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An approach to support model based definition by PMI annotations

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ABSTRACT
PMI annotations are widely used to support the Model Based Design within modern companies. In particular, the introduction of digital annotations marks the transition from the 2D drawings to the 3D representation in many manufacturing and design companies. However, today the implementation of the PMI technology presents some limits, such as the lack of functions to generate structure templates to be applied to similar CAD models. The proposed approach aims to overcome the limits of traditional tools which are not able to add a PMI annotation's structure from one model to another one. The paper describes a method to reuse digital PMI annotations in a new model during the design phase, where the annotations are inherited from similar CAD documents. The proposed approach is based on two levels of geometric analysis: the searching of similar template models from an XML database, and the identification of the related geometric entities, which are used as associated objects for the definition of 3D annotations. The test case is focused on the automatic generation of PMI annotations for exhaust duct items used in oil & gas applications. The proposed tool has been developed within a software program called Duct Designer, which is used for the CAD automation of duct items. Particularly, the test case enhances the retrieval and reuse of sizing schemes from previous 3D models in order to obtain an automatic rebuilding of the geometric annotations.

KEYWORDS
Model-based definition (MBD); Product manufacturing information (PMI); Digital annotations; Oil & gas

1. Introduction

Nowadays, the necessity to implement the paradigm of the Model-Based Enterprise (MBE) is a very common issue in many industries [8]. The development of hardware and computer graphics technologies allow to view a 3D model with a set of digital annotations and information throughout the product lifecycle [7]. The introduction of digital annotations marks the transition from 2D drawings to 3D representation in manufacturing and design companies. A 3D CAD model is considered as a source for delivering documentation and knowledge sharing [2]. Several ISO and ASME standards provide the specifications concerning the Model Based Definition (MBD) related to all extended 3D annotations such as Views, Product Manufacturing Information (PMI) and Geometric Dimensioning and Tolerancing (GD&T) [1, 4]. Generally, the task of adding annotations is assigned to designers. Before the introduction of digital annotations, the designer put dimensions and tolerances only in 2D drawings during the engineering phase. A CAD system was mainly considered as a tool to support the generation of 2D technical drawings [3]. Today, with the introduction of digital annotations, the designer has to add product lifecycle data on the 3D model in the modelling phase. Additionally, the digital information regards not only dimensions and tolerances but the whole product lifecycle (i.e. manufacturing, disassembly, energy consumptions, impacts, cost, etc.). Therefore, it is very important for the designer to pay attention and to take time when he defines the annotation in a digital model. Indeed, when the designer copes with similar 3D models, the definition of digital PMI annotations and GD&T could become a repetitive task. Generally speaking, 3D solid models are extensively used in Computer Aided Design, and there are notably increasing requirements of their retrieval [5]. In fact, designers benefit from design reuse, in which they copy–paste an ideal source model or part of it instead of re-designing from scratch. However, the information about PMI annotations is missed when assembly models are changed. The main issue in the reuse of 3D models is the searching of a model template from a repository. How to identify that two geometric models are similar? A good solution was given by Li, who proposed a geometric reasoning approach to integrate both topology and geometry information into a hierarchy [5]. Some researchers also studied a shape

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approach or a manufacturing classification based on feature recognition, while others proposed a combination of multi-approaches [6]. Moreover, the model retrieval based on the boundary representation (B-rep) seems to be the most reliable solution for the recognition of similar geometries.

The aim of the proposed work is to provide a method to generate PMI annotations in a 3D document by inheriting an existing PMI structure from a database of similar geometric models. According to a digital manufacturing paradigm, the use of 3D annotations is essential and necessary in 3D models. The database of 3D models can also be considered as a knowledge repository because much of implicit and explicit knowledge can be added through digital annotations. For example, the question of how to retrieve design intent in CAD models from digital annotations has already been evaluated in literature [3]. Additionally, PMI tags can contain details and specifications regarding product design or manufacturing. Usually, they are attached to specific geometrical entities such as faces or edges, and the 3D workspace of the CAD system is the domain of every annotation. However, commercial CAD systems do not provide tools to replicate a PMI annotation's structure from a 3D model to a similar one. Actually, many CAD systems fail to manage the updating of PMI annotations after the replacement of related components, because they do not manage it. Furthermore, many researchers have proposed studies to enhance the use and implementation of digital annotations [3, 7]. Some examples show how to use 3D annotations for knowledge sharing [2], and other works describe the limits of PMI annotations and how to improve their usability throughout the lifecycle management [8]. Nevertheless, in the literature studies about the possibility to inherit annotation's structures from similar models is lacking.

