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Preliminary communication

Tyre Design and Optimization by Dedicated CAD Tyre Model

Nikola KORUNOVIĆ*, Miloš STOJKOVIĆ, Dragan MIŠIĆ, Ana PAVLOVIĆ, Miroslav TRAJANOVIĆ

Abstract: Structural optimization by Finite Elements (FE) is proved very effective in tyre design. For that purpose, major tyre manufacturers use in-house applications. An alternative solution, involving dedicated CAD tyre model (DCTM), is here proposed. DCTM concept permits to easily change the FE tyre models, concerning shape and structure, by moving a part of pre-processing from FE analysis to CAD. No special skills regarding CAD or FEA are required. For every new tyre design, only a new DCTM and a corresponding FE model must be built. All subsequent model changes are automatically performed by mapping and translation routines. To test this concept, DTCM models of an existing tyre were created and used within a pilot design study.

Keywords: CAD-FEM integration; DCTM, structural analysis; structural optimization; tyre design; wheels/tyres

1 INTRODUCTION

An automobile is a complex electro-mechanical system that involves many mechanically interconnected components. The research related to such a complex system is quite versatile ranging from modelling tasks (e.g. [1-3]), over structural optimization from various perspectives (e.g. [4, 5]), to mechatronic systems that improve different aspects of ergonomics and safety (e.g. [6-9]). At a first glance, compared to some other automobile components and sub-systems, tyre appears to be a relatively simple one. However, its design is rather complex [10, 11] and it is the only component over which the automobile makes the contact with the road. All the necessary forces for acceleration, braking and steering are transferred between the automobile and the road through tyres. Obviously, this fact speaks for itself about the importance of tyre and the related research.

Finite element analysis (FEA) is widely used in tyre design as a reliable tool for virtual prototyping [12]. The best results are achieved when it is used in conjunction with structural optimization methods [13]. FEA plays an important role in multi-objective optimization of tyre characteristics, such as manoeuvrability [14-16], endurance [15, 17], rolling resistance [14], wear [18, 19] or riding comfort [17].

Within a structural optimization process, FEA is applied in design of experiments (DOE) phase as the means of virtual experimentation. DOE implies that many finite element (FE) models are created, which are characterized by different values of design variables. Because of the complexity and specificities of FE models of tyres, it is difficult to create them automatically for each new set of design variables. Thus, the automation of tyre optimization procedures represents a challenging task. To overcome this obstacle, large tyre manufacturers tend to use in-house software solutions, which are also very expensive and often unavailable to scientific community or smaller companies. These facts justify the development of an alternative solution, a semi-automated procedure for tyre optimization based on the general concept of "dedicated CAD tyre model" (DCTM). It will be presented here after a short overview of the existing FEA software used in tyre design and the approaches to structural optimization of tyres.

There are several commercial FEA software solutions that contain the functionality related to tyre design. Neither of these offers a fully automated approach to creation of FE tyre models. Abaqus [20], which is probably the most used commercial FEA software in tyre design, offers a rich set of functions for tyre analysis. Nevertheless, the analyses cannot be fully performed from the graphic user interface (GUI), which implies that command prompt-based procedures and text editor-based model building must also be employed. MSC.Marc [21] covers a larger portion of tyre analysis procedure by GUI based functions but does not offer as many analysis options as Abaqus. ANSYS [22] features a free add-on that facilitates the GUI-based tyre analysis process and speeds up the FE model building [23]. The add-on offers an extensive set of tyre modelling functions, nevertheless it is still not flexible enough to be used in conjunction with structural optimization. LS/DYNA [22] also facilitates the tyre analysis, but the creation of FE model is left to the user. Tyre analysis procedures in all the mentioned programs are based on tyre geometry that is created from scratch or translated from CAD models, as well as on standard mesh generation procedures. Detailed descriptions of in-house applications are, expectedly, not widely available, but there are occasional reports where useful information can be recognized. For example, Behroozi [24] developed an aircraft tyre modelling environment named TAIS (Tyre Analysis Interface System). The interface, developed on demand of a premium tyre manufacturer, is envisaged as a user-friendly tool for tyre designers that are not experts in FEA, which enables them to utilize the tyre analysis features of Abaqus. TAIS represents a noteworthy effort as it facilitates all essential operations in tyre analysis such as mesh creation with controllable density, material properties assignment, execution and monitoring of analysis process and post-processing of results. Nevertheless, the interface is limited to aircraft tyres, which are characterized by simple axisymmetric tread design. Also, the design process is based on non-parametric geometry of tyre profile and not suitable for automatized structural optimization procedures.

