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AN INTEGRATED STACK-UP ANALYSIS TOOL

A. Corallo, M. Lazoi and G. Pascali

1. Introduction

The development of a product requires the definition of its architecture and of its physical and functional elements that have to be assembled together to realize the new product. Functional elements are the set of operations and transformations necessary to reach the product performance while physical elements are related to parts, components and subassemblies and are established from the product concept or defined in the detailed design of the product. Functional elements are associated to one or more physical elements and together define the product architecture. [Ulrich and Eppinger 2008].

The design of the product architecture and of each physical elements is very critical in the development of a new product since a worst design will impact also on the product manufacturing and changes and stops in that phase requires higher costs for the companies. Therefore, accurately design the product, its physical elements and how to assembly them in the architecture, it's a critical activity for the company.

The product model including its architecture and physical elements, is realized in computer aided design (CAD) systems but also other systems (i.e. Computer Aided Technologies, CAX) are used to define engineering, manufacturing or testing data. In many companies, all the data generating by the CAD systems together with others product data (e.g. the bill of material - BOM) are integrated and available in PDM systems that store data and information about the product and its elements. They can be simple repository of information and the users manually search and access to the information required or can provide workflows and other tools to manage the product data. [Grieves 2006].

In the design of each physical element of a product, geometrical and dimensional values are established and for each value, the tolerance limits are forecasted and fixed. Tolerance limit are the upper and lower variation that a dimensional value can assume guarantying, however, a correct assembly of all the elements in the whole product. The tolerance limits depends from the type of materials or from the machines used to realize the product. Changes in a tolerance value have effect in the whole assembly generating a chain of changes.

Therefore, the need to correctly define the tolerance limits is very high to guarantee yet in the design a correct assembly. The stack-up analysis is the technique used to evaluate the tolerance chain created joining the physical elements and it is used to verify if there are problems to realize the final assembly and therefore, if the elements could be joined in the desired product architecture. The geometrical and dimensional information are available on the product engineering drawings or in the model based definition (MBD) dataset of the product. The engineering drawings provide a 2D vision of the product with dimensional and geometrical information. MBD datasets have been developed to integrate in the 3D model the information available in the engineering drawings providing a complete file with both information.

The paper aims to describe the case of an Italian aerospace company, Avio S.p.A., and the stack-up tool realized to improve the whole tolerance analysis process. The company has met some problems in the management of the stack-up analysis due to the use of IT tools that have led to human errors in the calculus and further time for reaching the results. Based on ten-month activities of a team of university researchers and company engineers, a new stack-up tool has been developed, it is integrated in the company CAD (Siemens Nx) and PDM (Teamcenter Engineering) systems and it is currently used by the company designers. It has solved the company problems in the stack-up analysis providing a solution for the calculus of the stack-up analysis both from engineering drawings and MBD datasets. In the next section of the paper, some remarks from the literature in the tolerance analysis field are described to guide the comprehsion of the concepts used in the paper. A further section treats the research design and provides the scenario in which has been developed the stack-up tool that is described in a successive section where technological choices and functionalities that have guided the tool development are discussed and an example of application of the tool enriches the view in the research results. A final section concludes the paper providing discussion and insights.

2. Tolerance analysis background

The development of a product requires the definition of its architecture and of its physical and functional elements that have to be assembled together [Ulrich, Eppinger 2008]. The constant flow of information evolutions during the different phases of development influences and improves the whole assembly. In fact, the process capabilities and the associated parametric variations of the product parts and subassemblies influence the choice of the assembly configuration to represent the product architecture. The selection of the right configuration is important to correctly fit all the parts together in the assembly. Furthermore, it is important to choice the right configuration and also the sequence of assembly of the individual parts in the products. In the design, therefore, the decisions about how the parts are located with respect to one another impact on the whole assembly configuration. In this logic, tolerance analysis is useful to verify if the key characteristics of an assembly are satisfied by the chosen configuration and assembly sequence. [Narahari et al. 1999].

The purpose of tolerance analysis is to study the accumulation of variations on a geometric attribute of interest (e.g. dimension, location, orientation, etc) to validate the upper and lower tolerance limits established for each attributes and to guarantee a correct assembly. The set of value and limits is collected together in tolerance chain, or stack path (i.e. the start and the end of a stack) that is a continuous and shortest series of specified dimensions linked with different features. The analysis can involve multiple parts in an assembly or variations on a single part. [Shah et al. 2007].