The described approach can be applied in all cases where the designer tends to reuse CAD models, but for different reasons cannot reuse annotations added in old documents. When a designer modifies/reuses a CAD model, there are several situations that limit the preservation of a PMI structure. As cited before, generally the replacing of an assembly component deletes the connections between annotation and geometry. Another case is when a designer models tailored components for a custom application but the delivered shapes are very similar to previous works. In all these cases and more, it would be useful to reuse a PMI structure already defined in previous digital models. The main advantage of this approach is the absence of the definition of knowledge-based rules because know-how is already intrinsic in the annotations.

2. The approach

The paper focuses on a geometrical analysis to define a tool to support the reuse of existing 3D annotations during the design phase of new models, such as parts or assemblies. The main idea is to inherit an annotation structure from a similar model collected in a database of previous CAD documents with PMI. Therefore, the proposed approach aims to enhance the reuse of knowledge in digital documents and reduce the time due to the modelling of annotations. A two-stage analysis has been proposed. The first stage concerns the matching of similar 3D models using a geometrical and topological analysis. The second stage regards the searching of equivalent geometrical entities to re-build PMI annotations in the new 3D model. Fig. 1 shows the proposed workflow from a user point of view. The input is a new 3D model that could be a simple part, a sheet metal, or an assembly model. A geometric analysis gets the main information from geometry by a developed tool, in order to match it with data extracted from the database of CAD models. The database of models collects 3D digital documents with PMI annotations, as cited before.

2.1. The comparison between parts

The comparison between parts is based on topology and geometry. It tries to recognize similar models without considering dimensions, because the searching aim is to find analogue models. Fig. 2 describes an example of a short list of parameters evaluated in the proposed work. The comparison is between a reference model (Model A) and a geometry to compare (Model B). The score of similarity for each parameter is evaluated as the percentage of the absolute value Bn/An if $Bn < An$, otherwise An/Bn if $An < Bn$. In order to avoid numerical problems, the indeterminate form 0/0 has been evaluated with score 100% because that means the parameter analyzed is not present for both models. Otherwise, the form N/0 has been evaluated as score 0%. The total score is expressed such as the average percentage value of every similar score. As cited before, the approach compares the geometry of a model with many geometries collected in the database.

A model is considered similar to another if these two conditions are true: it achieves the highest score of similarity and exceeds the minimum threshold value. The conditions of similarity are experimental rules defined during the early analysis phase, where the algorithm was tested on different geometries regarding components like parts. The introduction of a minimum threshold value guarantees a level of reliability. This value has been considered like a parameter with a default value and the

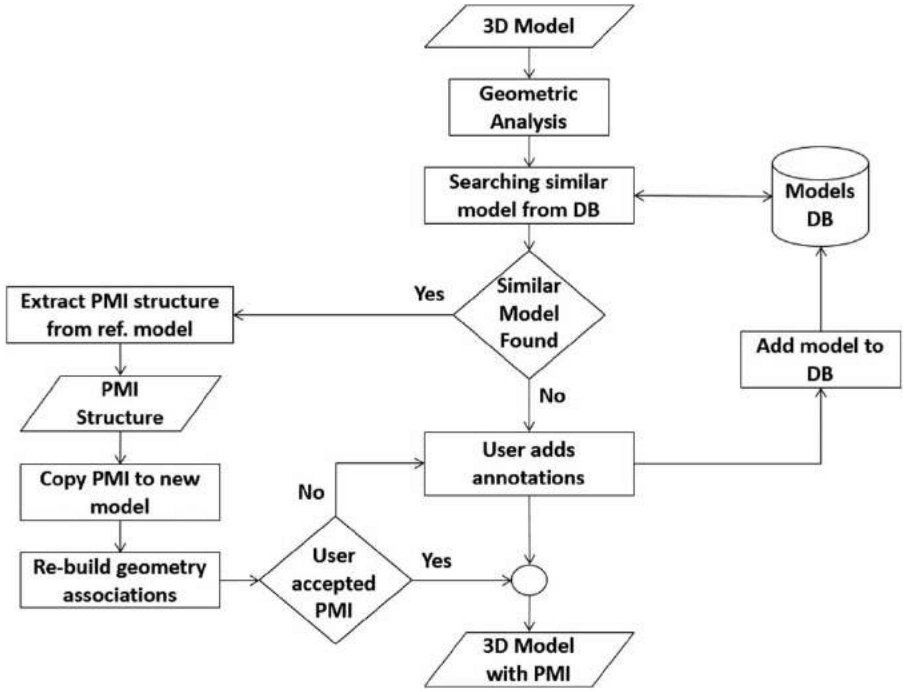

Figure 1. The proposed workflow to re-use PMI structure in new models.

