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A graph-based approach to CAD modeling: a digital pattern application to the sizing and modeling of manual transverse gearboxes

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Abstract

Purpose:

The paper proves that the representation of assembly/product dependencies based on graphs and represented through three levels of detail simplifies both the design of assembly/ product and the development of tools dedicated to the design activities.

Result:

The comparison of directed-graphs (digraphs) related to two different manual gearboxes highlights the usefulness of a graph-based approach for CAD modeling and its use in the development of a related Graphical User Interfaces (GUI).

Discussion & Conclusion:

One key issue for reduction the time to market of a mechanical product, of a software tool or any other product is the knowledge reuse. In such a context, a graph-based approach helps in those cases where a digital pattern setting is recommended. The approach and the software tool are useful both for designers and companies that want to customize and improve such reuse activity. Therefore, the paper presents the architecture of a three shafts gearbox and compare it with a classical architecture of a two shafts gearbox. The analysis of the differences existing between the two architectures are carried out by using a graph-based approach. Then, the comparison is used to set up a software tool useful for both gearbox architectures. Finally, the generation of a GUI, developed in MatLAB® environment, allows to easily generate the preliminary CAD models of different gearboxes, related to each architecture.

1 Introduction

Nowadays, the activities of engineering design and software development are increasingly linked. In particular, many large companies have a team dedicated to Information and Communication Technology (ICT) or a department for developing and customizing software tools according to the needs coming from collaborative development environments [4].

The design and development activities, within the product life cycle, could determine the largest profit losses [12]. Therefore, these activities need for a greater computer support, aimed to complex product design for lead-time reduction [1], as in case of means of transportation. To reduce the time of the design process (which detail activities are described in [6]) we can use knowledge-based system [7]. In fact, such design activity never starts from scratch but it starts and grows up from the reuse of product knowledge and old experiences.

Sometime, the degree of reuse depends from the specific designer who has acquired the experience. To make more objective the reuse of product knowledge, it could be useful a methodology able to detect, in automatic way, the common parts (i.e the differences) existing in mechanical assemblies, in order to reuse, for example, the common features for an assembly operation or the common source code for a software tool.

Large companies manage and distribute engineering knowledge by means of structured work teams [11].

In such a context, it is important to individuate user-defined features, assembly features, procedures and methodologies that could be reuse during a new product/assembly design development. In fact, the difficulty in reusing product knowledge is often linked to the difficult searching of the correspondence between what you are doing and what has been done in the past. To individuate one or more common features, existing between two or more mechanical assemblies, is not a trivial operation. Sometimes, the design of the architecture for a new product starts again from a scratch, just because it is not easy to identify such common features.

In such a context, we believe that software tools aimed to support the design tasks must adopt Knowledge Based Engineering (KBE) to capture and reuse knowledge [12], in automatic way, during design activities, acquiring it from each expert designer. In fact, Sandeberg [15] define KBE as "*the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way*". Lin et al. [10] claim that the current KBE systems exhibit difficulties in managing the whole design process and they wish for a CAD-based environment, able to control the whole design process. KBE is a useful practice for all companies that perform repetitive tasks or focus on the design of similar products. Several researchers worked on the re-use of product and process knowledge.

To meet the need of reuse product and process knowledge, within CAD-CAE environment, it is important the generation of a parametric CAD model [5],[9]. It is also possible to choose additional knowledge-based modules that make easier the design tasks for mechanical parts or assemblies [18]. All software, modules and support systems need to communicate and to share information. The Digital Pattern (DP) concept for product and process development, used in the present paper, is the mean to improve quality and reduce time and costs for product development, through a massive re-use of knowledge and the extensive integration of software tools.

A very useful tool that fits the needs of capturing and reusing knowledge is graph theory [13],[13]. Graphs, in fact, provide the right abstraction from the model while preserving the accuracy of the dependencies and then the interconnections [2],[3].

In [7] a way to associate a design methodology to graph theory is proposed. An editable transfer function graph-based is realized to control the dependencies among parameters to design a two shafts gearbox.

