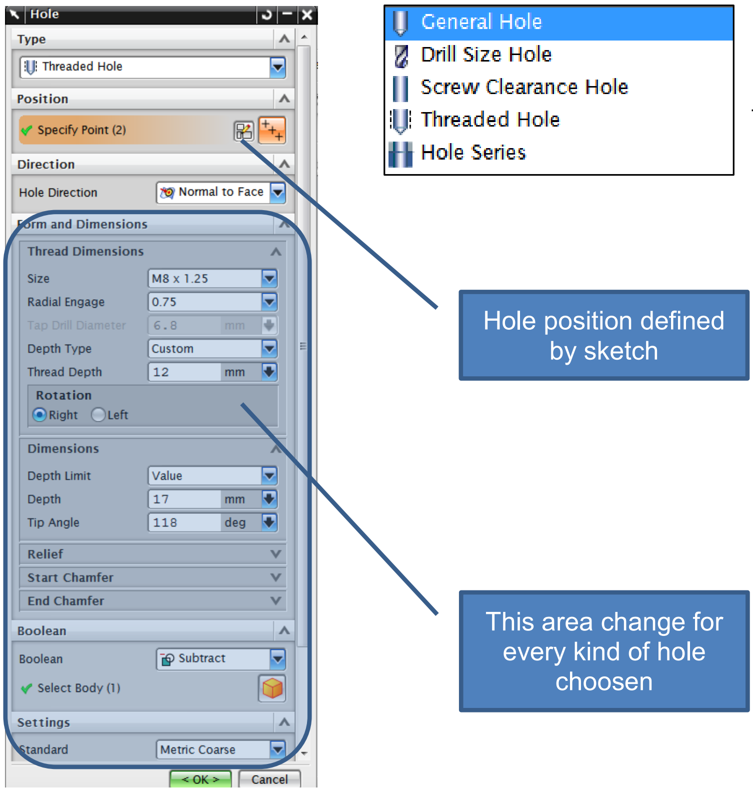
5. Unite the two bodies (*Insert → Combine → Unite*)



6. Create the holes (*Insert → Design Feature → Hole*)



The position of the hole could be defined using the sketcher options inside the command



Different kinds of holes

- Drill size (nominal size)
- Screw clearance (with tolerance)
- Threaded hole
- Hole series

Annex E. Drafting guide

Click on the icon with the number to watch the related video.

1

- Enter the drawing environment;
- Select the drawing sheet,
- Set the projection method and a suitable (standard) scale factor,
- Select the main view (the most representative of the part),
- Add projected views.

2

- **Refine the part view** by doing the following operations:
  - Hide the smooth edges,
  - Add centerlines and symmetry lines,
  - Add intersection symbols that represent the witness lines on a corner.

3

- Set your **NX preferences** for the drawing annotations:
- Preferences/annotation/...
  - Dimensions/Precision and Tolerance =2
  - Unit --> un-check the trailing zeros box
  - Lettering/Character size = 2
  - Line/Arrow: A=2

4

- Create the **section views** that are eventually necessary to show the internal geometry of the part:
  - Choose the proper section view icon,
  - define an initial section line (straight),
  - Customize the section line by using the edit option and the section visualization with the style settings.

5

- Define a **Datum Reference Frame** (DRF) that is representative of the workpiece function within the assembly. For example in this case the part is oriented by the surface that is coupled with the clamp support (primary datum feature "A") and is completely fixed by the pattern of two Ø6 holes for the positioning pins.
- Each datum feature (or pattern of datum features of size) shall be adequately qualified → form or orientation tolerances suitable for ensuring a stable contact surface for assembly and verification operations.

6

- **Qualify holes**:
  - Axis true position,
  - Dimension and dimensional tolerance,
  - Position tolerance.

7

- **Qualify** the true **profile shape and size**:
  - Thickness of the part,
  - Overall dimensions in each view,
  - Tolerances (e.g. profile tolerance with tolerance zone completely included in the nominal profile).

8

- **Adjust** the position of dimensions and tolerances in order to **improve the draft readability**.