List of parameters:	Model A:	Model B:	Score:
No. of edges	A1	B1	|B1 / A1|
No. of faces	A2	B2	|B2 / A2|
No. of hollows	A3	B3	|B3 / A3|
No. of convex edges	A4	B4	|B4 / A4|
No. of concave edges	A5	B5	|B5 / A5|
No. of pairs of parallel edges	A6	B6	|B6 / A6|
No. of perpendicular edges	A7	B7	|B7 / A7|
No. of right angles	A8	B8	|B8 / A8|
			% AVG

Figure 2. Example of the geometric parameters analyzed for the matching of part models.

user can modify it. The minimum threshold is fixed to 90% for the matching of simple component parts. Thus, only similar scores higher than 90% were considered reliable, otherwise the model analyzed does not have similar geometries in the database. In this case, the annotations will be added by the user and then the 3D model with PMI will be added to the database of models.

2.2. The comparison between assemblies

The case of the comparison between assemblies has been analyzed with additional conditions. In fact, an assembly model's structure can be variant. This implies a great difficulty in having a tailored PMI structure for many new CAD models to be generated. Thus, the analysis of assemblies also considers the tree structure of the child components. The similarity analysis has been extended from a single part to the model tree structure.

When two assemblies are compared, the components' structure of the one to be evaluated is matched with the reference one in order to obtain one of the four possible responses which are: the structure match is perfect, the reference model has less child components then the other one, the reference model has more different components then the reference one, or some components are in common but there are many differences between the two models. Actually, the proposed algorithm applies a weighted score in order to analyze all possible different cases. Fig. 3 describes the matching analysis of an assembly model, which regards the analysis of three weighted scores (Eqn. (1)): the similarity of the structures (**Tree Nodes Similarity**), the similarity of the parts' geometries (**Tree Leaves Similarity**), and finally the number of the leaf parts (**Tree Leaves Quantity**).

Eqn. (1) shows the calculation of the Assembly Similarity Score (ASS), which regards the weighted average about the Tree Nodes Similarity (TNS), the Tree Leaves Similarity and the Tree Leaves Quantity (TLQ). The a, b and c parameters are the weighted values used as constants. In particular, 0.4 is set for the parameter a and b, while 0.2 is set for c. The set of a, b and c parameters was defined after a trial of algorithm testing.

$$ASS = (a \cdot TNS + b \cdot TLS + c \cdot TLQ)/(a + b + c) \quad (1)$$

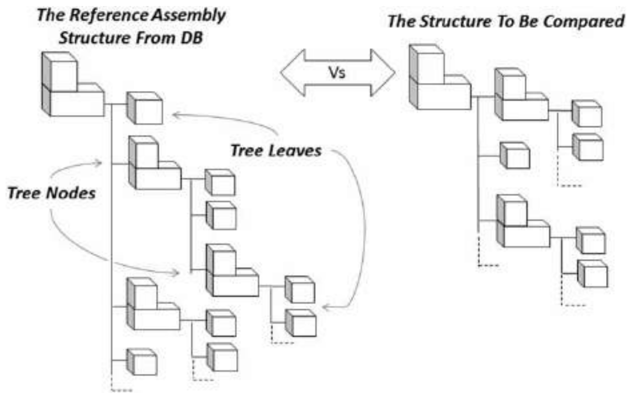

Figure 3. Example of structures to be compared.

2.3. The Re-Building of the annotations

The extraction of a PMI structure from a reference model is performed by the tool developed during the research activity. This tool can read geometry with the related list of annotations and generate an XML document with an ordinated structure of every extended data. The assignment of the reference structure to the CAD model requires the identification of the new geometrical entities to attach the data retrieved before. Thus, this phase regards the re-building of geometrical associations related to the annotations to be assigned. Two matching analysis approaches have been analyzed. The first one used an advanced function based on a geometrical analysis in order to recognize entities from a similar model to another one. This algorithm takes into account the relative positions of entities inside the normal bounding box, normal vectors and alignments. The geometry of the document to analyze is always rotated and aligned to the reference model, in order to enhance the entities identification and assignment. In particular, the advanced function consists of different search functions, which have been developed for both face and edge entities. Regarding planar faces, the base search function considers a geometric analysis based on the normal alignment and the minimum relative distance between the center of the original face and the center of the similar face to identify in the new model. This function works well for all models which present little and proportionated changes in sizing. The same approach has been employed for cylinder faces, linear edges, circular edges, etc. A function variation regards the face searching limited to the relative faces of the parent feature. If CAD documents, which are generated from a template file, are considered, each generated document has the same feature structure. Thus, a feature can be identified by id or name. This analysis option allows to reduce the geometric entities to be analyzed but requires a rigidity feature definition.