Various software solutions were used by multiple authors to perform parametric tyre design studies in which the chosen design parameters could easily be changed in the preprocessing stage. In those studies, a characteristic change of FE model involved a simple alteration of numerical values or inclusion and exclusion of design features, performed via graphical user interface or by direct editing of an input file. Typically, the chosen design parameters were the belt angle (the angle of cord in the belts), cord density or material properties of individual structural components. In addition, these studies considered the influence of operating parameters on tyre performance, and these were also easy to change in the preprocessing stage. Nevertheless, none of these changes influenced the tyre geometry and thus the FE mesh. For example, Olatunbosun and Bolarinwa [25] explored the sensitivity of lateral force and self-aligning torque to the change of belt angle, number of belts, belt cord density and elasticity modulus of carcass, as well as to the change of vertical load and tyre pressure. Ghoreishi et al. [26] studied the influence of belt angle on the contact pressure distribution and the rolling radius. Serafinska et al. [27] performed a multi-objective optimization study based on the aggregate objective function approach with consideration of fuzzy variables applied to structural tyre design, in which belt angle, thickness of tread layer and number of cap plies were chosen as tyre design parameters. Yang et al. [28] explored the application of various Artificial Neural Network (ANN) architectures within parametric studies in which belt angle, cord density, material properties, cord X-section and inflation pressure were varied. Korunovic et al. [29] also described a procedure for multi-objective optimization of tyre design parameters based on Pareto concept where belt angle, cord spacing, and elasticity of tread compound were considered as input parameters and the goal was to simultaneously minimize strain energy density at belt edges and in bead area. These studies were useful to a limited extent, as tyre behaviour very much depends on carcass profile that dictates the shape of tyre cavity [14] as well as on other geometrical features, such as bead area shape, thread shape or belt width [11, 30].

As opposed to many parametric studies in which FE model geometry stayed unchanged, a more limited group of authors approached the optimization of tyre geometry by changing the FE mesh. They considered the position of chosen nodes on FE mesh to be the design variables. In the multi-objective optimization study by Cho et al. [15], for instance, the positions of five nodes at sidewall portion of carcass were considered in order to improve tyre manoeuvrability and durability. Similar approach to the change of tyre geometry was used by Cho et al. [31] to optimize crown shape considering tyre wear by ANNs. Nakajima et al. [32] used a procedure which combined optimality criteria with finite element method to optimize the contact pressure on tread block surface, considering nodal positions on block surface as the input parameters. Nakajima et al. [14] also discussed the improvement of manoeuvrability and rolling resistance by Theory of Optimum Tyre Contour (GUTT) based on finite element method and an optimization technique, where the tyre contour was represented either by a polynomial or by several interconnected circular arcs. Tanaka et al. [33] proposed a unified approach to the optimization of tread pattern shape and tyre contour shape, in which a series of predefined basic forms were combined by modification of the basis vector method.

2 DEDICATED CAD TYRE MODEL (DCTM) CONCEPT

2.1 Aim and Scope

Having in mind the importance of an optimization process in tyre design and, at the same time, the difficulties in finding an appropriate solution to FE model building, the DCTM concept is proposed. It is devised to facilitate the easy changes of FE model concerning its shape and structure, by moving a part of pre-processing stage from FEA to CAD.

DCTM allows the potential user to perform sensitivity and optimization studies of tyre design parameters without the need to adopt specific software solutions, apart from standard software packages accompanied by a small mapping and transformation routine. The users need to be familiar only with the basic functions of any arbitrary parametric 3D CAD software, the predefined procedures used for the creation of tyre profiles and the corresponding procedures for the construction of FE tyre model in an appropriate FEA program. For each specific tyre design, only one DCTM and a corresponding FE model must be built, by following several predefined steps. The rest of the procedure enables the parametric study to be performed, according to a selected experimental plan.

2.2 The Challenges in FE Modelling of Tyres

The structural components of the tyre, apart from the tread, do not change their shape in circular direction. This is a substantial geometrical property of the tyre, which implies that tyre geometry is, almost to the full extent, defined only in the radial section. Radial sections of carcass and outer tyre contour represent starting geometrical forms in tyre design [34-36] (Fig. 1).

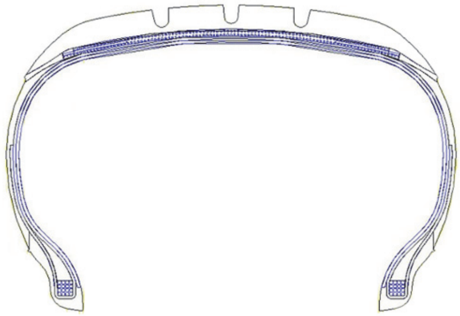

Figure 1 Radial tyre section with contours of structural components

Dimensional scheme that controls the radial section, and especially the shape of the carcass, influences the mechanical behaviour of the tyre to the great extent. It defines the expected shape of pre-stressed tyre structure (inflated tyre) and thus the stress and deformation fields in its structural components. For that reason, FE analyses of tyre behaviour demand very accurate description of its structural components' geometry.

The preprocessing phase of FEA, in which the CAD model is transformed into the FE model, is very challenging in FEA of tyres because of FE model complexity. The importance of the preprocessing phase is especially high if the FE model is to be used in an optimization study. Such a study ideally requires the full flexibility and robustness of FE model, i.e. the potential of FE model to be successfully rebuilt for any combination of values of design variables (dimensional parameters) that do not violate the design constrains. Global and local mesh densities of FE tyre model should also be variable to enable the performance of mesh independence studies and the control of solution accuracy.

The flexibility of FE model based on design variables related to material properties, cord dimensions, cord angle or cord spacing, is achieved rather easily. Those parameters are simply changed in the FE preprocessor or in the corresponding input files, by alteration of certain numerical values. The real challenge is to achieve the flexibility of FE model regarding the change of geometrical parameters that drive the shape of the tyre (profile shape, structural component borders) without significant influence on mesh quality: mesh density, regularity of element shape, description of cord layers etc. In this context, discretization of structural components of the tyre, as available in standard preprocessors, has two important shortcomings:

1) It is not possible to parametrically drive the shape and size of finite elements
2) It is not possible to parametrically drive the relative position of finite elements, i.e. to propagate the changes of tyre contour shape and geometry of structural components to the position of element nodes.

