

Direct Modeling Approach to Improve Virtual Prototyping and FEM Analyses of Bicycle Frames

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Abstract— Main target of this paper is to analyse the advantages in the use of the Direct Modeling in the Virtual Prototyping processes and in the multiphysics analyses with the help of Reverse Engineering procedures. It is a recent CAD technique that allows the creation and/or modification of models that don't need parameters and constraints, as on the contrary happens in the Feature Based Modeling. So, it is possible to change the shapes and the dimensions of the original prototypes very easily. Hence, in this paper a methodology devised to acquire and modify a "reconstructed" (non-parametric) model to improve and then to submit it to FEM analysis is presented. Furthermore, it is realized and doesn't even need the Feature Recognition phase of a typical Reverse Engineering process. In particular, this methodology was applied to a frame of a bicycle used as case study. Its shape was acquired by means of a laser scanner and its virtual prototype was "reconstructed". In addition, starting from it, two alternative frames were obtained and then easily modified by means of the Direct Modeling techniques. Then, they were submitted to FEM analyses to get different solutions with less weight but similar mechanical performances. Afterwards, the ergonomics of the modified configurations was tested by means of different percentile virtual manikins to plan the physical prototyping of a new improved bicycle.

Index Terms— Direct Modeling, Feature Based Modeling, FEM analysis, Reverse Engineering, Feature Recognition, Bicycle, CATIA Manikin, DELMIA Simulations.

I. INTRODUCTION

The Virtual Prototyping (VP) techniques allow to design and verify the behaviour of a new product in a virtual environment before its manufacturing; it is achievable, for instance, by means of multiphysics simulations performed on a geometrical model characterized by physical properties. Therefore, they are a very precious tool to reduce the cost and the time to market of new products avoiding errors and improving the quality of the results. [1 – 2]

Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computational Fluid Dynamics (CFD), Virtual Reality (VR), Augmented Reality (AR), Digital Human Modeling (DHM), Virtual Manufacturing (VM) and Reverse Engineering (RE) are included among the VP techniques [1 – 2].

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The VP techniques are used in a large number of cases, from educational to computer graphics (videogames and renderings), from industrial to medical fields [3 – 9]. Referring to the last years, there is a growing interest in the use of VP techniques in the nuclear fusion field [10 – 17]. In fact, they are becoming very important for the development of the nuclear fusion plants and their devices. For instance, the feasibility of the assembly operations of all the components of the tokamak (device for the production of the controlled thermonuclear fusion power) combining the CAD modeling with the Virtual Reality techniques is shown in [10 – 11].

In a virtual scene the main actor needed to apply the VP techniques is a detailed model that represents the real element to be analysed and improved. Several tools and techniques can be adopted to get it. In particular, many parametric (i.e. NX, CATIA, CREO, etc.) and/or non-parametric (RHINO, 3DS MAX, CINEMA 4D, MAYA, etc.) software can be used. Usually, in the aerospace and automotive field, the modeling phase is based on surfaces properly designed and optimized to be in the following converted in solid entities. Another common approach (*Feature Based Design*) contemplates the use of features as holes, cut-outs, extrusions, revolve, etc., realized on solid bodies. This is strongly oriented to the manufacturing phase taking into account the technological processes and the right sequence of operations to be followed on making products. So, the virtual models are defined by features, dimensions, parameters, relationships that allow to control the geometries [18 – 19].

Nowadays, new methods and approaches are available. In particular, the interest in the *Direct Modeling* (DM) is increasing because it allows a quick and complete control of the models and doesn't need parameters, modifications of sketches and history trees. So, as this approach allows to act directly on the geometry by means of few commands, it is flexible and easy to use [18].

Another way to get a model to be inserted in a virtual scene is the use of the Reverse Engineering (RE) techniques that allow to make 3D acquisitions of real objects and obtain their shapes in digital format. If their successive modification is needed (i.e. to perform FEM analyses and optimizations) a complex feature recognition phase, not free from errors, is required [7, 20]. According to the targets (i.e. quickness, precision, low costs) it is possible to use contact or contactless systems. In particular, the Photogrammetry techniques can represent a suitable solution [6, 21]. They allow to reconstruct the shape of 3D objects starting from an

adequate number of photos taken from different points of view [6]. In comparison with the *Coordinate Measures Machines* and the *laser scanners* they are inexpensive because they use a simple digital camera (*DSLR, Digital Single-Lens Reflex* camera recommended) instead of very expensive devices [21 – 23].

Main target of this paper is to describe an optimized methodology based on:

- The 3D acquisition of the frame of the bicycle selected as case study by means of a laser scanner;
- The virtual model reconstruction;
- The modification of the geometry by means of the new *Direct Modelling* techniques to improve the model without the *Feature Recognition* phase;
- The improvement of the geometry by means of FEM and Ergonomics analyses to plan the physical prototyping of a new enhanced bicycle.