9

- **Complete the drawing adding the refinements dimensions:**
  - Radius of fillets,
  - Angle and depth of chamfers,
  - General dimensional and geometrical tolerances,
  - General roughness tolerance

Annex F. List of videos

Table 48 – Videos of the Visualization Model

Number	Description
01	How to create a product structure
02	Manage pending components
03	Open support dataset
04	Save JT
05	Workflow assignment
06	Workflow running
07	Perform an item search
08	Duplicate parts
09	Modify a product structure
10	Move a part
11	Fix constraint
12	Touch and align constraints
13	Set to precise
14	Assembly release
15	Revise Assembly
16	Revise part
17	Create a drawing

Drafting guide

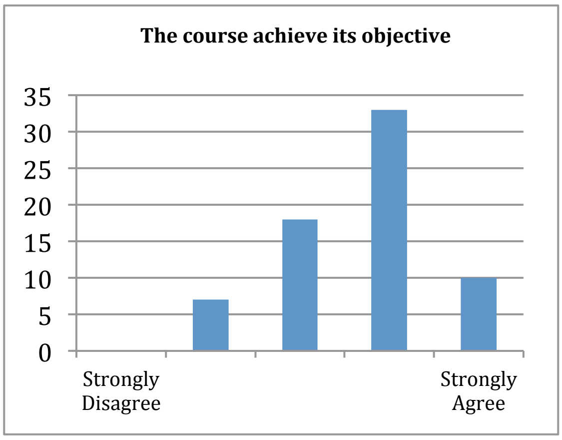
Table 49 – Videos of the drafting guide

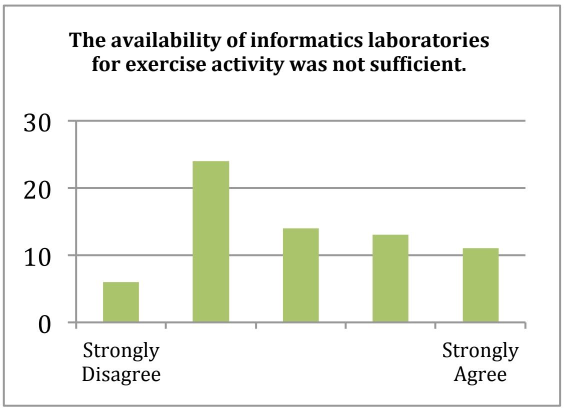
Number	Description
01	Drawing environment
02	Refine part view
03	Nx preferences
04	Section views
05	Datum reference frame
06	Qualify holes
07	Qualify the true profile shape and size
08	Complete the drawing