2.3 Multilayered System of Radial Section Models

The main assumption behind DCTM is that a precisely controlled discretization of contours, areas and volumes may be much simpler and more controllable in CAD than in FEA. The specific approach to preparation of CAD model of radial tyre section, aimed at tyre FEA, relies on the multilevel system of models, where the basic model is the outer contour of radial tyre section. Dimensional scheme of radial section of outer tyre contour is largely dependent on basic dimensional parameters. Basic geometry of radial section is constructed according to the procedure that is familiar to tyre designers, i.e. its construction circles and curves are based on the traditional way in which tyre profile is designed (Fig. 2). Such an approach enables them to familiarize with the model and easily make design changes, without having a thorough knowledge of the CAD system itself.

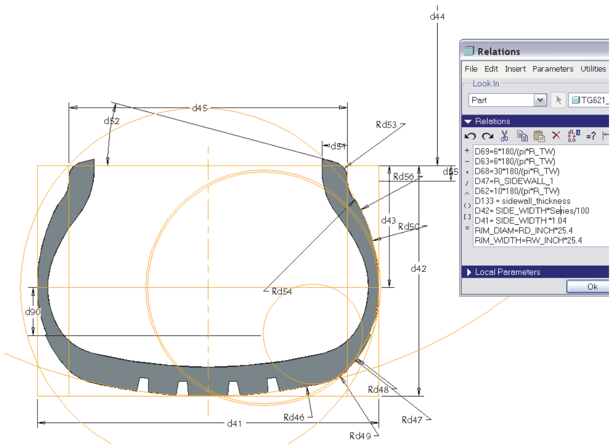

Figure 2 Dimensional scheme of radial section of outer tyre contour. The pilot version of DTCM was built in Pro/ENGINEER [29] (now Creo Parametric). Nevertheless, a similar approach to DTCM creation may be used in any parametric 3D CAD program

The next model, which is embedded into the previous one, represents the radial section of structural components of the tyre. Dimensional scheme of the radial section is devised to relate geometrical entities of outer contour to corresponding geometrical entities of structural components (Fig. 3). In this way, an uninterrupted and controlled propagation of geometrical changes from outer contour to structural components is enabled.

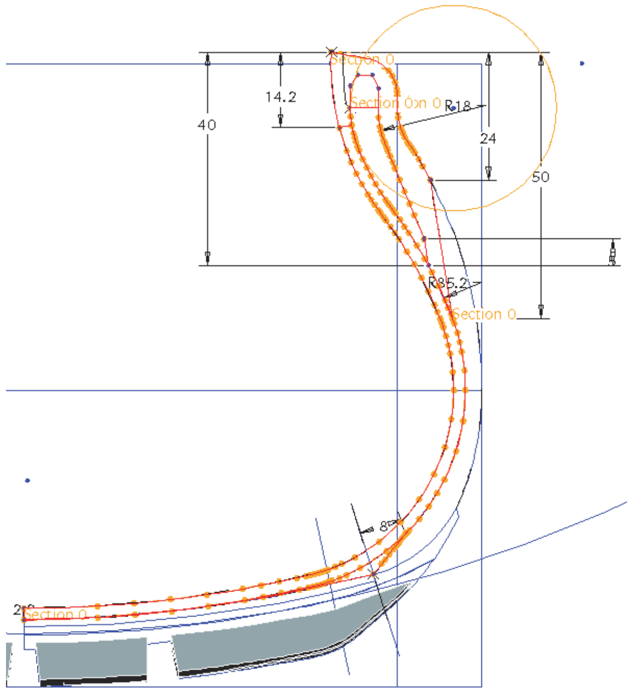

Figure 3 The scheme for connecting the outer tyre contour to structural components of the tyre in radial section

In the last layer, the model of discretized structural components is located. This model is comprised of geometrical (line) entities of discrete segments - contours of future finite elements, whose vertices are connected to contours of tyre structural components according to a discretization plan that defines element shape and density (Fig. 4 and Fig. 5). In this plan, the resolution of the discretization and layout of the vertices are defined relative to the outer contour and the structural components of the tyre (in radial section).

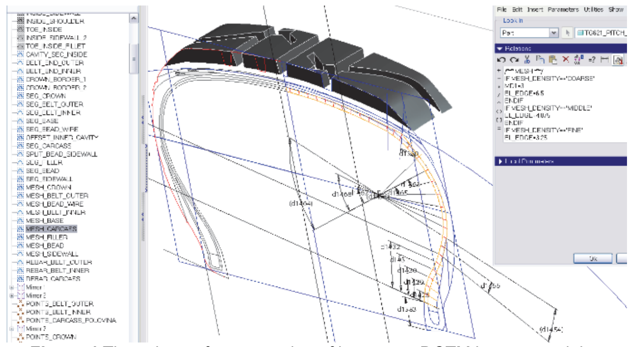

Figure 4 The scheme for connecting of innermost DCTM layer, containing vertices and contours defining future finite elements, with carcass contour defined on higher level layer

Discretization process is foreseen to enable automatic creation of lines and vertices inside the contour of each structural component, whereby their density is controlled by a single density parameter. The value of this parameter is indirectly defined by user, who selects a mesh density option (e.g. coarse, normal, fine). Depending on CAD program used, different routines for automatic discretization of structural components are created, which mostly rely on program macros and embedded scripting language. This feature of DCTM is yet to be implemented.