The section II of the paper describes the main concepts of the Geometric Modeling, section III analyses the Direct Modeling approach whereas section IV the Reverse Engineering techniques. The case study to validate the methodology used is presented in the section V whereas the results are shown in section VI.

II. GEOMETRIC MODELING

Geometric Modeling is a branch of Computer Science that allows the mathematical description of shapes. Over the years, methods and algorithms have been implemented to realize firstly 2D technical drawings and then 3D MCAD representations in virtual environments. So, now it is possible to represent real objects characterized by volumetric information and physical properties like mass, density, volume, etc. [19].

A. Wireframe

Wireframe Modeling is one of the oldest techniques to describe real objects in a virtual environment. The model is defined only by vertices and edges without any information about faces, surfaces and volumes. The main advantage in the use of wireframe models is that their data structure is very simple and suitable for visualization purposes. In fact, only vertices and edges have to be processed and displayed without time and resources consuming. Whereas, its main drawback is that it can cause ambiguous results.

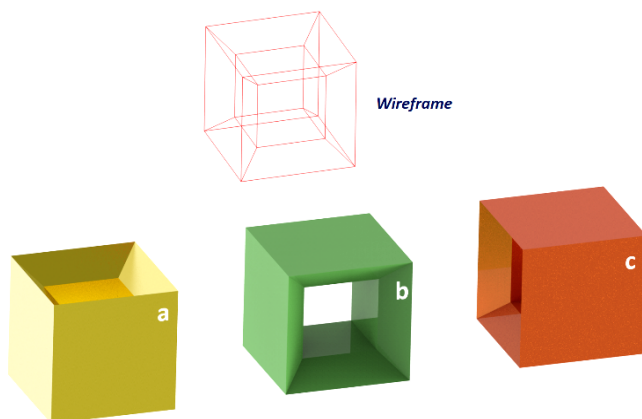


Fig. 1. Ambiguous results of a Wireframe representation.

So, for instance, the wireframe representation shown in

Fig. 1 can be interpreted in three different ways (*a, b* and *c* models) and not does uniquely identify one solid model [18 – 19].

B. Surface Modeling

Surfaces modeling allows to define and represent the skin of 3D components in a virtual environment. Usually, their thickness is assumed infinitesimal and the interior properties and important attributes for manufacturing (i.e. mass, volume, etc.) are not defined [24]. They are created by means of curves (i.e. Splines, B-Splines, NURBS, T-Splines, etc.) and operations on it (sweeps, lofts, blends, etc.). They can be characterized by poles, control points, guide curves [25].

One of the most important advantage of the surface modeling is the possibility to differentiate the representation of flat and curved surfaces. In a virtual environment this helps to better visualize the shaded image of the model. In the physical prototyping, surfaces help to generate the NC tool path for complex shaped components, structures, dies, moulds and sheet metal components used in aerospace and automotive fields. One of the main disadvantages is that if the solid part is required during the production phase (for instance for structural or multiphysics analyses) a conversion process, often not free from errors, is required [18].

C. Solid Modeling

At present, it is possible to create solid models to support a huge variety of applications in engineering and design fields. For instance, they can be used to perform multiphysics analyses with accurate results and create ultra-realistic renderings for visualization purposes [18, 26]. Solid modeling overcomes the drawbacks of the wireframe and surface modeling providing a complete definition of a 3D object in virtual environments. The result is characterized by mass and volume and all other important physical and mechanical properties (as center of gravity, moments of inertia, etc.) can be derived [24].

Some of the techniques commonly used to realize solid models are described below.

CSG and B-Rep

In *Constructive Solid Geometry* (CSG) the model is defined combining primitives (as blocks, spheres, cones, torus, etc.) by means of Boolean operations (union, difference, intersection). The main drawback is related to the limited number of the available primitives. With CSG the concepts of procedural modeling, history tree and parameters were born. They are the fundamental principles of the Feature Based Modeling. Fig. 2 shows the results of Boolean operations applied to a cube and a sphere.

In *Boundary Representation* (B-Rep) the model is defined only by its boundaries (Fig. 3). A B-Rep face represents an oriented surface. So, two sides are recognizable: the inner is inside the object (solid side), the outer is outside it (void side). A B-Rep model is created using Euler operations (similar to those used in mechanical drawing and wireframe model construction) [19].

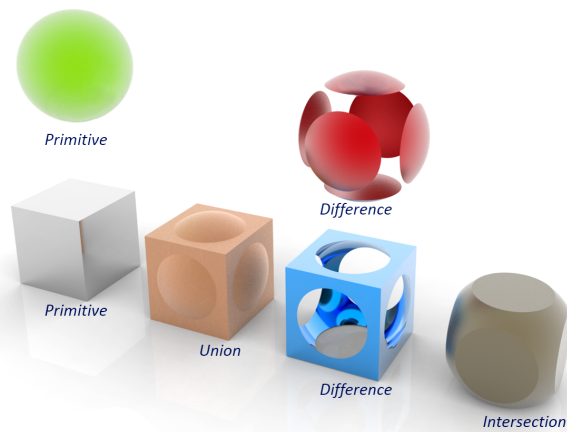


Fig. 2. Boolean Operations on CSG models.