Tolerances values are allocated by experience, trial and error and are analyzed to verify the satisfaction of the design requirements. If the requirements are unsatisfied, it is required to determine which tolerance to change and by how much [Shah et al. 2007]. Furthermore, tolerance analysis results impact on the product development plan since they can impact on the required time improving the design of the product and eventually, the time needed for re-works [Narahari at al. 1999]. In fact, dimensional variations of parts can lead the final product to vary causing problem in the assembly and the need of re-work parts with higher cost for all the production and can also lead to higher warranty cost or dissatisfied customers [Chase 2004]. Therefore, tolerance analysis predicts the accumulation of variation in an assembly [Chase 2004] and evaluates the impact of variations of elements dimensions on the dimensions of the resulting assembly [Sudarsan et al. 2005].

Generally, the tolerance analysis includes the identification of the chain of dimensions to control; the calculus of the assembling dimensions; the estimation of the variation in the assembly dimensions (stack-up analysis); the comparison between the predicted assembling variations with the engineering limits; any change in the design and production plan [Chase et al. 1997]. The stack-up analysis is the core step for the tolerance analysis in which using different methods *the variation in the assembly dimension is estimated by summing the corresponding component variation*s [Chase et al. 1997]. The most popular models to perform the stack-up analysis are: worst case, statistical, six sigma, sampled model and measured data that evaluate the variation in the assembly using different indexes. [Chase 2004].

Tolerance values can be dimensional or geometric ones. Dimensional Tolerances are measures controlling the variability of linear dimensions that describe location, size, and angle while Geometric Tolerances are the category of tolerance used to control shape, position and run-out. [Sudarsan et al. 2005] and are defined as GD&T (Geometric dimensioning and tolerancing). They are available on engineering drawings or MBD datasets.

Engineering drawings is a 2D graphical representation of a product based on a common graphical language to represent what to do and how to do it [French et al. 1990]. Engineering drawings are important to capture and distribute non-geometric information such as dimensions, tolerances, surface conditions, materials, manufacturing processes etc [McMahon and Browne 1998]. Nevertheless, engineering drawings are not the primary source of information about the product. In fact, solid model based on a 3D representation of the product enable to make analysis and virtual realize the product. Solid model are realized with CAD systems and define the product geometry providing a further source (i.e. in addition to engineering drawings) of product information. The use of both engineering drawings and solid model generates a redundancy of information. To remedy this problem and create a unique source of product data and information, the Model based Definition datasets have been introduced. MBD datasets integrate dimensional values, geometrical dimensioning and tollerancing (GD&T) data and further notes in the solid model that implies the un-need to create also engineering drawings. Even if the use of the MBD datasets has an high potential, they are not wide used, especially in the aerospace company, due to technical, legal and processes problems [Quintana et al. 2010].

There are several software available for the tolerance analysis calculus [Turner 1993] both proprietary and commercial ones. They are mostly simulation-based and simple analytical or probabilistic techniques are provided [Narahari 1999]. Nevertheless, many of the existing tools are neither comprehensive nor accurate for assisting designers in allocating tolerances and identifying trade-offs during the design process [Shah et al. 2007]. Furthermore, different geometry dimensions could be available on different systems (i.e. physical elements of a product realized by different suppliers) and it is needed to adopt strategies and solutions solving also this issue, especially when complete different applications are used. Current studies try to develop standard for solving this problem and achieving a DB integration among different application [Feng and Yang 1995].

3. Research design

3.1 Research method

The paper explores the tolerance analysis issues in an aerospace company and presents the solution applied to improve the whole tolerance management process trough the realization of a case study based on the aerospace industry. The main research question that the project wants to address is:

R.Q. How does an aerospace company faces stack-up analysis issues? Which are the issues? Which is the technological solution?

This question has emerged as objective of an action research in which University of Salento was involved for its partner company Avio S.p.A. Action research is the act of making research for problem solving [Reason and Bradbury 2001] and it is based on a learning by doing practices [O'Brien 2001]. In fact in the study, problems and solutions have been deducted from observation and participation to the organizational practices.

Therefore the paper presents an industrial case study based on the results of an action research. In fact, a case study is particularly appropriate to study contemporary events and non-controllable units of analysis [Yin 2003]. The study is not aimed to build new theory but rather to discuss and share a real practice of particular relevance given the features of the subject company. The case is thus guided by the pragmatism knowledge claim: it is problem-centric and the attention is therefore placed on the problem and how to solve it in a real organizational setting [Creswell 2003]. Multiple sources of evidences have been used to increase the case study's construct validity [Yin 2003]: the direct researcher's observations and participation and interviews with key users. The University researchers have participated for ten-month to the activities of stack-up analysis exploration that have included the observation of the company practices in the stack-up analysis, the specification of gaps and the development of a new stack-up tool that is actually used and perfectly integrated in the company CAD

(Siemens NX) and PDM (Teamcenter Engineering) systems. Key users have been also involved and they have identified the main problems and the desired requirements for a new stack-up tool. The key-users involved comes from different company product units (i.e. turbine, trasmission module, mechanical trasmission module, engine components, rotating components and combustion module engineering units) and have been chosen for their expertise in the stack-up analysis.