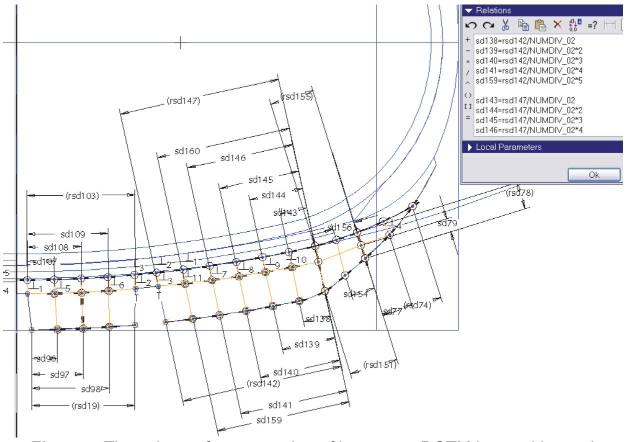

Figure 5 The scheme for connecting of innermost DCTM layer with tread contour defined on higher level layer

3 FEA and Structural Optimization based on DCTM
3.1 FE Model Building

After a DCTM of radial section (that is defined by initial set of design parameters) is created, an axisymmetric FE model is built that is based on DCTM geometry. FE model, described in detail in [37], generally consists of linear axisymmetric quadrilateral and triangular finite elements representing rubber [38], in which axisymmetric rebar elements, representing tyre cord, are embedded [39]. FE model building procedure described here is tailored for Abaqus, but it is generally applicable to any FE program which features an appropriate set of functions related to tyre analysis.

In the first step, the following sets of geometrical entities are exported from DCTM (Fig. 6, Fig. 7):

1) Surface entity representing the area of radial section.
2) Set of lines that correspond to contours of future finite elements that represent rubber portions of FE model.
3) Set of lines corresponding to future embedded finite elements that represent carcass.

Set of lines corresponding to future embedded finite elements that represent belts - number of sets depends on the number of belts layers. In current example there are two belt layers.

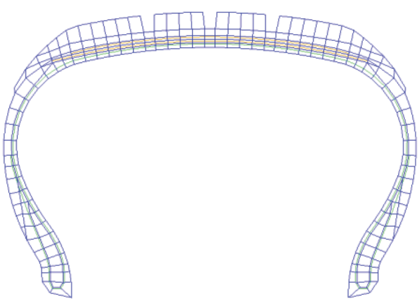

Figure 6 Sets of line entities exported from DCTM, representing contours of finite elements, carcass and belts

Exported sets of geometrical entities are imported in FE preprocessor. Then, an axisymmetric FE model is built, using the procedure depicted in Fig. 7.

The surface entity that represents the radial section is segmented using the exported set of lines as a "cutting tool", whereby each resulting surface segment represents one finite element. Those elements are then grouped into larger segments that represent structural components of the tyre and attributed by hyperelastic or viscoelastic material properties. Next, the finite elements representing carcass and belts are created using corresponding exported sets of lines and embedded into elements representing rubber. Rebar elements, defining cross-sectional area, spacing and angle of cord are then added inside surface elements representing carcass and belts, to finish the definition of tyre reinforcement components. Linear, bilinear or Marlow material models are used to describe the behaviour of cord. Bead wire is modelled by axisymmetric solid elements that are characterized by equivalent material properties. A finished axisymmetric FE model is shown in Fig. 8. Finally, loads and boundary conditions are added to simulate tyre inflation, as described in [37].

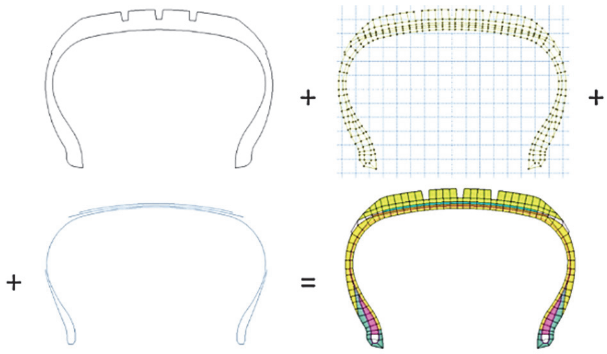

Figure 7 Creation of FE tyre model based on sets of geometrical entities exported from DCTM

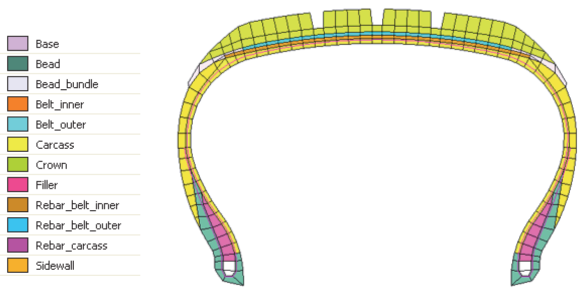

Figure 8 Axisymmetric FE tyre model for simulation of tyre inflation, also used as the basis for creation of 3D FE model. Finite elements are grouped to represent structural components of the tyre and each group is characterized by appropriate material properties. The coarse mesh is used for clarity

After the axisymmetric FE model is created, simulation of inflation, static loading, braking and acceleration as well as cornering, may be performed using the algorithm described in [37]. In that way, inflated shape, load-deflection and braking curves, cornering forces and moments and many other types of output data may be obtained for a given set of tyre design parameters.