The second analyzed approach aims to assign an identification (ID) tag to each face and edge, and in particular to the entities involved in the geometric associations of 3D PMI annotations. This approach is generic because can be applied to different application cases with a great reliability in the context of the virtual models generated by a CAD automation method. The ID assignment can be performed in different ways via programing language or manually on the CAD template models by the user involved in the CAD automation. Particularly, the authors used an algorithm for the tagging of the entities. This algorithm is able to read every face, edge and additional entity such as axis from the geometry related to a specific feature. Fig. 4 shows the interaction between a configuration tool and the proposed approach to apply PMI annotations from a repository of models. The rebuilding of the annotations proposed in Fig. 4 is based on the tagging of the entities. The Configuration tool generates 3D models starting from a requirements list. The proposed PMI tool applies the ID tags to the geometry of each generated 3D model. As cited before, a function finds the related PMI structure from a collection of models and tries to replicate it into the generated 3D models. This approach, which is based on the tagging of the entities, is the most used way in our research because it guarantees a higher level of reliability for the test cases analyzed. The first approach is used in the situation regarding the identification of geometric entities, which are members of simple parts.

Object-oriented classes have been developed in order to describe the data of the 3D annotations. In particular, a PMI class collects all information required to rebuild the same annotations in a similar geometry. The annotations data is directly read by a function, which analyzes each PMI information collected in a CAD document. The main fields defined in the PMI class are: the ID-code of the annotation analyzed, the reference to the first and second geometric objects, the type of dimension (horizontal, vertical, parallel, diameter, etc.), the related model view, the computed size value, and the preference settings such as lettering, lines and arrows. Regarding the reference to the geometric object, the type of this data depends on the approach used for the identification of the geometric entities. If the geometric identification is based on the matching of the same ID tags between the geometric entities, this value is a string. So, if the geometric analysis approach is chosen, this data contains all the geometric information about a face or an edge such as: the normal, the bounding box points, the origin, the axis, etc. The automatic assignment of a PMIs structure to a CAD document should always be reviewed by a technical user that validates the quality of the functions developed for the reuse of annotations. If a model requires some changes

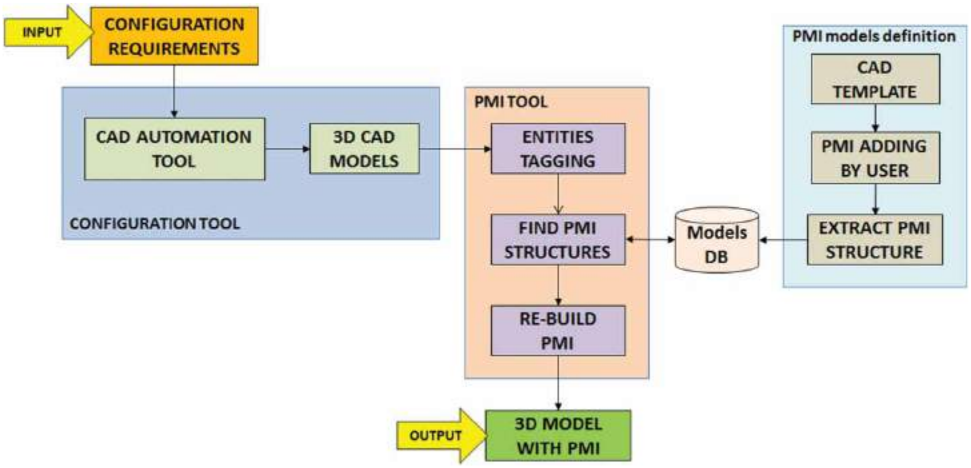

Figure 4. The interaction between a configuration tool and the proposed approach to apply PMI annotations from a repository of models.

in the definition of annotations, it will be collected in the main database of models in order to enhance the further reuse of knowledge.

3. Test case

The proposed method has been validated in the context of an oil & gas application. A power gas turbine requires a design of inlet and exhaust ducts with many details. The functional design of each duct is like a configuration of many items and levels. A duct is a collection of flanged items and each item is structured in different functional levels such as the insulation level, the casing level and the arrangement level. Generally, oil & gas applications require a tailored design because each plant has different specifications, constraints and boundary conditions from other projects. However, regarding the duct design, there are a lot of components with common shapes which are used in different power plants. The sheet metal parts and assemblies, which represent the level of a metal casing of a duct item, can of course take different tailored shapes, but there is always a typology of common structure used, as observed over different design approaches analyzed in collaboration with oil & gas partners.