The present paper applies the approach proposed in [7] to a three shafts-gearbox architecture with a particular focus on the identification of common design features belonging to different gearbox architectures, in order to accomplish the geometric modeling of mechanical assembly and supporting the preliminary phase of dimensioning as well as the updating during the reuse of consolidated CAD models. In particular, the use of directed graphs improves the management of company know-how according to a KBE point of view and allows the creation of an easy-to use graphical interface based on directed graphs.

The paper is arranged as follows. Section 2 and Section 3 summarizes the approach proposed in [7] and the architecture of a three shaft-gearbox, respectively. Section 4 provides the application of the approach to the case of the gearbox; in Section 5 the contraposition of two manual transverse gearbox are presented; section 6 deals with the implemented GUI. Finally, Section 7 draws conclusions.

2 Approach overview

Patalano et al. [7] propose an approach to CAD modeling dealing with three different levels, within the geometric modeling of assemblies. The three levels are:

- *Functional level* (Level 1) where functional groups are defined (as for example, product architecture, company constraints, standards);
- *Logical level* (Level 2) where datum, parameters and control rules for dimensioning are defined (as for example geometrical datum and control function);
- *Geometrical level* (Level 3) where the geometries of parts, that compose the assembly, are modeled.

This approach also aims to define an editable transfer function, based on directed graphs, that allows designer to directly edit the relations among parameters. The graph is accomplished by associating vertices to parameters and, then, expressing the existing relations by directed edges. This association can be expressed through a matrix representation, in order to use it for a software tool implementation.

Such a representation of the product allows you to lift up the issue, clearing it from the shape concepts and focusing only on existing dependencies.

3 Three shafts gearbox 3SG-6G

The present section describes architecture and functionality of an automotive manual transverse gearbox with three shafts and six gears [6] called “3SG-6G”.

As shown in fig. 1, the gearbox is composed by three shafts and the differential. It has got a main shaft (M) that engages with others two transmission shafts (transmission shaft (T) and transmission shaft auxiliary (T_{aux})). The gears on the two transmission shafts are alternated:

1) 1^{th}, 3^{th}, 5^{th} and 6^{th} gear on transmission shaft;
2) reverse, 2^{th} and 4^{th} gear on auxiliary transmission shaft.

Both transmission shafts are engaged with differential gear with the same speed ratio.

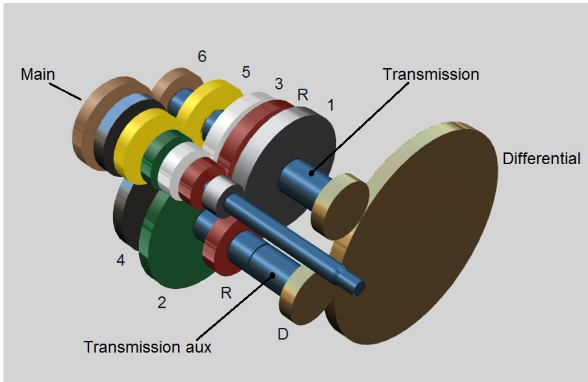


Fig. 1 Simplified model of 3SG-6G gearbox (pitch diameters)

The above mentioned architecture is mainly realized to reduce the axial dimensions even if it could increase the transverse dimensions.

To define and to constraint the position of axes it is useful to identify two subsystems: the reverse and the differential subsystems composed by wheels aimed to realize the reverse and rear-axle ratio, respectively.

The first subsystem consists of three gears which are constrained by tangent conditions. Its axes have a triangular layout depicted in fig. 2.

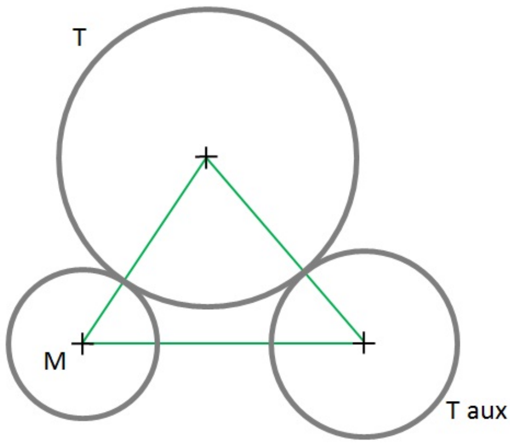


Fig. 2 Reverse subsystem

The second subsystem (fig. 3) is constituted by two wheels engaged with the differential wheel with same speed ratio. Therefore, the two pinion gears and the axles base are equal. In this subsystem the axles base always assume an isosceles triangular layout. This reduces the numbers of control parameters because the axle base T-T_{aux} is equal to the other two axles base.