B-Rep main advantage is to be more flexible than CSG and much richer in the operations to be used.

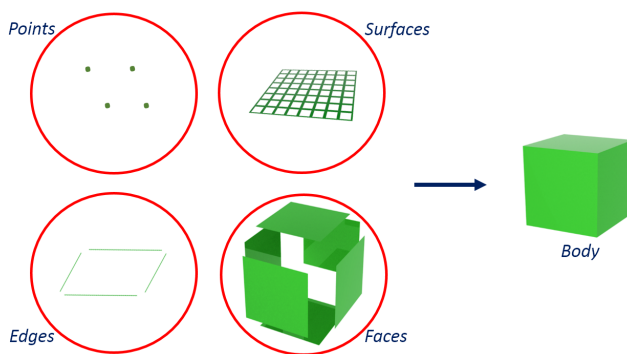


Fig. 3. Structure of a B-Rep model.

Fig. 3 shows the B-Rep model structure. It is based on several entities as faces, edges, surfaces and points [18].

D. Feature Based Modeling (FBM)

This technique allows to realize virtual prototypes starting from a base component and adding or subtracting material from it. Each operation coincides with a technological feature as extrusion, cut-out, revolve, chamfer and so on and it is “stored” in order to define a history-tree of the features and of the operations realized. The user has to carefully plan the design and preliminarily define which elements will be dependent upon the others. The parametric modeling is an essential CAD approach that significantly reduces the costs related to the modification of the project. This method was originally developed for machine design, and it is much used in engineering with large part assemblies, digital testing and rapid prototyping [18]. At present, it is one of the most common techniques used to realize solid models.

The result of a FBM process is a geometric model with parameters that can be modified to obtain different design alternatives. However, there are some drawbacks related to the use of the *History-Based* approach. In particular, the most significant are its complexity and absence of clearness for the user. For instance, to modify the shape of a model it is necessary to find the particular feature in the history-tree and to understand which specific parameter has to be changed. Furthermore, the main principle of a user’s interface, WYSIWYG (*What You See Is What You Get*), is

not applicable because to change the shape of a model the modification of a value is required and it is sometimes not possible to act directly on the geometry in an interactive way [27].

E. Hybrid Modeling

The most common 3D CAD software allow to use Feature Based and Surface modeling together. These are hybrid modelers and may allow to make surfaces and solids interact without failures. For instance, they allow to modify a parameter of the curve used to define a surface that is a reference for a solid feature. But, the models generated often depend on a very high number of parameters, dimensions and constraints and some mistakes can occur. Furthermore, due to the complexity of the model and/or some bugs of the software used, they could be subject to failures. It implies to try to solve the problems and to redefine the geometries wasting time and increasing the costs of the process. So, as it usually happens in the automotive industry, more accurate and robust results are obtained by means of dedicated software that allow to create complex surfaces and operations on it and then to import the result into a solid modeler [28].

At present, the additive manufacturing techniques, as Rapid Prototyping, are very common and allow to create new prototypes and products. Similarly, hybrid modelers facilitate to realize the concept design phase of new products and prepare them for manufacturing. For this reason, hybrid modelers could represent a major solution for the additive manufacturing techniques [18].

F. Behaviour Modeling

Behaviour Modeling allows engineers to make robust CAD models characterized by “smart features”, specifications, constraints and rules. By means of an intelligent process of knowledge capture and iterative solving, it is possible to include the experience of engineers and designers in the CAD models. It implies that the final geometries are easily usable and avoid design errors [18]. The models created in this way contain engineering and functional specifications imposed by the standards (ASME, ISO, UNI, etc.). Smart features can define the component assembly connectivity, welds or pins or slider joints. Grabbing the design intent, the CAD model realized is robust, easily modifiable and highly flexible. The main advantage is that in case some geometry changes are needed, the model can be easily regenerated driven by the rules used. Furthermore, the modifications can be realized by a simple CAD user and the designer of the smart model is not needed [18].

III. DIRECT MODELING

A. Description

Direct Modeling techniques, also called *Explicit Modeling*, allow to overcome most of the drawbacks of the *History-Based* approach. Firstly, each part is fully modifiable even if the modeling history is not available. It means that the user can interact straight with the geometry and not with a complex list of rules. Another important

advantage is the possibility to work with Multi-CAD models. *History-Based* software, in fact, don't allow to modify the parametric model in a CAD environment different from the one used to create it. In this case, only B-Rep prototypes can be imported without sketches, constraints, parameters and features. So, although it is possible to use expensive translators to convert it into suitable formats, the result is often not a full parametric model free from errors. Furthermore, it is possible to avoid the definition of many constraints but in this case the "design intent" may not be kept.