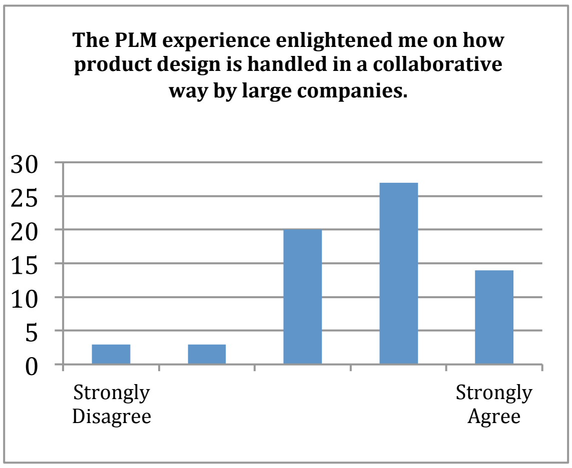
Annex G. Questionnaire and answers

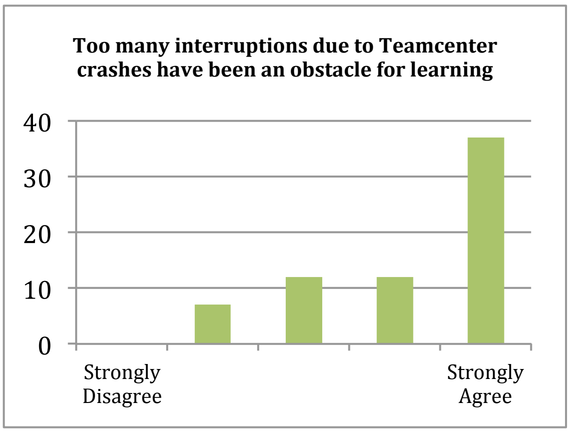
Evaluation of the PLM Experience

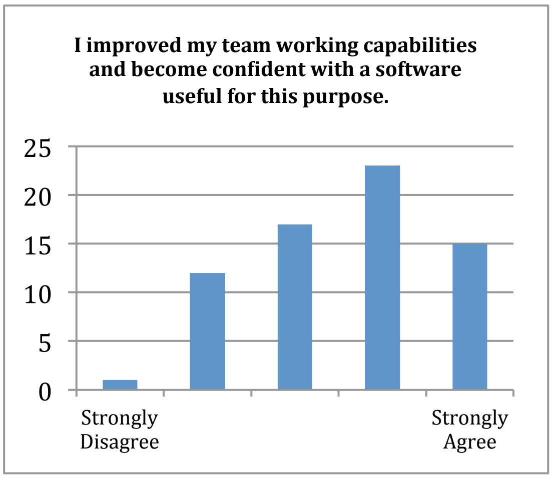
	Strongly disagree				Strongly agree
1) The course achieved its objectives	○	○	○	○	○
2) The availability of informatics laboratories for exercise activity was not sufficient.	○	○	○	○	○
3) The teaching method (guided exercises plus Visualization Model for support) was adequate	○	○	○	○	○
4) I didn't understand clearly the role I acted and the activities I performed during the team exercise.	○	○	○	○	○
5) The PLM experience enlightened me on how product design is handled in a collaborative way by large companies.	○	○	○	○	○
6) Too many interruptions due to Teamcenter crashes have been an obstacle for learning	○	○	○	○	○
7) The PLM experience gave me useful skills for my future career.	○	○	○	○	○
8) The use of videos as a support to front lectures is pointless.	○	○	○	○	○
9) I improved my team working capabilities and become confident with a software useful for this purpose.	○	○	○	○	○
10) I think the increase of theoretical lectures against exercise would not improve the students understanding of PLM.	○	○	○	○	○

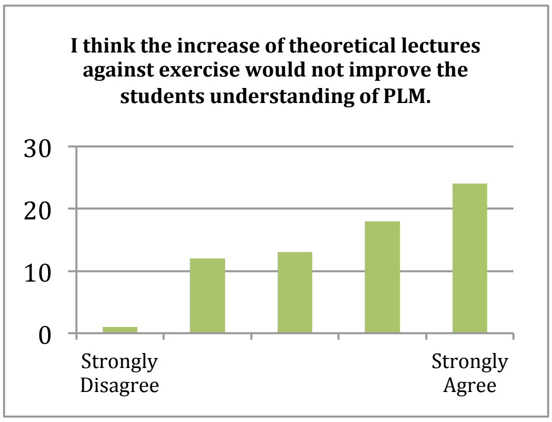

The course achieve its objective
35
30
25
20
15
10
5
0
Strongly Disagree
Strongly Agree

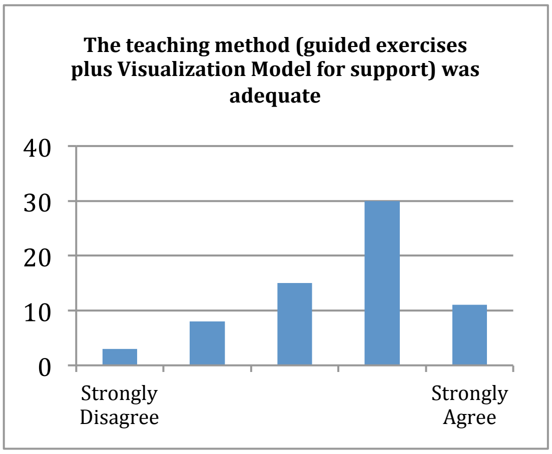

The availability of informatics laboratories for exercise activity was not sufficient.
30
20
10
0
Strongly Disagree
Strongly Agree

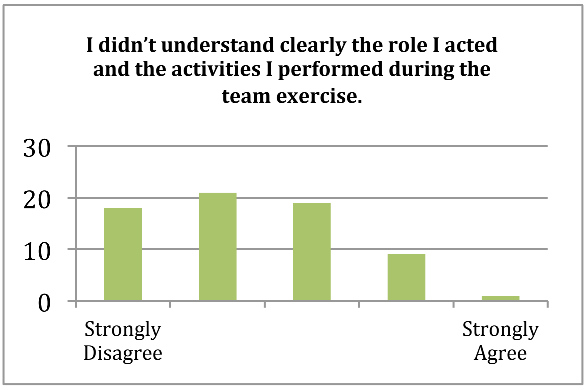

The PLM experience enlightened me on how product design is handled in a collaborative way by large companies.
30
25
20
15
10
5
0
Strongly Disagree
Strongly Agree