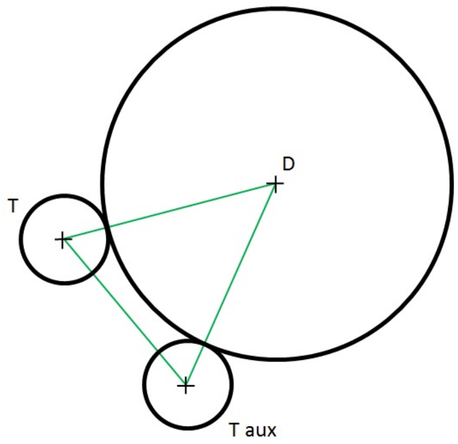


Fig. 3 Differential subsystem

The condition of concentricity for the gears (on the transmission shafts) imposes the location of two subsystems in the final gearbox layout (fig. 4). The remaining DOFs are constrained by assuming that:

- the origin of the reference system coincides with the axis of the main shaft;
- the x-axis is oriented along the joining line between the axes M and T_{aux}.

T-T_{aux} axle base dimension is obtained by speed ratio in the reverse subsystem.

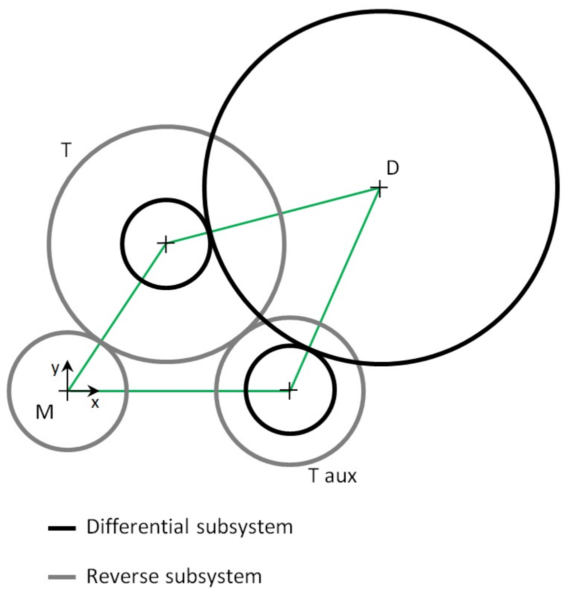


Fig. 4 Final gearbox layout.

4 Graph representation

In [7] the graph theory is applied to describe a product into three levels of detail, in order to represent and control the dependencies. In this paper the same approach is applied to the gearbox 3SG-6G, described above. As proposed in [7], to accomplish the complete modeling of the gearbox, the functional, the logical and the geometrical levels were defined. For more details, related to elements to be included within each level, see [7].

4.1 Functional level

To accomplish the designing of a family of gearboxes, a set of functional parameters was taken into account (tab. 1), according to the know-how of a European automotive group.

Materials for gears	Mat_G
Materials for shafts	Mat_S
Costs	*Cs*
Number of shafts	*Ns*
Number of gears	N_G
Teeth Modulus	*m*

Tab. 1 - Functional parameters

The bounding volume of the assembly is a significant requirement in gearbox design as it deals with the characteristics of layout engine compartment. Often, similar gearboxes have to be assembled within different engine compartments and this induces several changes to the whole architecture of gearbox as for the dimensions of gears, the speed ratios, the distances between shafts. As the same 3D bounding volumes could be accomplished through different combination of functional or datum parameters, the 3D bounding volumes were not settled as functional parameters but they were used as inspection parameter during re-design activities.

4.2 Logical level

At this level, the equations (see Appendix) that control the correctness of geometry and the datum scheme that controls the layout of gearbox (as a skeleton [5]) are introduced; furthermore, the assembly digraph and gears digraph are placed.

Datum set is characterized by four axes; one of such axis is referred only to the differential ring gear. The other three axes are related to the main shaft, the transmission shaft and the transmission auxiliary shaft, respectively.