3.2 Mapping and Transformation Routines

For DCTM to be used in design studies, there should be a methodology that enables an easy transformation of the axisymmetric FE model to match a new set of tyre design parameters. To facilitate such a transformation, special mapping and translation routines were created. The mapping routine compares the coordinates of vertices in DCTM (CAD model) with coordinates of nodes in axisymmetric FE model. Each vertex and the corresponding node, which reside in the same location, are related to each other and a mapping file is created. After the driving parameters of DCTM are changed, all its layers are automatically updated to reflect the new geometry of radial section. Thus, the locations of vertices in the third layer, which correspond to positions of nodes in FE model, are updated. Transformation routine is then used to change the coordinates of corresponding nodes in FE model, according to their updated locations in DCTM and the earlier created mapping. In this way, the change of tyre geometry performed in CAD model is simply propagated to the FE model.

Translation and mapping routines were set in a standalone Java application with a very simple interface, which enabled quick and simple creation of FE model based on appropriate CAD model. The interface was created using Swing, GUI widget toolkit for Java.

3.3 The Procedure for Application of DCTM in Design Studies

In previous chapters the procedures for creation of DCTM and FE model based on geometry exported from DCTM were described, as well as the methodology for automatic modification of FE model based on the change of design variables performed in DCTM. All those together, enable the use of DCTM in design studies (sensitivity or optimization) to facilitate the easy propagation of design changes from CAD model to FE models, according to the algorithm shown in Fig. 9.

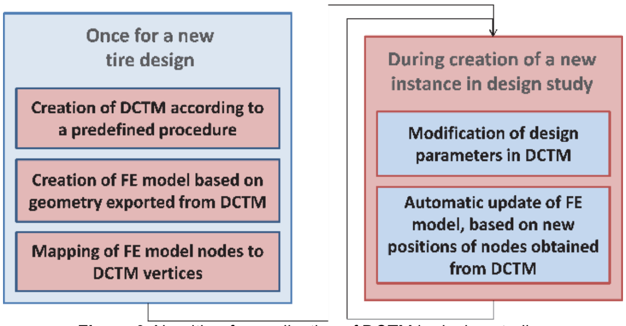

Figure 9 Algorithm for application of DCTM in design studies

The algorithm for application of DTCM consists of two sections: the actions that are performed only once, in the beginning of design study, and the actions that are performed after each change of DCTM parameters, i.e. creation of a geometrically new instance. In this way, tyre designer can create just one DCTM and one axisymmetric FE model of a new tyre design and still be able to perform design studies in which many geometrically altered instances are created, with minimal user effort.

4 ENHANCED DCTM CONCEPT

The experience in FEA of tyres [37, 40, 41] has shown that the simplified FE model (without detailed tread discretization) may successfully be used for prediction of tyre stiffness, forces, and moments. Nevertheless, to achieve the optimal design of tyre tread a detailed tread tyre model is needed, which may be used to obtain a detailed distribution of contact pressure on tread surface [42]. Thus, the proposed preprocessing procedure that involves DCTM may be enhanced to enable creation of detailed tread segments, which serve as a base for creation of detailed tread FE models.

The tread represents a structural component of the tyre that is characterized by variable design in circular direction, i.e. there exist dimensional as well as morphological differences between its radial sections. Thus, the system for discretization management must take this specificity into account. The basic phase in discretization of tyre tread is segmentation to radial "slices" that correspond to steps of the tread pattern (visible in Fig. 4). In a simple case, where the segments are only dimensionally different, it is possible to create a single 3D slice that is stretched or compressed proportional to the length of the step. In a more complex case, where the segments are also morphologically different, a separate slice must be created for each morphologically specific segment. It should be mentioned that only in the first case it is possible to create FE model for steady-state rolling analysis of the tyre based on mixed Eularian-Lagrangian definition of deformation kinematics [20, 42].

The first step in creation of a radial slice is idealization, which implies the removal of details that will not have significant influence on analysis results, such as small radii and holes, or very small surfaces that can cause difficulties in mesh generation. Thus, a part of geometry cleaning and defeaturing process is also transferred from FEA to CAD (Fig. 10 and 11). Then, the slice is divided into volume segments (Fig. 12) and surface contours and/or seed vertices are created that define finite elements that will be created in FE software.

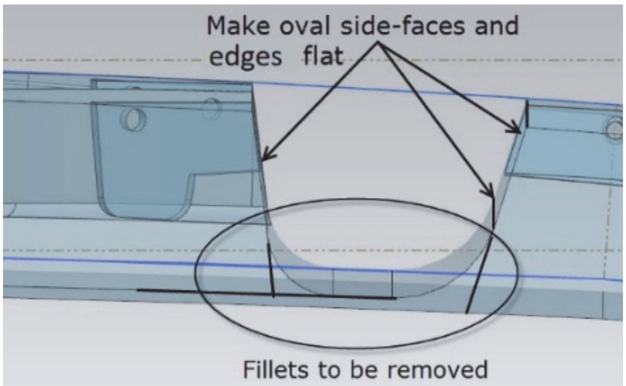

Figure 10 Simplification of radial slice geometry

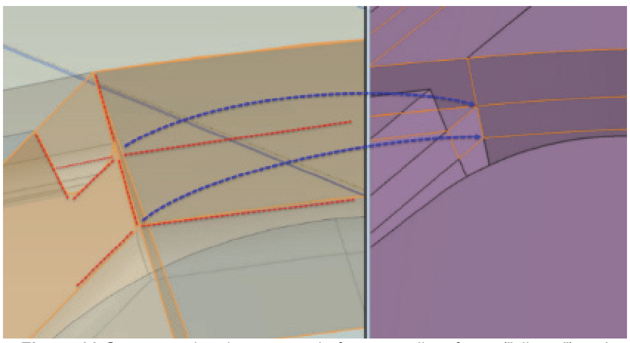

Figure 11 Geometry cleaning: removal of very small surfaces ("slivers") and edges by slight modification of tread geometry, i.e. repositioning of vertices