Several software based on the Direct Modeling Techniques are available on the market. The most common are: PTC CREO Direct, SpaceClaim, Siemens NX and Solid Edge with Synchronous Technology [29 – 31].

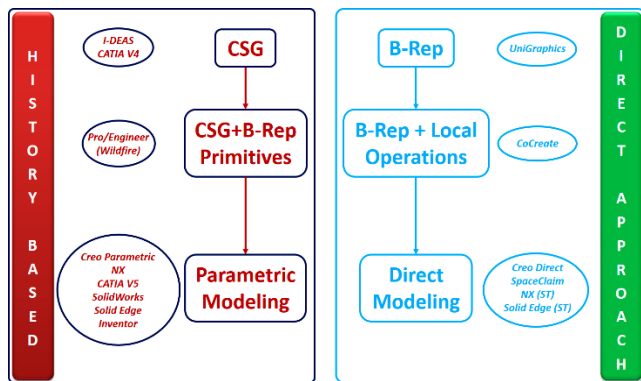


Fig. 4. Evolution of Solid Modeling.

The main phases of the evolution of the History-based and the Direct Modeling approaches together with the software based on it are shown in Fig. 4 [27].

B. History-Based versus Direct Modeling

In this subsection a comparison of the main characteristics of the two approaches is presented.

If History-Based software are employed to design the part, the use of sketches, parameters and features is strictly required. These entities are stored following the order which they were built with, this generates "rigid sequences" of strong parent-child relationships. This kind of relationships can often cause many problems. In fact, if the model is complex and characterized by many features it makes harder to control their interdependencies. So, in case of failure, most of the times, it can be more suitable to reconstruct the whole model from the beginning than to try to solve the problem.

Instead, when a *Direct Modelling* approach is used, the creation of parameters is not required for the editing of the model. So, the main entity is the geometry that can be subdivided into simpler geometries modifiable as needed. The result will always be a geometry that can be changed and reconstructed without restarting the modeling from the beginning.

Although the rigid sequence of the History tree often represents a drawback, in some cases it can be the main strength of the *History-Based* approach. In fact, it allows to define a complex assembly based on tons of parts thoroughly. If the whole project is well planned and realized, for example following a *Top-Down* approach with a skeleton and a reference system, it will be robust respect to

each kind of failure regardless of the time used to realize it [32].

The last aspect to be considered is related to the easiness of the learning process for a beginner. Due to the complexity of the use of sketches, constraints, parameters and features, the *History-Based* could be considered more difficult than the *Direct Modeling* approach.

Table I resumes the main characteristics to be used to compare the *History-Based* and the *Direct Modeling* approaches [27].

Table I. *History-Based* versus *Direct Modeling*

Main characteristics	History-Based	Direct Modeling
Easy to learn and use	No	Yes
Dynamic Changes	Limited by rules	Yes
System Response	Slow	In real time
Direct Editing	Limited	Full
Parametric Editing	Yes	No
Editing of imported geometry	No - Impossible	Yes – Possible
WYSIWYG approach	Often	Yes – Always

C. Direct Modeling for FEM Analyses and Manufacturing

In most cases, it is important for the designers to simplify the parts to be submitted to structural and multiphysical analyses. In fact, the meshes must be optimized and then imported into the FEM environment. So, in this case, at present, *Direct Modeling* techniques represent one of the best tools to be used. In fact, as previously described, they allow the straight interaction with the geometry and is not important to know the original model creation process. Furthermore, due to the absence of a complex history tree, it can strongly reduce the data size even before the simplification process.

One fundamental aspect to consider is that, now, software that integrate *Direct Modeling* techniques with the FEM environment are available on the market (i.e. ANSYS *SpaceClaim*) [30]. This not only allows the modification of the geometries and of the meshes in real time, but it makes easier and improves the whole optimization process. So designers and engineers can simulate the mechanical performances of their virtual prototypes without converting the models and without complex recognition phases of the features needed to eventually modify the prototype during the FEM analyses.

Furthermore, this kind of software contemplates the possibility to generate NC programs for CNC (*Computer Numerical Control*) machine, to manufacture the design of the physical prototypes, inside the *Direct Modeling* environment. Besides, their flexibility allows to evaluate several design alternatives improving the performances, avoiding to waste time. So, the products can be faster on the market and of a better quality.

IV. VIRTUAL PROTOTYPING AND REVERSE ENGINEERING

A. Virtual Prototyping of a Real Object

Fig. 5 shows two different approaches to get a virtual prototype. The *A procedure* is used when the parametric model, realized by means of a 3D MCAD software, is available. At present, it is the best case as the creation/modification of each feature is possible in real time and the model is usually robust enough to avoid errors. In particular, when the model is really complex, the full control of the geometry, by means of sketches, parameters and

constraints, allows to interact with FEM software in order to perform its optimization [19, 32]. It has to be considered that it is not often possible to count on parametric models.