The datum set is located by means of three parameters (fig. 6):

- *Axel base main-transmission* (I_1) = distance between the axis of the main shaft and the axis of transmission shaft;
- *Axel base main-transmission aux* (I_2) = distance between the main axis and the transmission auxiliary shaft;
- *Axle base transmission-differential* (I_D) = distance between the axis of the transmission shafts and the axis of the differential gear.

4.2.1 Digraph representation

The digraph, depicted in fig. 6, shows the association parameters-vertices and the association relations-edges, for each gear. The digraph [13] for the reverse gear reflects the presence of three wheels. As the reverse gear has spur gears, the main difference in the digraph, is the lack of the parameter β and all parameters directly related to it ($\beta = 0$).

Therefore, the digraph of gearbox (fig. 7) is composed by a reverse digraph, a differential digraph and by a number of subgraphs equal to the number of gear belonging to gearbox. To characterize the gearbox with a different number of gears, it is possible to add or delete the sub-graph depicted in fig. 6.

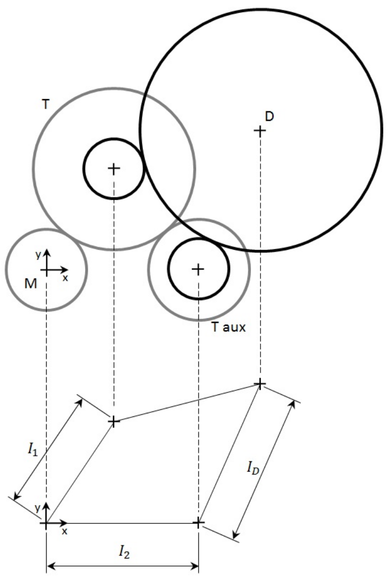


Fig. 5 Datum set of the 3SG-6G gearbox.

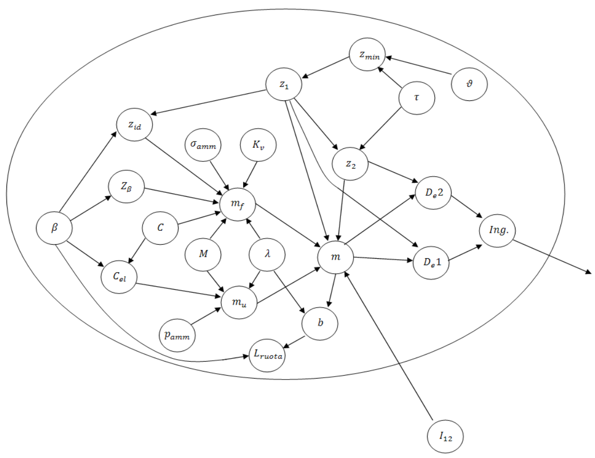


Fig. 6 Sub-graph for helical toothed gear.

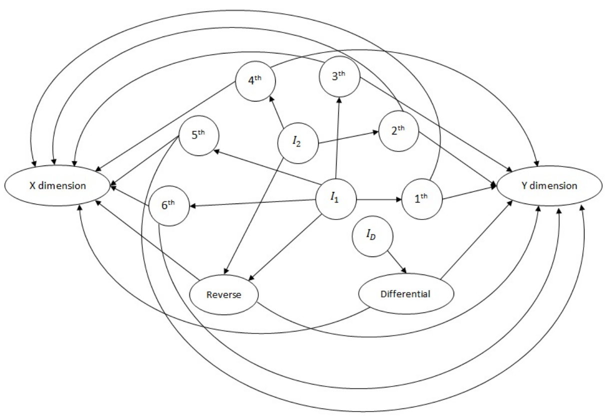


Fig. 7 Digraph for 3AG-6G gearbox.

4.3 Geometrical level

Fig. 9 depicts the 3D model of 3SG-6G gearbox corresponding to the geometrical level. At this level, the independent parameters i.e. the ones that are not included in the digraph could be updated.