3.2 Research context

The company is a large Italian aerospace firm, Avio SpA, leader in the realization of propulsion aerospace systems and works in the sector with different roles and responsibilities in the most important aerospace programmes. The company designers are supported by different ICT applications (i.e. CAD, spreadsheet, GRIP tool) to provide stack-up analysis results. The company uses as CAD the NX suite of Siemens for parametric solid surface feature-based modelling and as PDM the Teamcenter 9.1.3.2 suite developed by Siemens PLM Software. In detail, the NX features used for tolerances analysis can be of different types: 1) a dimensional tolerance; 2) a dimensional tolerance with a GD&T in the appended text; 3) a GD&T feature; 4) and a GD&T in a text area. The CAD NX has an own application to perform the stack-up analysis with MBD datasets but it is not widely used since engineering drawings are preferred for cultural issues, routines and compliances with company policies. The stack-up analysis from engineering drawings is done with a spreadsheet of Microsoft Excel or with a custom GRIP application in both the cases the designers create the stack-up reports on their own PC and can send them by email. Only the stack-up reports sent by email are traced and they are completely unassociated with the related CAD files. A loss of information is observed by the designers. Furthermore, if the designers use the spreadsheets the data have to be manually copied from th CAD files with risks of human errors; otherwise, if the GRIP application is used, this is integrated in the CAD system and save a text file with the stack-up chain that has to be imported in the spreadsheet for the calculus. For evaluating tolerance chains of different product parts, the tolerance values are available on different sheets or drawings, and several run-cycles of the GRIP application have to be launched with different export of the text files and following entry in the spreadsheet, also the necessity of better formatting the values in the spreadsheet could emerge. With both the applications, in case of changes in the tolerance values of a stack-up chain, the value has to be manually searched by the designers and changed.

Table 1. Stack-up analysis problems and organizational impacts

Stack-Up analysis Problems	Impacts
Loss of information	− Long Time Required
Unassociativity among the results and the CAD files	− Human Errors
Manual upload	
Many run-cycles of the GRIP application	

Based on the need for the company to solve these problems, the team of industrial engineers and university reserachers has worked to realize a powerful stack-up tool ables to provide improved performance for the stack-up analysis.

4. The stack-up tool

A new stack-up 2D tool based on the evaluation of two side per component, per time has been developed by the team. It is an NX custom tool integrated in the company PDM that is able to take the stack-up feature directly from a CAD file both for engineering drawings and MBD datasets, to collect the data from more than one drawings or sheets and to save the tolerance analysis results on an item revision dataset in the PDM system supporting tolerance value updating and traceability.

4.1 Technological choices

The stack-up tool has been developed through NX Open C API technology. NX Open API is a programming interface towards NX that allows users to create custom application by using programming languages like C and C++. It is used by NX developers, customer and partners.

NX Open is a collection of Application Programming Interface (API) toolkits that allow a flexible integration of custom software applications with NX through an open architecture for automate complex and repetitive tasks. It allows also the integration of diverse applications, as third party and NX applications, to share data on different computer platforms, from different locations using heterogeneous networks, and also on Internet. The NX Open APIs provide applications and tools that enable customers to: access the NX Object Model; create and edit objects in the NX Object Model; select the preferred programming language; create and manipulate User Defined Objects (UDOs); manage associations between UDOs and other NX objects; configure NX as a service, using standard facilities to create remote applications; customize the NX interface to tailor the NX environment to best meet their specific workflow needs; create integrated custom menus with third party developers for their applications.

The stack-up tool comunicates to NX thanks to the pre-existent interface module between NX and Teamcenter called NX Manager also named as Teamceter Integration.

Teamcenter Integration is a data management tool used in conjunction with NX. When NX is used with Teamcenter Integration, Teamcenter is running at the same time as a separate process. Since the two programs communicate, an user can create, store, and access the data within a Teamcenter database. It combines the power of NX in modeling and generating data from geometric shapes, with the power of Teamcenter in storing and retrieving data in a controlled fashion.

When NX is not used with Teamcenter Integration, data is not stored in a managed environment but are is stored on theuser local file system.
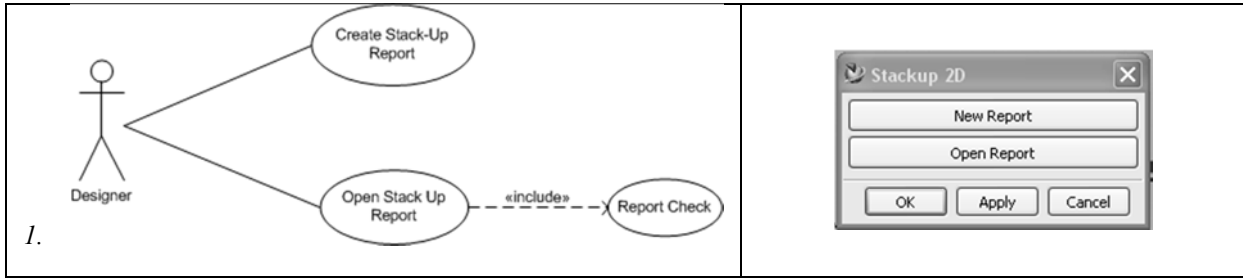
4.2 Functionalities