The *B procedure* is instead adopted when the parametric model is not available. For instance, it happens when the prototype used is the result of a Reverse Engineering process. So, it is imported into a dedicated software to perform the Feature Recognition phase to define geometrical entities and dimensional parameters to be used later in MCAD environment. This process could be very complex, long and not free from errors.

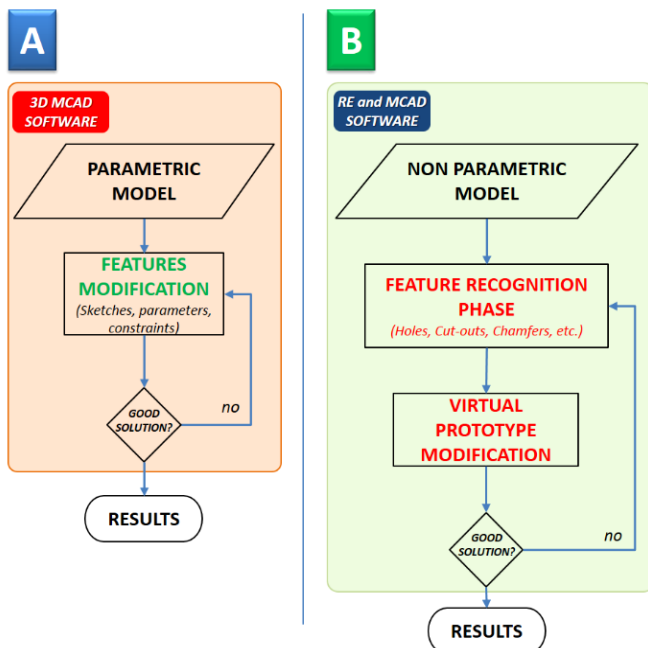


Fig. 5. Comparison between the two procedures to be used to create virtual prototypes.

So, a different approach is presented. It was based on the new *Direct Modeling* techniques (Fig. 6).

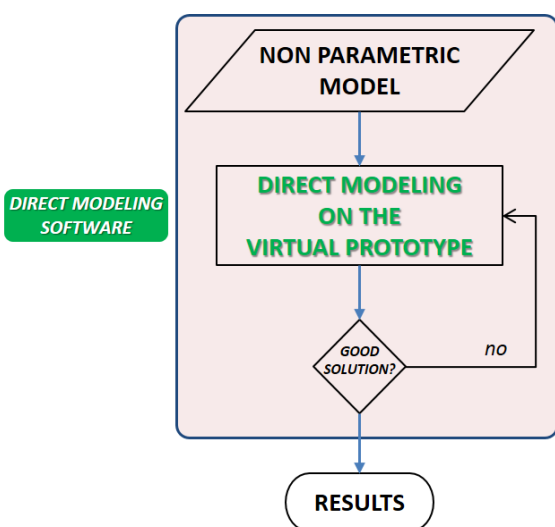


Fig. 6. Use of Direct Modeling instead of Feature Recognition.

In this case the *Feature Recognition* is avoided and the modification is realized quickly and easily in the *Direct Modeling* environment. Furthermore, as it is possible to

work in a unique CAD environment, this process can be performed without additional failures related to the data exchange procedure.

B. Reverse Engineering Techniques

The RE techniques are used to get the virtual prototype of a physical object starting from a 3D acquisition when the original CAD parametric model is not available. They allow to get the “external skin” of real objects in a mathematical formulation recognizable from CAD software [7, 33].

A typical RE process is based on several steps. The first one is the acquisition done by means of contact (i.e. *CMM-Coordinate Measure Machine*, “slow” but very accurate) or contactless system (i.e. *Laser Scanner*, “fast” but less accurate) to obtain a dense points cloud. If the best accuracy is not required, the use of a laser scanner can be a good solution. In this case, the 3D acquisition of a real object is usually troubled by occlusion problems and noises caused by the incorrect settings of the ambient as lights, reflective surfaces, inappropriate distance between the laser scanner and the model. To avoid these problems, many scans around the object, preferably in a dark room, have to be realized using a proper reference system to allow the merge of the point clouds. Furthermore, if the material of the object is highly reflective (i.e. steel or similar), it has to be preliminarily dazzled with particular powders to make its surfaces opaque and to avoid unwanted problems due to the laser beam. Afterwards, the final points cloud is obtained and it has to be edited and properly treated to tessellate and to prepare it for the successive phase. During it, the original shape can be better reconstructed by means of NURBS geometries. Finally, if the modification of the model is needed, a *Feature Recognition* process is required. In this way it is possible to define adequate parametric entities. In particular, geometrical elements as planes, lines, points, circles, cylinders, etc., have to be used to identify the features corresponding to the technological characteristics of the real objects acquired and reconstructed during the previous steps. So, the sequence of the technological features can be (re)defined and it is possible to modify the values of the parameters of each operation and allow the modification of the geometry. It has to be considered that the recognition of the main features of the objects can be a very slow process and some errors can occur. In particular, in this phase, several geometric entities (points, lines, planes, circles, cylinders, etc.) have to be identified in the CAD environment to assign the features to the elements reconstructed by means of the previous steps of the *Reverse Engineering* process. So, it is possible to recognize all the holes, the rounds, the fillets and the features of the real model [33 – 35].