Fig. 5 shows some examples of typical duct items used in oil & gas applications. The cross section of a duct item depends on the flange of the related power machinery and it can be rectangular or circular. The duct routing can be horizontal, vertical or mixed. Transition items guarantee the possibility to change the cross section. Many option components are usually present in an oil & gas duct, such as silencers and expansion joints. Every exhaust duct has an internal insulation structure which includes an internal casing of many plate claddings. Each

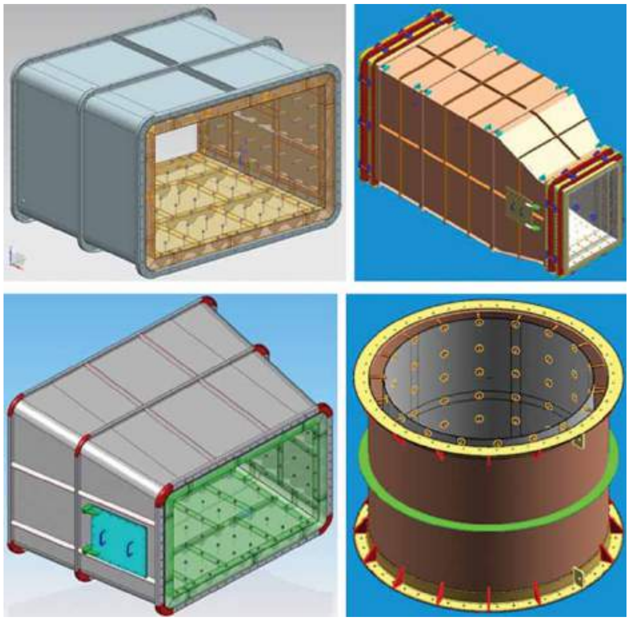

Figure 5. Example of duct items used in oil & gas applications.

cladding is fixed to the external casing by a collection of studs and bars. Between the internal and external casings there is the insulation material.

The proposed test case regards the use of the developed tool to add 3D annotations in the models of a duct item. The experimental workflow has also been a way to promote the use of 3D digital models for communicating all the information otherwise present in traditional 2D drawings. Generally, 3D annotations in this field concern not only dimensions and tolerances, but also know-how on important details about assembling and manufacturing. Fig. 6 shows an example of an assembly where the 3D annotations were reproduced by the proposed tool.

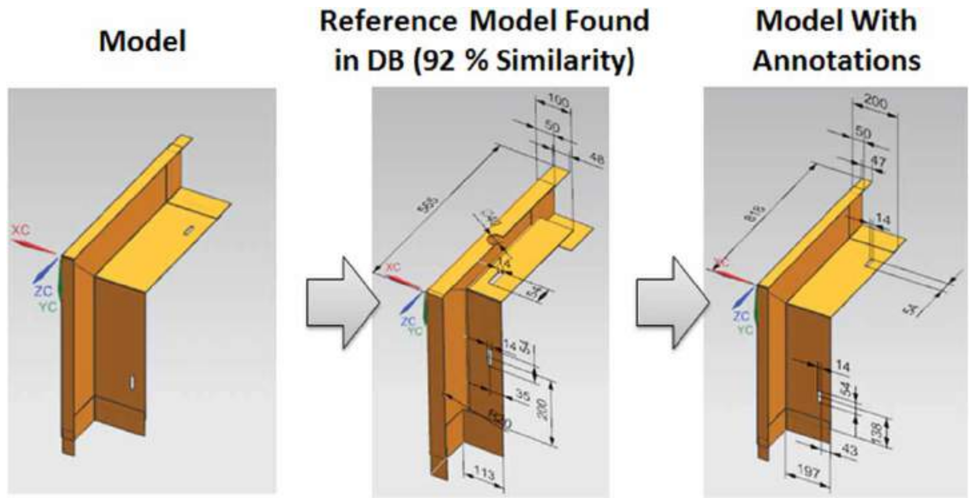

Figure 6. Example of PMI inherited in an assembly model.

As described, the structure of digital PMI was inherited by a previous model searched in the database. The same example could be extended to other more complex components.

Encouraging results have been achieved using the developed tool. The algorithm for searching similar geometries has provided a good level of reliability. The definition of a high threshold value for the similarity score has reduced the risk to inherit annotation from non-similar geometries. The calculation to re-build the associations between each PMI tag and related geometrical entities has failed in few cases where the model presented special details.