Starting from the requirements defined by the key users, the technical functionalities of the system have been specified and have guided the software development. These requirements are been grouped into six categories: functionalities to manage stack up reports; functionalities to manage tolerance chains; functionalities to manage drawings and models; functionalities to manage stack up features (i.e. it can be: a GD&T, a dimension with a tolerance, a dimension without a tolerance to which is assigned the general tolerance value (+/-0.1) and a squared dimension without any tolerance.); functionalities to manage NX material library; functionalities to manage spreadsheet. For each category of functionalities, the UML use-case and a screenshot of the developed tool are reported.

4.2.1 Functionalities to manage stack up reports

They provide to create a new stack up report or to open an existing one (Table 1). When a new report is created, it is generated a new item, with a new item revision and a PDM dataset. In details, the stack up analysis report is contained in the PDM dataset of a custom item revision called Engineering Variant (EV). This pre-existent item type is used in the company to manage engineering data and to contain FEM (Finite Element Method) context models. It has a workflow with signoff task that can be used to make official a stack up analysis results. The application does not control over the type of item used allowing maximum portability over other types of customized systems or out of the box solutions.

Functionalities for the management of the stack up report include, on the report opening, a report check over the stored stack up features. It allows the system to verify the states of the features that are presents inside every stack up chain. In particular, if a stack up feature is deleted from the sheet (or model view) then it is removed from the stack up report, if a dimensional feature or tolerance is updated then the user is notified and the report is updated. Furthermore the system will notify to the user every changes in GD&T features. Changes in the material associated with a stack up feature causes the automatic update of the thermal variation coefficient related to the stack feature itself.
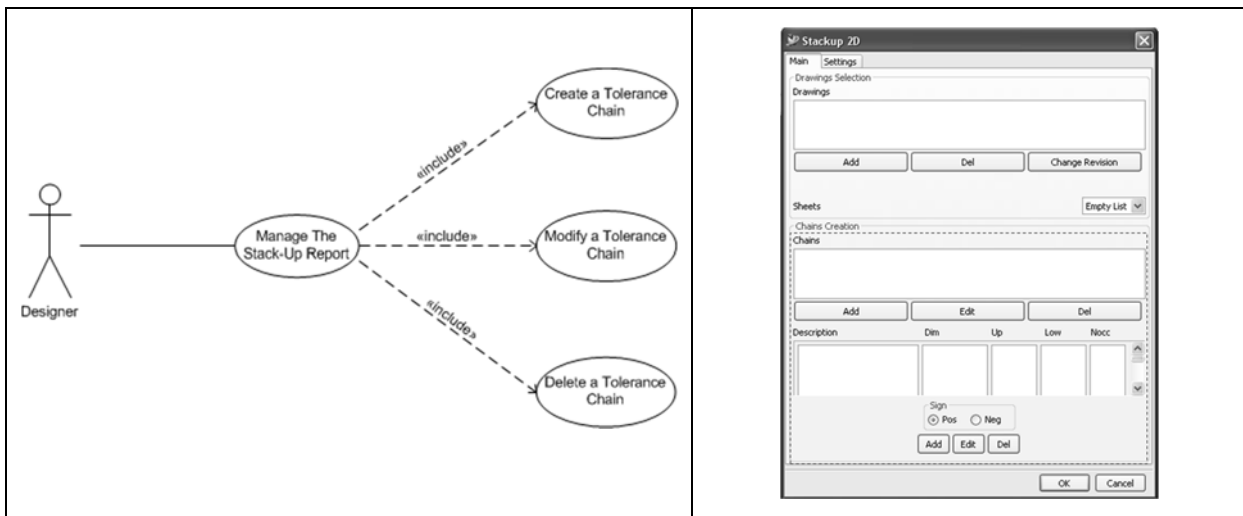
Table 2. UML use case and the Stack-up 2D starting window

1.

4.2.2 Functionalities to manage tolerance chains

Through these functionalities (Table 2), a designer can create, delete or modify a tolerance chain in which the stack up features are stored.

Table 3. UML use case and the tool Chains section

4.2.3 Functionalities to manage drawings and models

These functionalities (Table 3) allow the designers to load a set of drawings in the stack up analysis tool, for a following use in the tolerance chain definition; to select drawings and the sheets inside the drawings; to select model and the model views inside the model; to delete a drawing or model from the stack up analysis report. The latest functionality is enabled only if in the report are not present stack-up features belonging to the drawing/model to be deleted.