The efficiency of enhanced DCTM creation process depends on the available functionality of the CAD program. Controllability of 3D network of contours and vertices of tyre tread is, like in the case of radial sections, envisaged via predefined plan for connection of network vertices to outer and inner surfaces and edges of tread segments.

After the tread volume and geometry segments that define finite elements are exported, the FE model of the tread is created by following a similar procedure to the one used in the case of simplified model. During rotational disposition and multiplication, the basic segment of tyre tread is stretched or compressed to follow the predefined scheme of tyre tread steps. Then the vertex-node mapping is performed which facilitates automatic changes of FE tread model with changes of enhanced DCTM. Finally, FE model of the tread is combined with 3D model of the remaining portion of the tyre (simplified tyre model without tread) to form detailed tread tyre model, according to the procedure described in [42], which is based on nodal tying between non-matching nodes.

At this moment, the complete and fully functional enhanced DTCM model is not developed. A combined model is used instead, in which the tread is modelled separately, and the rest of the tyre is modelled using DTCM. Nevertheless, the modelling effort is still significantly reduced as the combined model is used to analyse only the narrowed set of near-optimal solutions, obtained by structural optimization of the simplified tyre model based on DTCM.

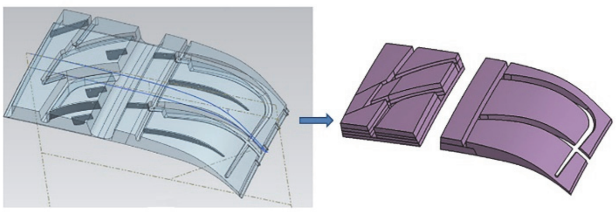

Figure 12 Transformation of radial tyre segment geometry to a set of interconnected volume segments, which serve as a base for creation of regular mesh of finite elements

5 TRIAL APPLICATION OF DCTM

To test the DCTM concept, a parametric design study was performed. The sensitivities of tyre forces, tyre moments and footprint contact stress to the change of sidewall geometry and belt width were explored, using the simplified thread FE model of an existing 165/70R13 tyre. Detailed results of the study were presented in [43] and here only the highlights are shown. In addition, the difference in the effort needed to perform this and similar studies with and without DTCM is estimated.

Two structural parameters were chosen as design variables: the radius defining the part of the sidewall close to the crown (R_1) and inner belt width (W). Both parameters had the influence on the geometry of tyre profile and/or its structural components. Radius R_1 was in turn set to three different values, 53.8 mm, 64.4 mm and 75.0 mm, while belt width was kept constant at nominal value of 131.4 mm. In this way, three different variations of radial section were obtained (Fig. 13).

In addition, inner belt width W was altered to get three variations: narrow-belted, normal and wide-belted tyre, while sidewall radius was kept constant at 64.4 mm. (Fig. 14). The difference between inner and outer belt widths was thereby maintained constant. In this way the total of five different tyre instances was obtained, as shown in Tab. 1.

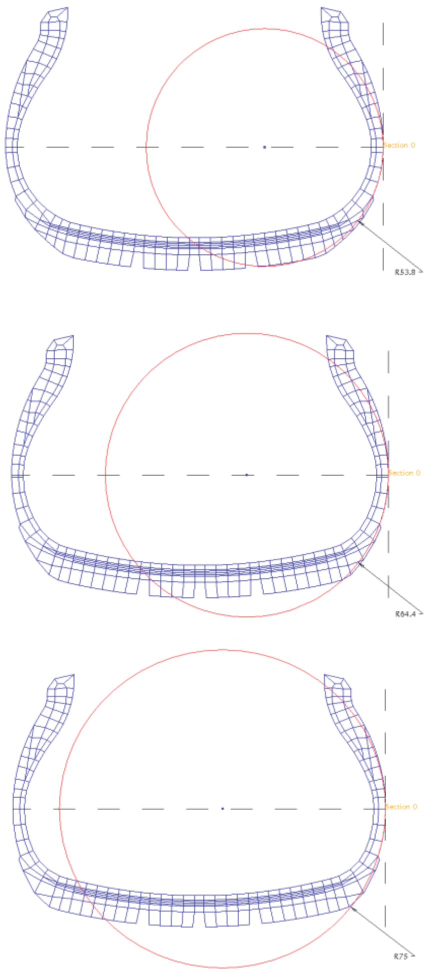

Figure 13 Three variations of tyre profile shape obtained by alteration of sidewall radius in DCTM