V. CASE STUDY

A. Description

The frame of the 26” mountain bike wheel bicycle in T6061 Aluminum Alloy, shown in Fig. 7, was considered as case study. Each tube is characterized by different diameters in a range from 36 to 46 mm. So, three targets were pursued: 1) the use of the same diameter (30 mm) for each tube to make the manufacturing phase easier, 2) the reduction of the

length of the seat tube in order to get a lower size of the bicycle, 3) the minimization of the weight of the frame.



Fig. 7. Real frame of the bicycle used as case study.

B. Methodology devised and adopted

The optimized procedure shown in Fig. 8 was devised in order to reach the defined targets. Starting from the real model, several laser scanner acquisitions were realized. The results of this phase were treated in a typical RE software to obtain the non-parametric prototype of the frame (Fig. 9). In particular, starting from the reconstructed model of the case study, two variants based on some changes were realized. Afterwards, they were imported into DM environment and then modified as needed. Lastly, they were submitted to the FEM solver to optimize the structure of the bicycle.

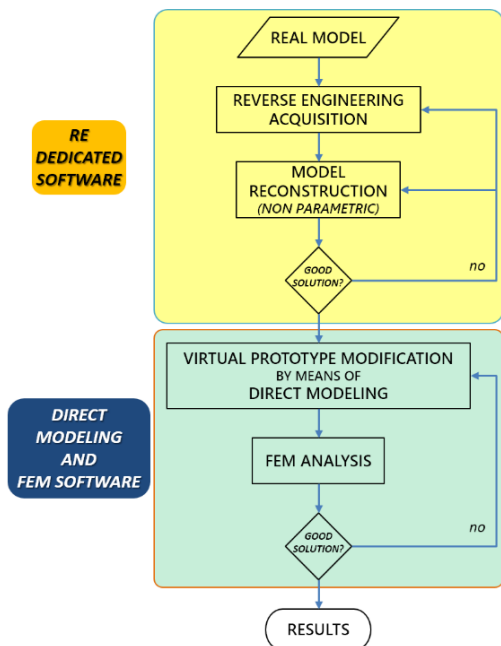


Fig. 8. Flow diagram of the methodology devised for the case study.

C. 3D acquisition and model reconstruction

A common 3D laser scanner was used to acquire the main tubes of the frame. So, several point clouds were obtained. They were merged, edited and properly filtered in *Geomagic Studio Environment* (one of the most common RE dedicated software). After the successive tessellation phase, the reconstruction of the non-parametric model was possible (Fig. 9). Then, according to the procedure devised shown in Fig. 8, the reconstructed model was submitted to the DM techniques, avoiding the complex *Feature Recognition*

phase.

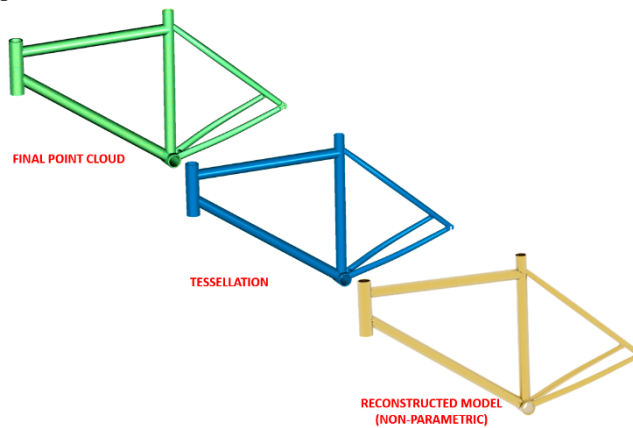


Fig. 9. Results of the Reverse Engineering process of the case study.

D. Direct Modeling Results

By means of this approach, it was firstly possible to modify the diameter of the main elements of the frame as shown in Fig. 10. The *A-Frame* is the (non-parametric) reconstructed model previously described. The *B* and *C frames* represent two alternative configurations realized thanks to the flexibility of the DM techniques.

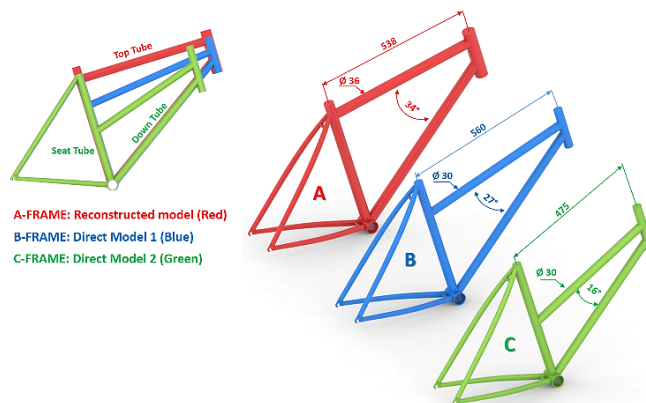


Fig. 10. Comparison among the several modifications applied to the frame by means of the Direct Modeling techniques.