Table 4. UML use case and the tool Drawings section

DESIGN SUPPORT TOOLS
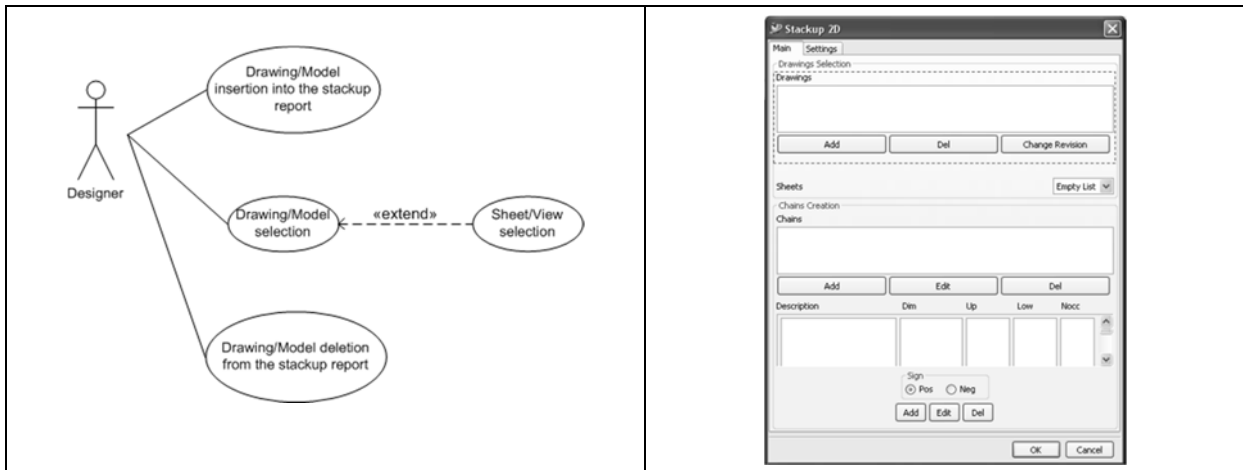
4.2.4 Functionalities to manage stack up features

The designer can select on the sheets or in the model views all the annotation needed for the stack up analysis. Furthermore, it is allowed to manually add other information useful for the analysis. A functionality to insert a dimensional features (and relative sign) is also included. The dimensional feature can be a dimension with plus/minus tolerance values or a reference dimensional feature that is enclosed in a square, or a dimensional feature to which applies a general tolerance (+/-0.1). Information stored during the entry phase allow to maintain associativity between features inserted in the stack up report and the CAD models the features belongs (Table 4).

Table 5. UML use case and the tool Drawings and Chains Sections with values
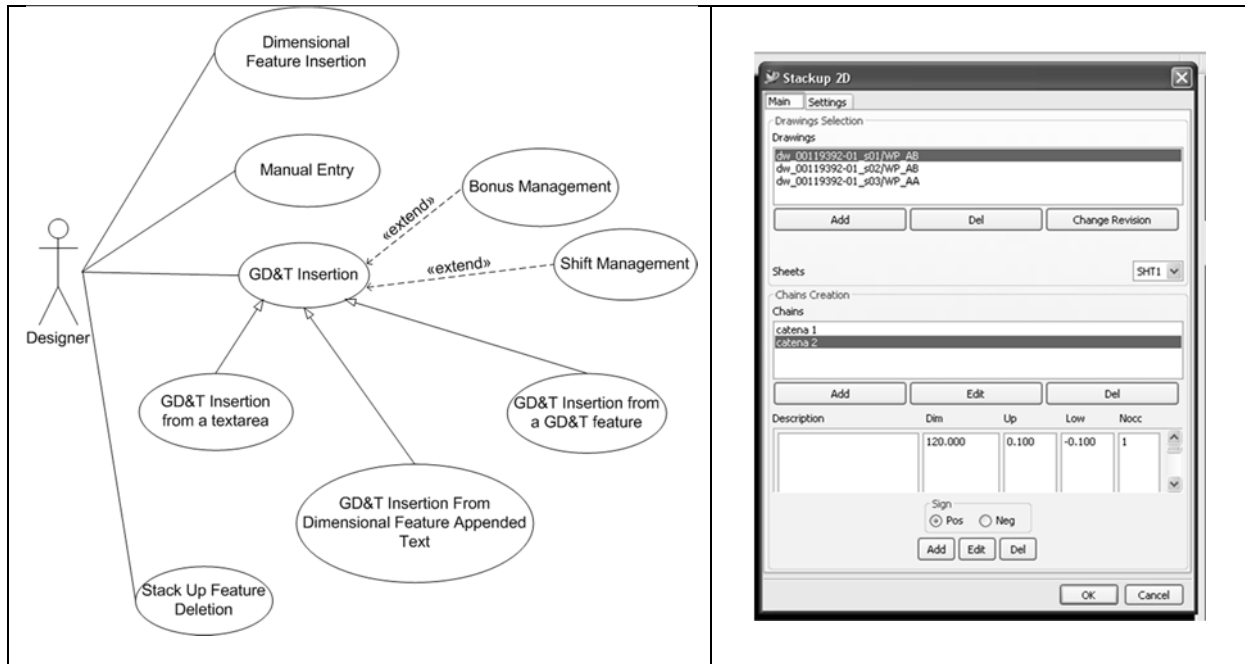