3.1. Software implementation

The proposed method has been implemented as a prototypical tool within a CAD automation software called Duct Designer. This software has been developed and tested in several oil & gas industries. Generally, Duct Designer aids the user to configure desired solutions of exhaust ducts through simplified layout. This tool implements an objected-oriented product structure based on the real product architecture. Different design alternatives can be configured and automatically generated in CAD documents on the basis of functional specifications. The related CAD documents are both 3D models (assemblies and parts) and 2D drawings. As cited before, the proposed research approach aims to automate the generation of 3D annotations in order to enhance the use of MBE technology. This is because the necessity of MBE tools is a requirement of many mechanical and electrical companies. The main scope of Duct Designer and its tools is to shorten design and manufacturing processes.

The prototypical tool to generate PMI annotation is a Windows-based application implemented using the .NET framework and the Siemens NX 8.5 CAD system (Fig. 7). Fig. 4 shows how the workflow of PMI annotation tools is integrated in the base architecture of Duct Designer. Fig. 7 describes the prototypical graphical user interface (GUI), which allows the administrator user to populate a database of XML documents regarding the geometry and 3D annotations from different CAD documents. Each document is analyzed by dedicated functions, which are used to populate the object-oriented class structures and save all needed information in XML documents inside a database folder. When a new product is configured using the Duct Designer software (Fig. 8), the developed tool can read the product geometry data and compare it with several model structures present in the database as XML documents. The selected template model contains all PMI information inside the line of the XML documents. A generation function is able to run the modeling of the PMI structure from the XML document to the new CAD model. The comparison of models and the recognition of the geometrical entities use the approach described in section 2.

3.2. PMI structure applied to part models

Fig. 9 shows some examples of cladding components with PMI annotations. These parts were generated using the Duct Designer software, and the PMI structures have been applied using the PMI tool developed. The average success rate of the approach is about 85% for part components, which means that 1 or 2 dimensions could be lost during the generation of the annotations. The PMI annotations allow the user to see the product dimensions within the 3D views. Additionally, the 3D annotations can be projected in 2D sheets reducing the time spent for the drafting activity.

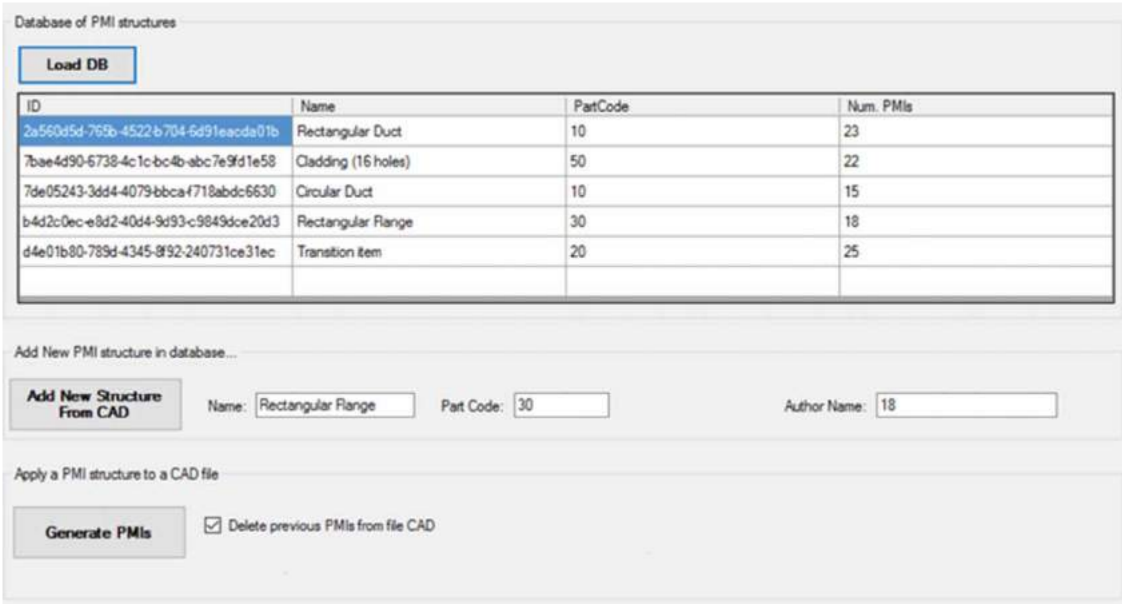

Figure 7. Test tool used to load PMI structures in the XML database and generate 3D annotations on a similar CAD document.