In fact, it was possible to modify the length of the top tube easily and very quickly (Fig. 10). Then, the same diameter values (30 mm) were defined for the main tubes. Another modification concerned the lowering of the *Top tube*. Furthermore, the value of the angle between the *Down* and the *Top* tubes to test different style solutions was changed. It is important to remark, instead, that several difficult operations would have been needed to realize each one of these changes in a *Feature Based* modeler. In similar cases, in fact, it is usually requested to interact with a (complex) *Top-Down* structure realized by means of skeletons, rules, constraints, sketches, parameters [28]. It implies that the user has to analyze and study the model deeply. Then, he has to define the best way to upgrade the structure and the model, hoping that no failures happen among the many different features due to the parent-child relationships.

So the Direct Modeling was very useful to create different design solutions and modify it in a very short time (only some minutes).

E. FEM Analyses

The results obtained thanks to the Direct Modeling techniques allowed to submit the final models to FEM analysis in order to validate the procedure used, to reduce the weight assuring the mechanical performances of the bicycle adopted as case study. In fact, as the modifications realized on the frames were related to the reduction of the diameters of their sections to let the weight of the final model decrease, a preliminary structural analysis was needed and performed. Due to their characteristics related to their limit conditions, only the A and C frames were considered for the FEM analyses and for the successive ergonomics tests. In fact, in terms of length, the A-frame is the longest and the C is the shortest.

The boundary conditions were defined taking into account the “EN 14764 December 2005 ICS 43.150 - City and trekking bicycles - Safety requirements and test Methods” standard [36]. So, as load condition a 1200 N force was applied to the seat tube. A cylindrical constraint on the rear part of the frame and a displacement in correspondence of the front tube were defined. The results of the FEM analyses on the A and C frames are shown in figures 11 - 14 to confirm the goodness of the methodology conceived. The results of the stress analyses show that the yield limit was neither reached nor exceeded for all the components, according to the Von Mises criterion. Moreover, under the hypothesis of cyclic load, the fatigue life is fully acceptable [37].



Fig. 11. Results of the FEM Analysis (Stress) on the A-Frame.

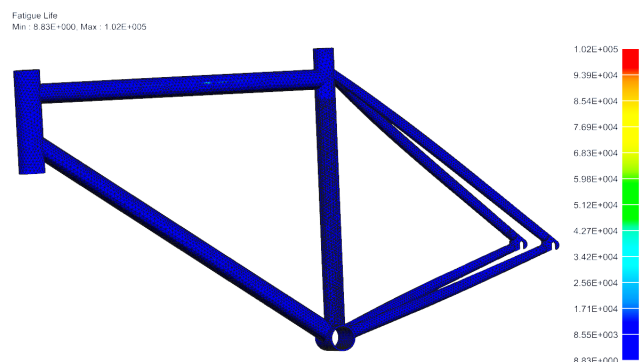


Fig. 12. Results of the FEM Analysis (Fatigue) on the A-Frame.

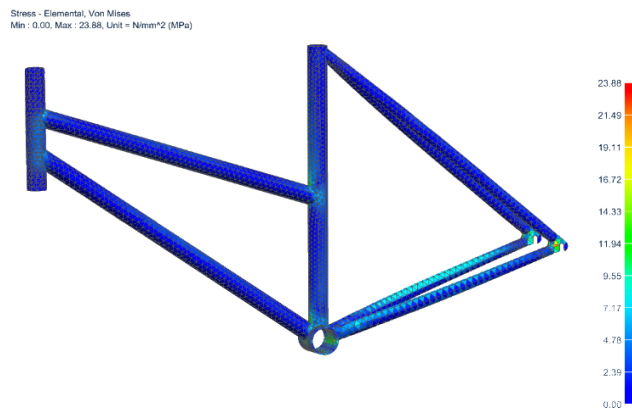


Fig. 13. Results of the FEM Analysis (Stress) on the C-Frame.

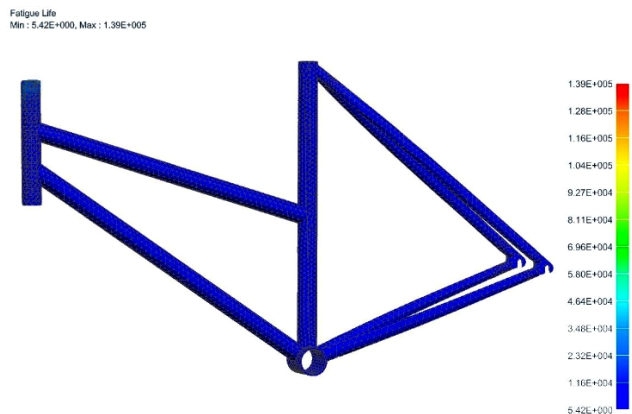


Fig. 14. Results of the FEM Analysis on the C-Frame (Fatigue).