4.2.5 Functionalities to manage NX material library

With the set of "functionalities to manage NX material library" (Table 5), it is possible to associate a material available in the library of the CAD system to an annotation for assigning the right coefficient of thermal expansion that is used to execute the hot stack up analysis based on the working performance of an assembly.

This feature is enabled when the tolerance annotation has no modeling object and then no material associated to it, like in the case of entry of manual tolerance annotations.

**Table 6. UML use case and the tool thermal coefficient section**
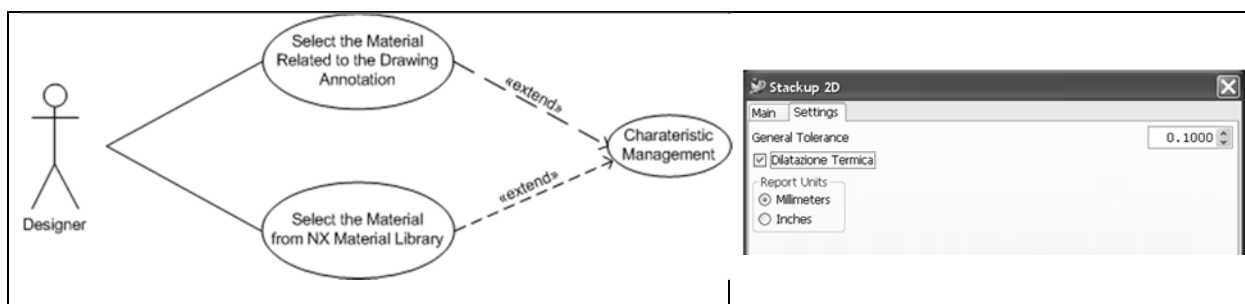
4.2.6 Functionalities to manage spreadsheets

Through these functionalities (Table 6), the spreadsheet used for the stack-up analysis is managed. A new spreadsheet can be created choosing between two templates including or not the thermal

expansion coefficient. In the template fields not used from the application, the users can add other information to support tolerance stack up analysis e.g. "tolerance stack-up sketch". It is an Excel file that is automatic created and used to perform the stack-up analysis. It is part of the CAD file and represent the stack-up report in the form of modeling spreadsheet. It has the same content of the stack-up report but this last one is the object stored in the PDM system while the spreadsheet is a simply interface of transition. Furthermore, the spreadsheet can be exported in an external MS file.

Table 7. UML use case and the Spreadsheet section
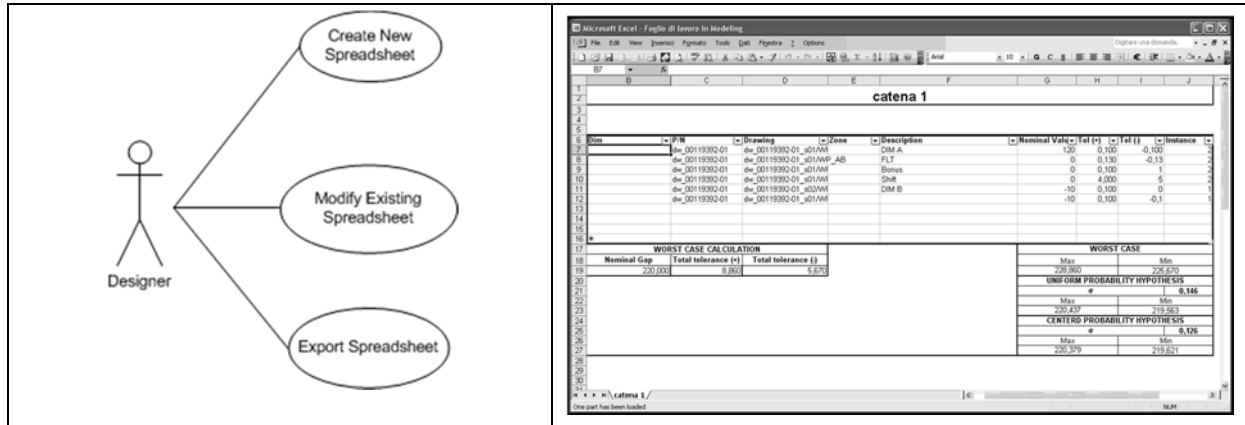
4.3 An example: Selection of a dimensional tolerance with an annexed GD&T

In this section, an example of the application is provided. The designer can need to select a dimensional tolerance with annexed one or more GD&T as highlighted in the figure 1 by the arrow on the left.