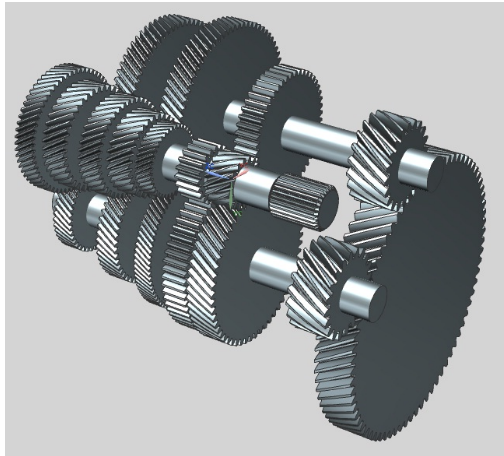


Fig. 8 3D CAD model of 3SG-6G gearbox at geometrical level.

5 Contraposition of CMT-6M and 3SG-6G

In this section we are going to compare the three levels of two different manual transverse gearbox architecture: 3SG-6G vs. CMT-6M in order to evaluate the existing differences and similarities. The identification of similarities makes it much easier to implement the new architecture within the tool already developed; in fact, the only differences will be implemented, in order to generate even the geometric models of 3SG-6G gearbox.

5.1.1 Gearbox CMT-6M

The CMT-6M is a manual transverse gearbox with two shafts (main and transmission) depicted in fig. 9. It also has got a little shaft to realize the reverse and the differential ring gear which, fixed on differential carrier, transmits the motion at the live axles of a single wheel.

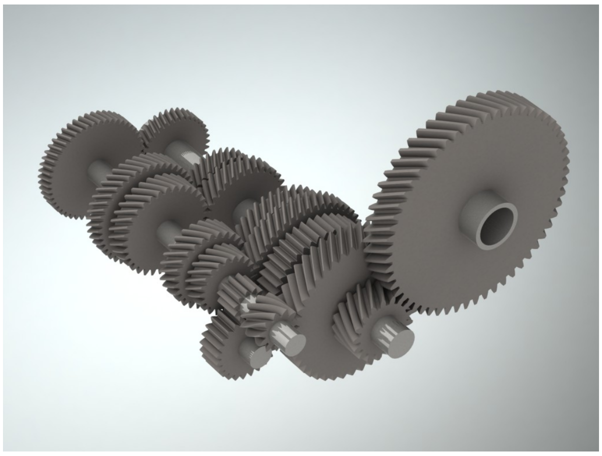


Fig. 9 3D CAD model of CMT-6M gearbox at geometrical level.

5.1.2 Comparison

Comparing the datum sets of two gearboxes (fig. 10), it is possible to identify the existing differences.

At the functional level there are no difference. Few differences at the logical level can be noticed.

The first difference is the reduction of the number of control parameters from four to three. This is due to the presence of more geometric constraints on 3SG-6G gearbox. The double engagement of the differential ring gear and the concentricity of the two pinions on the transmission and transmission auxiliary shafts respectively, are the additional constraints which identify the differential axis position.

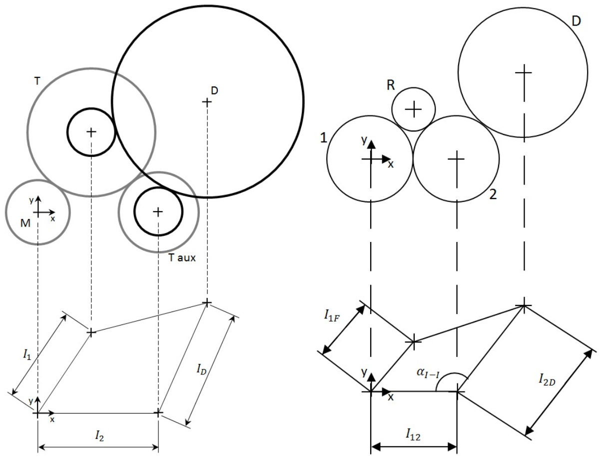


Fig. 10 Contraposition of the 3SG-6G (left) and CMT-6M (right) datum set.

The existing geometric constraints simplifies the computational tasks. The positioning of the reverse gear is the same, while the positioning of the differential is simplified because the angle for its positioning is already defined by the isosceles triangular layout.

Other small differences in the gearbox digraphs can be appreciated. In fig. 11 the changes in the dependencies, by means of digraphs and due to the distribution of the gears on more shafts, are shown.