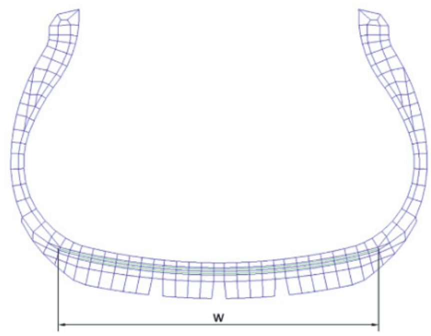

Figure 14 Design parameter W, defining inner belt width

Table 1 Tyre instances created in the study and the corresponding values of design variables

Tyre instance number	Upper sidewall radius R_1 / mm	Belt width W / mm
1	53.8	131.4
2	64.4	131.4
3	75.0	131.4
4	64.4	121.4
5	64.4	139.4

The axisymmetric FE models created by DCTM based procedure contained 473 nodes and 403 elements. The 3D

FE model with simplified tread, obtained by rotation of axisymmetric model around tyre axis, contained 21712 nodes and 18538 elements. The road was modelled as rigid surface and constant friction coefficient equal to 0.6 was used for simplicity and analysis speed. The axisymmetric model was applied in inflation analysis. The 3D model was used in footprint analysis and steady state rolling analysis (braking and cornering). The vertical load was set to 2750 N and the rolling speed of 10 km/h was used to obtain fast convergence.

Typical results of the study include load-deflection curves obtained by FEA of tyre models with different belt width (Fig. 15). The distribution of contact stress at the footprint was also obtained by analysis of different FE model instances subjected to vertical load (Fig. 16) or to cornering at free rolling [43].

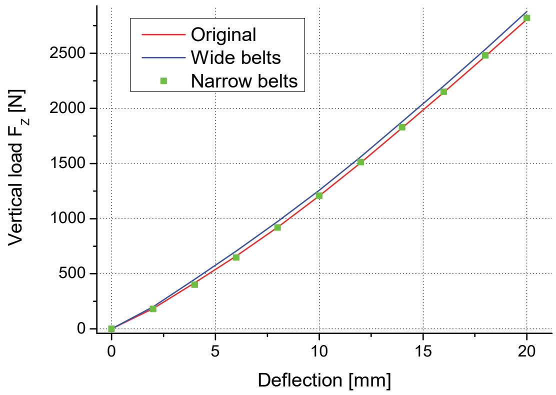

Figure 15 Comparison of load-deflection curves obtained by footprint analysis of FE models with different belt widths

The necessary steps in creation of axisymmetric FE tyre model based on a CAD model, with or without the use of DCTM, are listed in Tab. 2, together with estimated step duration and step frequency. The time estimates are based on authors' own performance and represent the typical times needed by an experienced CAD or FEA program user to complete the featured modelling steps.

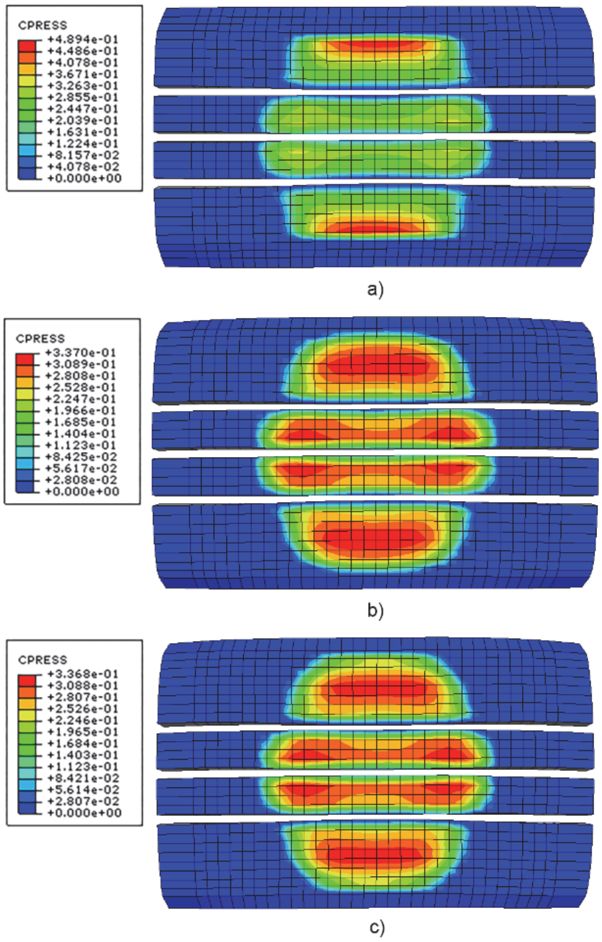

Figure 16 Contact stress distribution at vertical load of 2750 N for a) R_1 = 53.8 mm, b) R_1 = 64.4 mm and c) R_1 = 75.0 mm

Table 2 Necessary steps in FE model creation, duration and frequency

Step No.	Step name	Estimated Duration / min	Frequency with DCTM	Frequency without DCTM
1	Creation of structural components layer in CAD program	90	Once	Once
2	Creation of mesh geometry layer in CAD program	90	Once	Never
3	Export of geometry from CAD program	3	Once	For each FE model instance
4	Creation of axisymmetric FE model in FEA program, based on the exported geometry	120	Once	For each FE model instance
5	Mapping of CAD model vertices to FE model nodes, based on coordinates' coincidence	5	Once	Never
6	Change of design variables' values in CAD program	1	For each FE model instance except the first	For each FE model instance except the first
7	Export of vertices contained in the mesh geometry layer from CAD program	3	For each FE model instance except the first	Never
8	Transformation of nodal coordinates of axisymmetric FE model, based on vertices-nodes mapping and updated coordinates of the vertices	3	For each FE model instance except the first	Never

If DCTM is used, the estimated overall time for the initial axisymmetric FE model creation consists of the times necessary to complete the steps 1-5 listed in Tab. 3 and equals 308 min. The estimated time for creation of each following instance corresponds to the time needed for completion of steps 6-8, which is equal to 7 min. If FE models are created without the use of DCTM, the contours of structural components still must be created in CAD or FEA program, but there is no need for steps 2 and 5 and the overall estimated time for creation of the first FE model instance is 213 min. The necessary time for creation of each of the following instances consists of the times that are needed to perform steps 6, 3 and 4 and is equal to 124 min.