F. Ergonomics

The possibility to quickly change the dimensions of the frame is a remarkable advantage also for ergonomic purposes [38]. The analysis of comfort associated to the design of bicycles can be performed on the different geometries obtained with the Direct Modeling and directly imported into the Ergonomics environment. In this way, the frames modified can be tried on several human percentiles to evaluate postural comfort, usability, etc. For instance, Fig. 15 shows the A and C frames tested by means of the virtual manikin provided by the CATIA environment [39]. Limit conditions were analyzed to evaluate the models realized. In particular, considering the 95th percentile manikin (#4 case depicted in Fig. 15), the C-Frame (due its smaller dimensions) had shown to be more uncomfortable than the A-Frame (#2 case). Besides, by means of the DELMIA environment [40], the movements of the manikins were tested. In particular, several collisions between the legs and the handlebars (for the sake of simplicity not shown in the Fig. 15) occurred. It even happened when the bicycle turned. So, this kind of analysis allows to identify also the actions needed to avoid errors and to optimize the geometries in order to improve the ergonomics of the frames modified.

So if interferences or mistakes occur, the Direct Modeling software allow to change the geometries as needed and then the designer can count on these environments to test and evaluate the solutions conceived [39, 40].

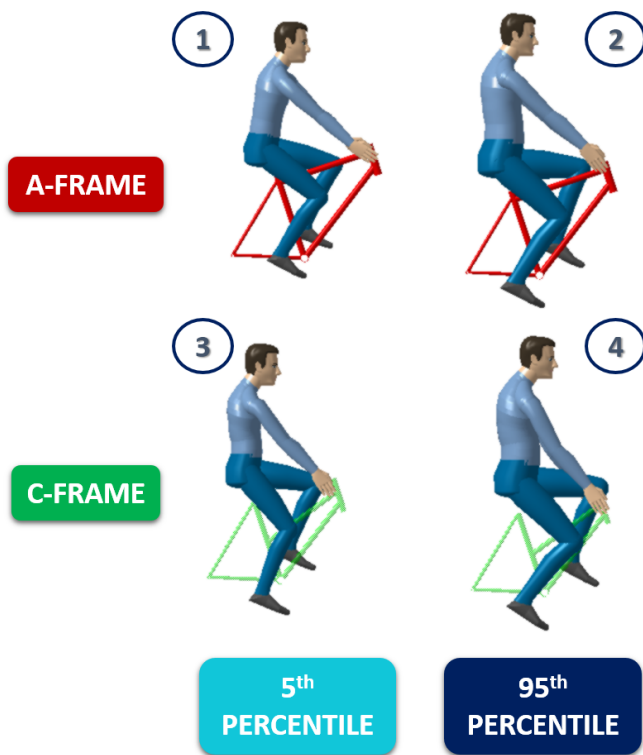


Fig. 15. Comparison between different configurations (A and C frames and 5th and 95th percentile manikin respectively).

VI. RESULTS

The results achieved show that *Direct Modeling* techniques allow to create and modify virtual prototypes very easily and quickly. Their use can strongly improve almost all the steps of the design and manufacturing processes from the *Concept Design* to the *Physical Prototyping* phases. In particular, it is important to remark that the outcomes obtained show that DM is particularly useful for the modification of non-parametric prototypes. In fact, as commonly needed in the FEM analyses, it is possible to efficiently remove the features (as chamfers and rounds) and upgrade the geometry in a very short time (seconds). Besides, no difficult *Feature Recognition* phase is needed. Moreover, it is possible to modify solids and surfaces without complex operations in real time and submit the results to the FEM solver integrated into the same DM environment.

Afterwards, the virtual manikins and the kinematic simulations (carried out in the DELMIA environment) were used to test the solutions conceived. At the end, the FEM and the Ergonomics analyses have validated the procedure devised to optimize the frame used as case study driving to design the best *Digital Mock-Up* (DMU) in terms of dimensions, weight and ergonomics.

VII. CONCLUSIONS

An optimized methodology to improve virtual prototypes and to perform FEM analyses was presented. Starting from several laser scanner 3D acquisitions, the virtual prototype of a bicycle was reconstructed. Then, the new *Direct Modeling* techniques were used to modify the geometry avoiding a complex, and often not free from errors, *Feature Recognition process*. Furthermore, no changes of parameters

and constraints were needed. The consequent result was the optimization of the starting model by means of a FEM analysis performed in order to reduce its dimensions and to modify its shape. Afterwards, ergonomics tests were carried out by means of virtual manikins in CATIA and DELMIA environments, to verify the solutions designed and to avoid errors. The methodology devised and adopted, based on Direct Modeling, was very rapid and showed very interesting results particularly if compared to the common Geometric Modeling techniques. Moreover, it will allow the physical prototyping of a new improved bicycle and its quick eventual upgrades.

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