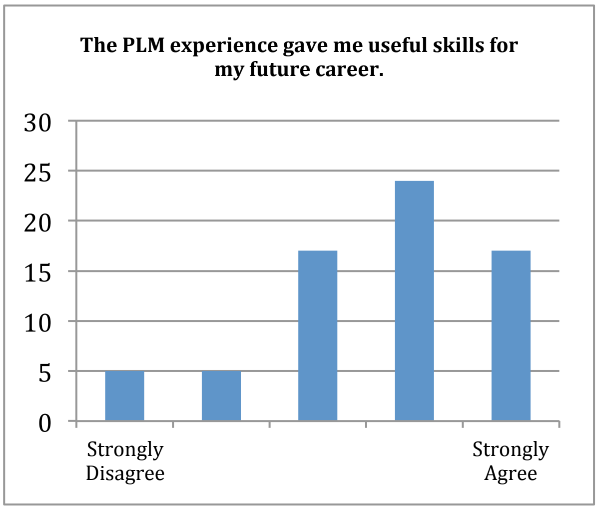

Too many interruptions due to Teamcenter crashes have been an obstacle for learning
40
30
20
10
0
Strongly Disagree
Strongly Agree

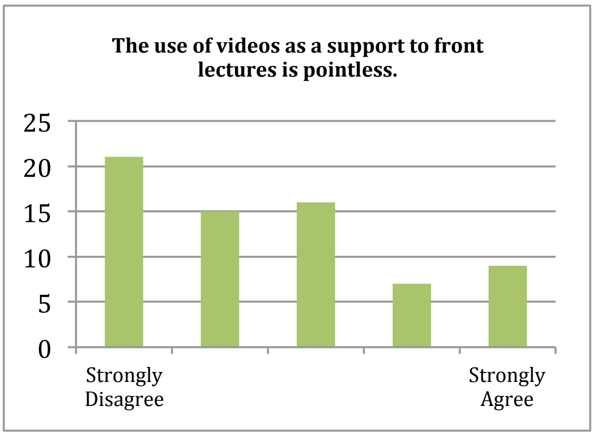

I improved my team working capabilities and become confident with a software useful for this purpose.
25
20
15
10
5
0
Strongly Disagree
Strongly Agree


I think the increase of theoretical lectures against exercise would not improve the students understanding of PLM.
30
20
10
0
Strongly Disagree
Strongly Agree


The teaching method (guided exercises plus Visualization Model for support) was adequate
40
30
20
10
0
Strongly Disagree
Strongly Agree

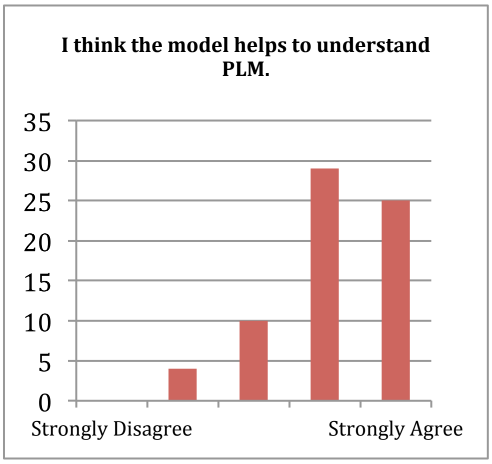

I didn't understand clearly the role I acted and the activities I performed during the team exercise.
30
20
10
0
Strongly Disagree
Strongly Agree

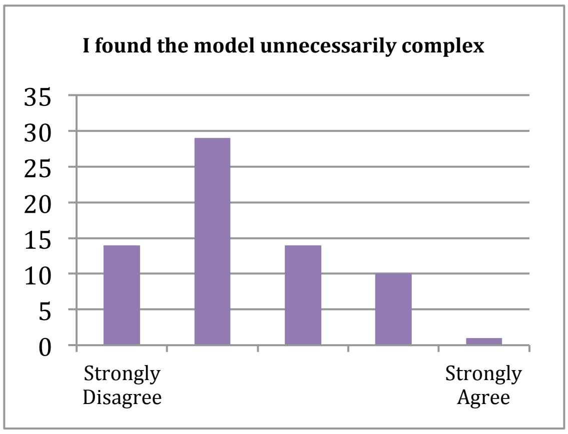

The PLM experience gave me useful skills for my future career.
30
25
20
15
10
5
0
Strongly Disagree
Strongly Agree


The use of videos as a support to front lectures is pointless.
25
20
15
10
5
0
Strongly Disagree
Strongly Agree

Visualization Model perception from users.