The designer choose to add this type of stack up feature in an existing tolerance chain. Specified the tolerance chain in which add the dimensional tolerance, the designer select the stack up feature on the drawing by clicking on it so the dimensional tolerance is automatically added to the chain. Afterwards the designer has to choose the Edit functionality to entry the GD&T, as indicated in the figure 1 by the arrow on the right.
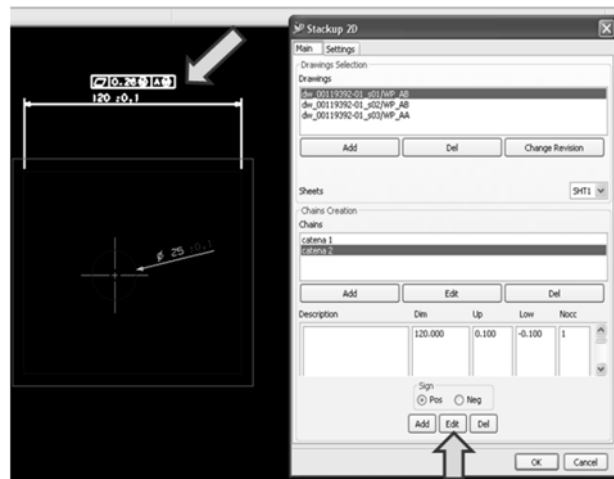

Figure 1. A drawing with a dimensional tolerance with an annexed GD&T and the stack-up 2D interface

To add the GD&T, the designer has to select them in the "Available Tolerance" section and click on "+", the value is added in the "Used Tolerance" section(figure 2-A). In this example, the GD&T has some bonus & shift (i.e. bonus tolerance or shift in the zone can be added for managing deviation in the dimensions due to material modifiers) that can be manually added (figure 2-B). To open this interface the designer has to double click on the tolerance value in the "Used Tolerances" section.

Finally, the designer has to add the description and number of occurrences of the dimensional tolerance and GD&T (figure 2-C) and click on "ok", the values appear in the description section of the tolerance chain (figure 2-D). The figure 2-D is similar to the figure 1 but with the GD&T values inserted.
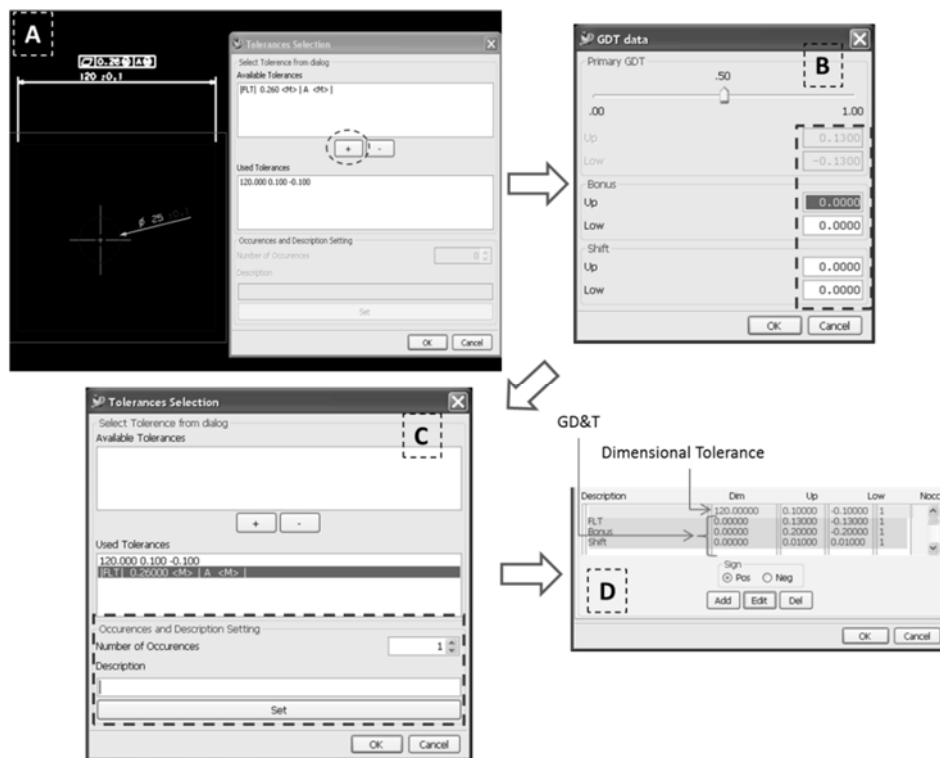

Figure 2. Phases for the entry of dimensional tolerance with an annex GD&T

The designers have to create all the tolerance chains and after, launch the stack-up analisys. The result is stored in the PDM dataset of an engineering variant item revision that represent the report itself at Teamcenter level.