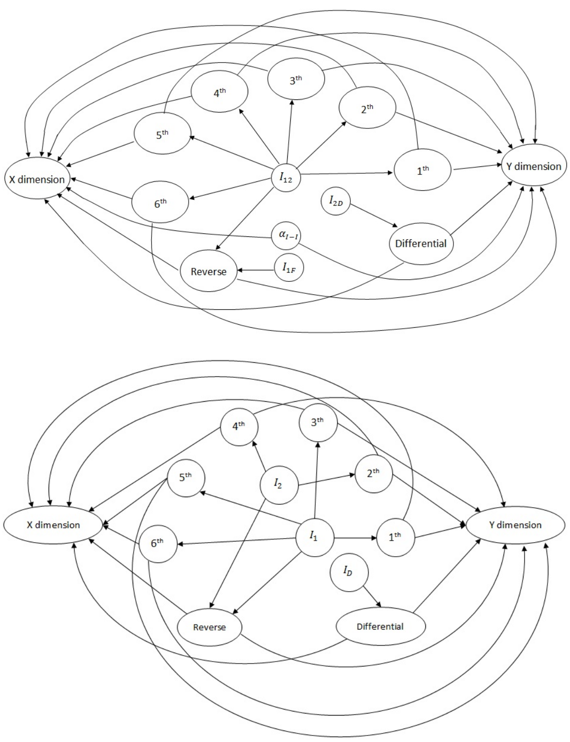


Fig. 11 Comparison of the CMT-6M (up) and 3SG-6G (down) digraph.

At geometrical level the two architectures seem so distant. However, the digraph representation has proven to be very similar.

6 GUI implementation

A Graphical User Interface (GUI), developed in MatLAB environment, was released in order to support the design of two automotive manual transverse gearboxes presented above. The source code is very basic and is made only in order to validate the approach used.

The study of graph representation figured out how minimize the changes in the GUI to include a new architecture.

The first step was to revise the interface appearance (fig. 12) to make it more user-friendly.

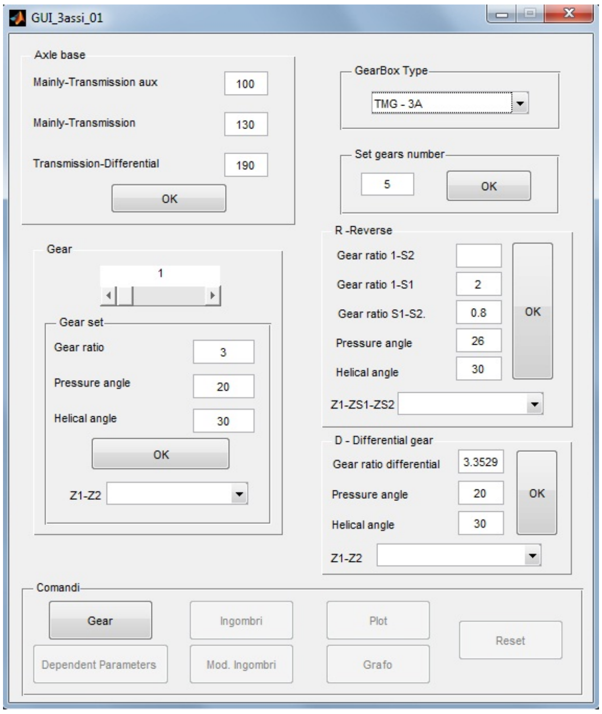


Fig. 12 GUI for gearbox modeling

The greatest effort in the implementation dealed with the location of the source code and the functions to be reused and generalized.

By setting of the “Gearbox type” parameter, the choice of the gearbox type, that must be dimensioned, was introduced. The selection allows designer to load only the differences, in order to reuse all the common source code related to different gearboxes, and, therefore, to reuse existing knowledge.

The designer can set the number of gears, belonging to the gearbox, up to a maximum of six, even if it is possible to extend the number of gears with no limits, of course foreseeing the possible architectures.