When DCTM is used, the estimated overall time for creation of 5 instances is 308 + 4 · 7 = 336 min. i.e. 5 hrs. 36 min. Without DTCM, estimated overall time is equal to 213 + 4 · 124 = 709 min, i.e. almost 12 hours or 211% of the estimated time for DCTM based procedure, as shown in Tab. 3. The necessary time for building of 3D FE model with simplified tread as well as for performance of the FE analyses stays the same regardless of the use of DCTM, thus it is not considered for comparison.

The number of FE model instances created in the study was very small, yet considerable savings in time and effort needed for axisymmetric model creation were achieved. Nevertheless, a typical structural optimization procedure requires creation of many different FE models, typically tens or hundreds of these, and it is easy to calculate the difference in times needed for their creation with and without DCTM (as presented in Tab. 3). This suggests that it is not feasible to perform any design optimization study that involves the changes of tyre geometry if an automated approach to FE model creation is not used and further confirms the value of DCTM based approach.

Table 3 Total estimated FE modelling time with and without DCTM, where t_N represents the necessary time for completion of step N

No. of FE model instances	Necessary step times with DCTM	Necessary step times without DCTM	Total estimated duration with DCTM min.	Total estimated duration without DCTM min.	Difference / %
1	$1 \times (t_{1\text{-}5})$	$1 \times (t_1 + t_3 + t_4)$	308	213	69%
5	$1 \times (t_{1\text{-}5}) + 4 \times (t_{6\text{-}8})$	$1 \times (t_1 + t_3 + t_4) + 4 \times (t_3 + t_4 + t_6)$	336	709	211%
10	$1 \times (t_{1\text{-}5}) + 9 \times (t_{6\text{-}8})$	$1 \times (t_1 + t_3 + t_4) + 9 \times (t_3 + t_4 + t_6)$	371	1329	358%
20	$1 \times (t_{1\text{-}5}) + 19 \times (t_{6\text{-}8})$	$1 \times (t_1 + t_3 + t_4) + 19 \times (t_3 + t_4 + t_6)$	441	2569	583%
50	$1 \times (t_{1\text{-}5}) + 49 \times (t_{6\text{-}8})$	$1 \times (t_1 + t_3 + t_4) + 49 \times (t_3 + t_4 + t_6)$	651	6289	966%
100	$1 \times (t_{1\text{-}5}) + 99 \times (t_{6\text{-}8})$	$1 \times (t_1 + t_3 + t_4) + 99 \times (t_3 + t_4 + t_6)$	1001	12489	1248%

6 CONCLUSIONS

The originality of the proposed DCTM concept lays in its ability to enable the easy and fast propagation of tyre geometry changes from the CAD model to the corresponding FE model. Without the use of DCTM, the modifications of FE tyre models created in commercial FEA software are limited to changes of material properties and cord angles.Thus, DCTM facilitates the performance of design studies that consider many design variations, bringing considerable benefits to tyre designers. At the same time, it does not require the extensive CAD and FEM modelling skills from its user. For many companies dealing with tire design, this may be a cost-effective alternative to creation of expensive specialized applications.

The DCTM concept was fully applied to tyre models with simplified tread. Similar principles are envisaged to be used in "enhanced DCTM" that will enable creation of tyre models with detailed tread. Nevertheless, detailed tread models may be created using a hybrid approach, which implies nodal tying between treadles, DCTM based, axisymmetric tyre model and detailed model of tyre tread created in a FE preprocessor without the help of DCTM. Then, a set of near-optimal tyre models obtained by an optimization study based on simplified tread DCTM may be enhanced by addition of tread patterns and reanalysed for final comparison.

The achievement of full flexibility of enhanced DCTM is foreseen as one of the main goals of the future research. Other aspects of DCTM concept that leave the space for improvement are the procedures for creation of innermost layer of DCTM and creation of axisymmetric FE model. The latter can probably be shortened by introduction of new set of custom, tyre design-oriented CAD features, scripting templates or similar improvements.

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Contact information:

Nikola KORUNOVIĆ, Associate Prof.
(Corresponding author)
University of Niš, Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: nikola.korunovic@masfak.ni.ac.rs

Miloš STOJKOVIĆ, Associate Prof.
University of Niš, Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: milos.stojkovic@masfak.ni.ac.rs

Dragan MIŠIĆ, Associate Prof.
University of Niš, Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: dragan.misic@masfak.ni.ac.rs

Ana PAVLOVIĆ, Adjunct Prof.
University of Bologna, Department of Industrial Engineering DIN,
Via Risorgimento 2, 40136 Bologna
E-mail: ana.pavlovic@unibo.it

Miroslav TRAJANOVIĆ, Full Prof.
University of Niš, Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: miroslav.trajanovic@masfak.ni.ac