5. Discussion

At the end of the stack-up tool realization, a training course has been organized by the research team to allow at the users to familiarize with the tool and to increase its diffusion in the company. The new stack-up tool is, in fact, used by thirty users working on different company projects and units . The designer is asked to use the new application for their stack-up calculus and to avoid the use of the older practices. In fact, the company problems in the stack-up analysis have been mitigated or solved. The loss of information is not more critical because all the stack-up operations and reports are automatically stored in the PDM systems and furthermore, the associativity among the stack-up reports and the CAD files is guaranteed using the Design Variant functionality of the PDM system thanks to which if changes in a CAD files are made, the stack-up report is updated. The upload is not more manual but the tolerance values are directly selected on the CAD files and automated inserted in the stack-up chain for the stack-up calculus. The GRIP application has been completely substitute by the new stack-up tool and the problem of several run-cycles is solved.

Therefore, the use of the stack-up tool has allowed to solve the highlight problems and the related company impacts in terms of long time and human resources errors. A key element in assessing the benefits of technology-enabled improvements in product design is, in fact, about the time savings that allow to reduce overall process costs by using fewer engineering hours during the design and to re-invest time savings to design products with more features or enhanced quality. Also, less human errors positively impact on organization because employees being wrong fewer times are better satisfied for

their activities and find positive stimulus in their work, furthermore, the work quality is improved and also the time required for operations is positively impacted.

During the stack up tool development several issues have emerged and have been addressed and solved. In the analysis phase, it is found that each company product unit had his own stack-up report template but through the requirement analyses, we found that templates belonging to several product units contains almost the same information, thus a the templates have been standardized and two standard templates have been introduced (i.e. one template that includes thermal variation, and another one that does not include it). These templates actually used by the stack up tool have been designed according key users needs and indications. Therefore, each unit actually use the same template.

During the design phase, an issue also in the GD&T insertion has been discovered, designers doesn't only use the standard CAD functionality to insert them but also other fuctionalities such as label, text box and others ones. In order to extract information from all the types of GD&T positions, a purposeful parsers have been developed. In such way users can continue to use the CAD functionalities that prefers for the GD&T annotation on drawings and the stack-up tool is able to take these information from everywhere. This is very important because the stack-up tool doesn't impact on the CAD designers way of product design using drawings or MDB datasets.

Furthermore, the paper results provide a further evidence to the still wide use of engineering drawing against MBD dataset and reinforce the findings of Quintana et al. (2010) that recognize in technical, process and legal issues the reasons for considering the engineering drawings essential for the product design.

6. Conclusion

The paper describes an industrial case study specifying the needs of an aerospace company and the developed technological solution. In fact, coming from the need of Avio SpA to improve the stack-up analysis and solve the existing lacks (loss of information, unassociativity among the results and the CAD files, manual upload and many run-cycles of the GRIP application), an integrated stack-up tool has been developed. It is perfectly integrated in the CAD system to automatic collect the tolerance values from the selected drawings/models and with the PDM system in which store the stack-up results for further reworks. The tool is actually widely used in the company with improved results in terms of errors and time and with guarantee of a complete traceability of all the tolerance analysis results.

The tool can take the tolerance values both from the engineering drawings and MBD datasets and supports the company in the use of the traditional engineering drawings but also extend the potentiality of use of MBD datasets. Through the same tool and the same functionalities stack-up analisys can be performed on MBD datasets without the need to learn another tool for stack-up analysis specific for MBD datasets.

The findings are based on a case study focused on an aerospace company and extension to other companies and sector requires an analysis of the tolerance analysis process and of the technological tools available for specify common points or constraints in the findings application. The application of the stack-up tool in other companies has perhaps some technological limits due to the integration with the specific company systems. It is implemented for NX CAD integrated with Teamcenter PDM and will enable the associativity management only for annotations belonging to drawings created with this CAD. However, the realized technological solution provides reflections, ideas and findings to optimize the use of technologies for stack-up analysis.

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Mariangela Lazoi, PhD
Research Fellow
Università del Salento, Dipartimento Ingegneria dell'Innovazione
Via per Monteroni, s.n., 73100, Lecce, Italy
Telephone: + 39 0832 297 992
Telefax: +39 0832 297 927
Email: mariangela.lazoi@unisalento.it
URL: http://www.pub.cpdm.unisalento.it; http:// www.unisalento.it

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