The computational results are currently displayed in a dedicated environment. By clicking on “Plot” command, the characteristic surfaces of toothing i.e. head, sides and foot of helical-toothed gears are displayed on screen (fig. 13). In this environment it is also possible to change the mesh degree (fig. 13) and to accomplish the desired accuracy of geometries. Then, it is possible to export the points of meshes, related to the geometry of whole assembly, by using a text format to generate the 3D model in any CAD environment.

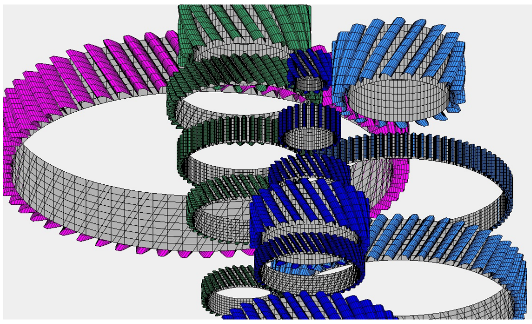
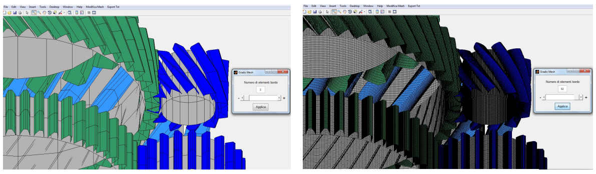


Fig. 13 Environment for display of the surfaces.



a) **b)**

Fig. 14 a) minimum degree mesh: 2 elements for edge; b) maximum degree mesh: 50 elements for edge

7 Conclusion

The paper presents the study of two different architectures of manual transverse gearboxes by using a graph-based approach, aimed to CAD modeling. The main focus of the paper is the individuation of common and, vice-versa, different features belonging, respectively, to the functional, logical and geometrical level. The identification of common features existing between different gearboxes, through a graph-based approach, is the start point to perform the re-use of company knowledge and to reduct time and costs, according to a DP point of view. All focused common features, in fact, were used to release a new software tool for the sizing and the preliminary CAD modeling of the examined gearboxes.

The present approach fits with the design of products/components, whose geometrical and design features are fixed. Of course, the definition of the functional, logical and geometrical levels is a time consuming activity and it requires a careful and thorough study of the product or component under consideration. For this reason, in the present paper, the greatest part of a previous digraph, in the definition of the logical level of a different gearbox architecture, was re-used.

Otherwise, when designers tackle with a product/component whose geometrical and design features are not fixed, a series of relations are not known. The lack of a fixed architecture or specific equations, for example, could bring to the partial definition of the logical level. In such cases, the use of a digraph, related to a different level of detail, could improve and accelerate the processes aimed to the definition of geometrical and design features.

Appendix

Tab. 2 summarizes the general equations for gear sizing. Tab. 3 and tab. 4 show the additional equations for spur and helical toothed gears sizing, respectively.

For the sizing of modular toothing the classic theory for gears [16],**Errore. L'origine riferimento non è stata trovata.** was used.

Minimum number of teeth	$z_{1\min} = 2\dfrac{1+\sqrt{1-\tau(2-\tau)\sin^2\vartheta}}{(2-\tau)\sin^2\vartheta}$
Gear ratio	$\tau = z_1/z_2$
Tooth width	$b = \lambda * m$
Pitch diameter	$D_p = m * z$
Outside diameter	$De = D_p + 2m$
Max size	$Ing = De_1 + De_2$

Tab. 2 General equations for external gears

Bending	$m_f = C * \sqrt[3]{\dfrac{M}{\lambda * z_1 * K_V * \sigma_{amm}}}$
Wear	$m_u = C * \sqrt[3]{\dfrac{M}{\lambda * p_{amm}^2}}$

Tab. 3 Additional equations to characterize straight-toothed gears

Bending	$m_n = C * \sqrt[3]{\dfrac{M}{\lambda * z_{id} * K_V * z_\beta * \sigma_{amm}}}$
Wear	$m_n = C_{el} * \sqrt[3]{\dfrac{M}{\lambda * p_{amm}^2}}$
Number of teeth dummy	$z_{id} = {}^{z_1}/_{\cos^3\beta}$
Gear width	$L = b * \cos\beta$

Tab. 4 Additional equations to characterize helical-toothed gears

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