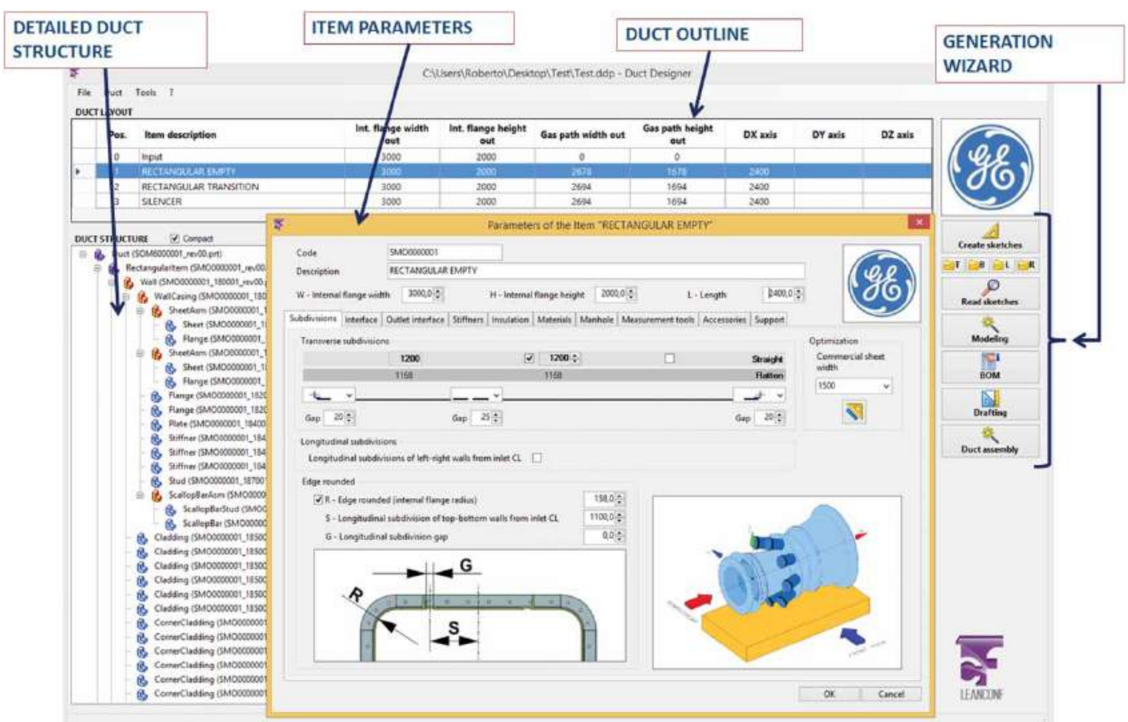

Figure 8. The CAD automation tool implemented to generate the 3D models.

3.3. *PMI structure applied to assembly documents*

An example of a rectangular duct item is described in Fig. 10. This assembly document was automatically generated by the described CAD automation software. The PMI annotations have been generated using the proposed prototypical tool, which was developed as a plug-in of the Duct Designer software. The automatic generation of the annotations within assembly models has shown about 75% average success rate for assembly documents.

4. Discussion

The proposed approach has been implemented into the Duct Designer platform as an additional plug-in. The user is involved into the loop in order to feed the

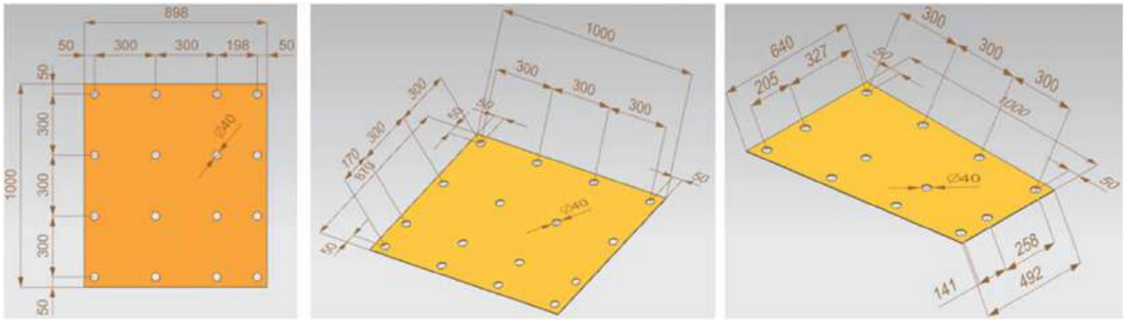

Figure 9. Example of PMI annotations automatically added to cladding components generated using the Duct Designer tool.