	Strongly disagree				Strongly agree
1) I think the model helps to understand PLM.	○	○	○	○	○
2) I found the model unnecessarily complex	○	○	○	○	○
3) I think that the model is easy to understand and use.	○	○	○	○	○
4) I think that I would need the support of a technical person to be able to understand and use this model.	○	○	○	○	○
5) I found the various elements in the model (items, roles, activities, etc) were well integrated.	○	○	○	○	○
6) I thought there was too much inconsistency in this model.	○	○	○	○	○
7) I would imagine that most people would learn to use this model very quickly.	○	○	○	○	○
8) I found the model lengthy.	○	○	○	○	○
9) I felt very confident using the model.	○	○	○	○	○
10) I needed to learn a lot of things before I could get going with this model.	○	○	○	○	○


I think the model helps to understand PLM.
35
30
25
20
15
10
5
0
Strongly Disagree
Strongly Agree


I found the model unnecessarily complex
35
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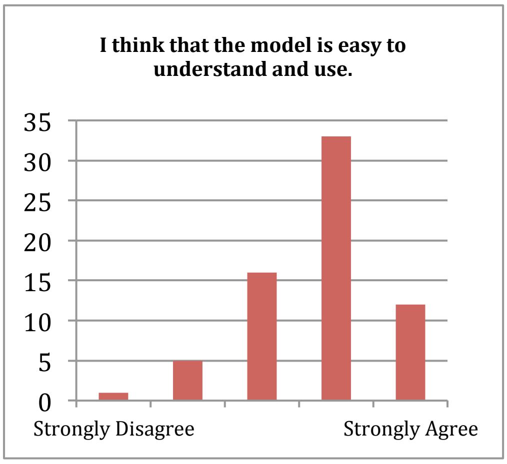
Strongly Disagree
Strongly Agree


I think that the model is easy to understand and use.
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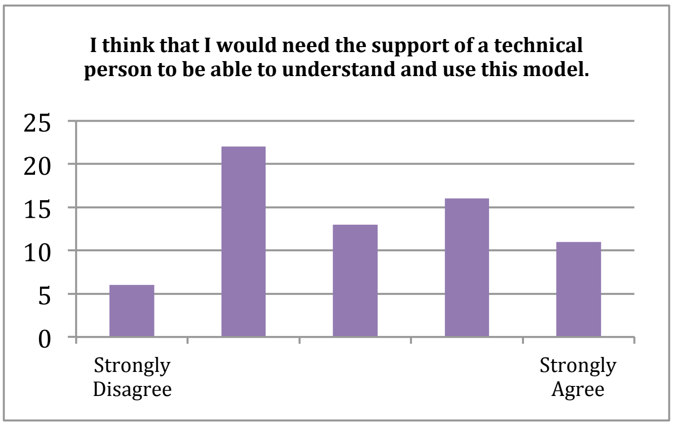
Strongly Disagree
Strongly Agree


I think that I would need the support of a technical person to be able to understand and use this model.
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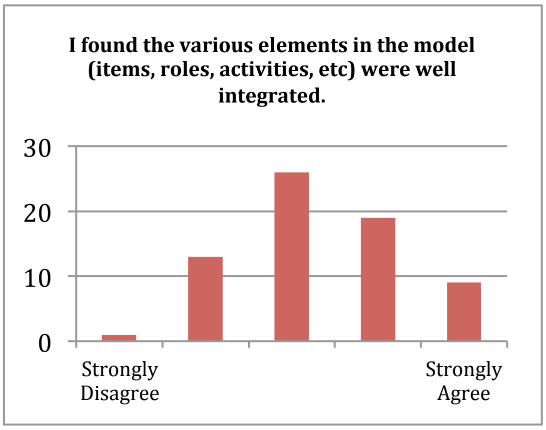
Strongly Disagree
Strongly Agree


I found the various elements in the model (items, roles, activities, etc) were well integrated.
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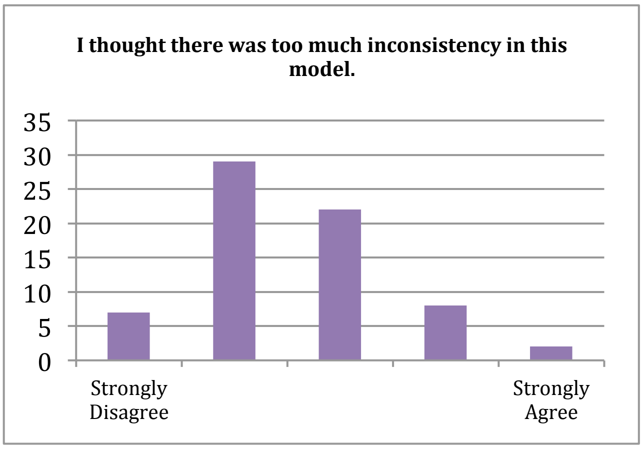
Strongly Disagree
Strongly Agree


I thought there was too much inconsistency in this model.
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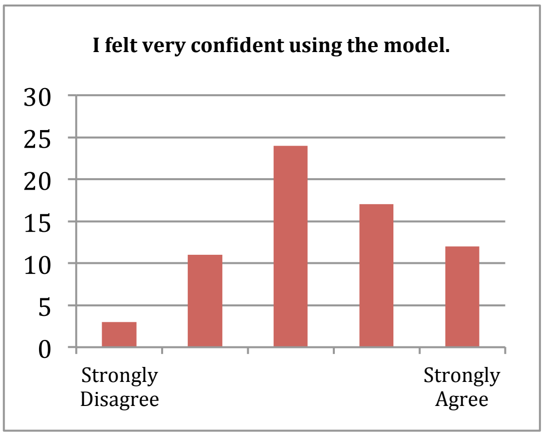
Strongly Disagree
Strongly Agree


I felt very confident using the model.
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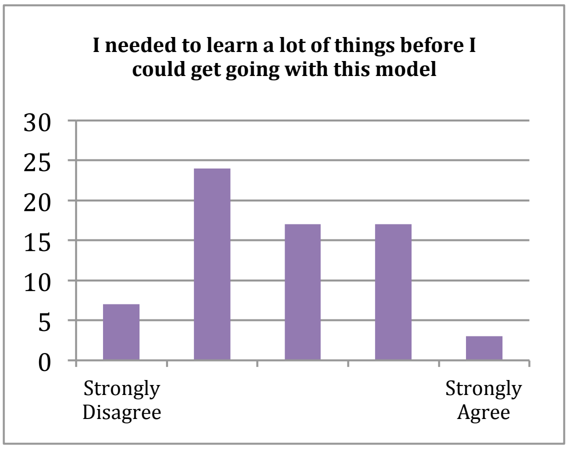
Strongly Disagree
Strongly Agree


I needed to learn a lot of things before I could get going with this model
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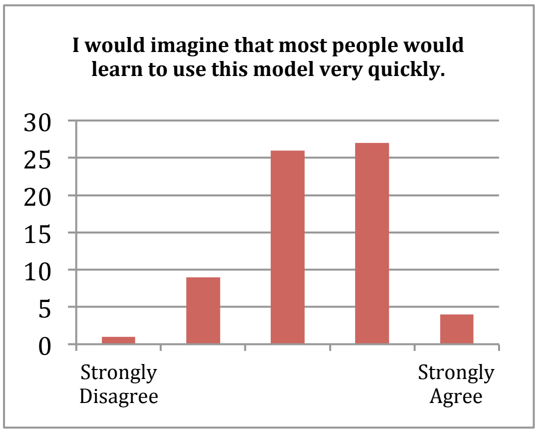
Strongly Disagree
Strongly Agree


I would imagine that most people would learn to use this model very quickly.
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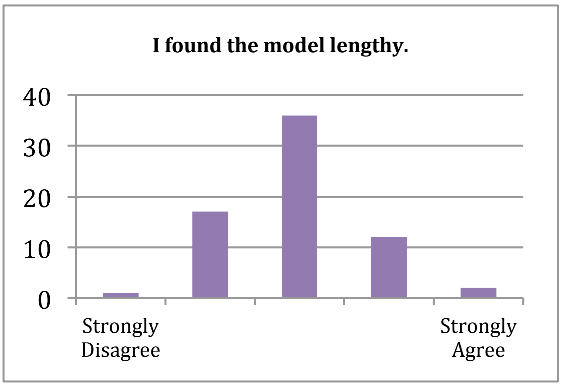
Strongly Disagree
Strongly Agree


I found the model lengthy.
40
30
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Strongly Disagree
Strongly Agree