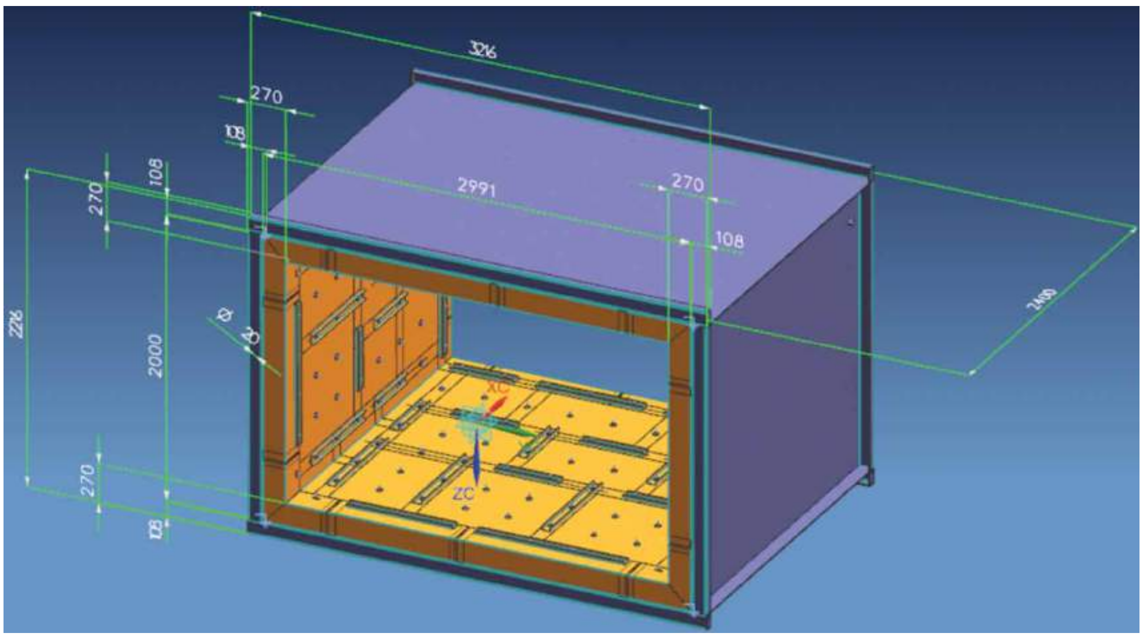

Figure 10. Example of PMI annotations automatically added to a rectangular duct item.

repository of knowledge with the information related to the correction applied during the review activity. When the PMI knowledge is captured, the information such as the geometric objects and the annotation definition is read and imported into virtual classes which are also saved as XML files in the filesystem. A function to read the annotation data has been developed as well as a second one to generate new annotation instances. Both functions require the connection with the application programming interface (API) of the CAD system involved. The automatic reuse of PMI annotations in models which are generated by a CAD automation tool means a great reduction of time, even if the designer has to review a part of them. The benefits of the proposed approach can be estimated in terms of time. In fact, the generation of PMI annotations is automatic and takes more or less 1 minute for an assembly with about 100 parts. However, the designer has to take time in order to define a database of the most representative 3D models including the PMI annotations; this phase could involve the previous CAD documents present in the company. The Duct Designer can generate 3D models of duct items, but also create 2D drawings. If the PMI annotations are defined in the 3D models, the same layout will be available in the drawings. The manual definition of PMI takes a lot of time as well as the drawing execution. The time saving depends on the models, a reduction of about 10 min can be estimated per assembly document such as a duct item which includes dimensions and manufacturing annotations. The necessity to have a database of models is a limit of the proposed approach. Additionally, similar geometries do not always provide similar annotations. The proposed method to retrieve similar models is fast, but it works well with simple geometries such as the models proposed in the test case like the duct claddings. The limitation of the approach can be overcome in this phase by the review of the expert designer who corrects the definition of the annotations.

5. Conclusions

An approach to enhance the reuse of knowledge and best practices, held in digital 3D CAD annotations, has been proposed. The developed tool aims to overcome the limits of traditional CAD tools which are not able to add a PMI annotation's structure from one model to another one. The knowledge repository is represented by a collection of CAD models with annotations, thus the user is not required to define and formalize any design rules. The information about each PMI structure, which is related to a specific template document (CAD model), has been exported in a repository constituted of XML files. The test case has been focused on oil & gas exhaust ducts. The proposed method has been performed in combination with the design automation and configuration of duct items in order to reduce the design time. In particular, the prototypical tool has been used to generate PMI annotations in models such as claddings and duct items with a success rate between 75% and 85% for the models analyzed.

As future developments, the approach should be tested with more complex geometries. The function used to add ID tags and to recognize the associated geometrical entities should be improved in order to increase the efficiency of the system. Finally, the approach could be extended and tested considering other types of 3D annotations such as notes, material specifications, roughness, and geometrical tolerances.

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