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Design, Optimization and Manufacturing of an Aluminum Wheel Rim for the IDRAkronos Vehicle Prototype

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ABSTRACT

The present paper describes the topology optimization of an aluminum wheel rim for IDRAkronos, a low consumption vehicle prototype that participates at the Shell Eco-marathon competition from 2016. The design of the previous rim (designed in 2015) was renewed according to the more severe new loads on the vehicle imposed by the change of the track. The main goals of the optimization were the increasing of the stiffness without additional mass of the rim. The accurate setting of the topological variables for the new rim made possible a reduction of displacements and stresses, respectively of 17% and 50%, compared to the previous version of the rim without increasing the mass of the wheel rim component.

Keywords: topology optimization, optimal design, low-consumption vehicle, wheel rim, mass reduction.
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1 INTRODUCTION

This paper describes the design of a new aluminum alloy rim for the IDRAkronos vehicle prototype (Fig. 1), designed to race at the Shell Eco-marathon (SEM) from 2016 (SEM2016), a low consumption competition, where the mass reduction is an important goal [1-4].

The study started from the vehicle dynamics multibody model, evaluating constraints (tire, bearing, hub, etc) and load case relative to the track. A finite element topological optimization of the rim was required to maximize stiffness and reduce the component mass. In fact, the design of the aluminum alloy rim has to present characteristics of low mass and inertia, ensuring the structural strength required both in terms of stress and in terms of stiffness.

The static analysis carried out with Optistruct solver, will be described referring to a "neutral" rim, although in the final model there will be slight differences between the front and rear wheels, because the rear is directly fixed to the transmission gear.

The first release of the wheel rim presented in this paper was realized for the Shell Eco Marathon of 2015 (SEM2015) held in the Rotterdam track. The change of location for the SEM2016 in London imposed a verification of the 2015 rim for the new track, highlighting problems related to the stiffness of the component with the new loads, which could compromise the performance of the entire vehicle. In fact take into account the vehicle dynamics model of the vehicle in the new track the identification of the loads in the most critical condition (for example curves) has been possible and this data has been used for the rim FEM models.

The new releases of the rim for the SEM2016 took into account these issues and some modifications have been made to the CAD referring to the topological optimization notices. To evaluate the effectiveness of each change on FEM, the wheel hub was tested with the blocked channel and the product of rim mass for the maximum displacement of the vehicle has been studied as a 'delta parameter'. For the 2015 rim on the 2016 track loads, this is equal to 256 gmm, the target for the new release.

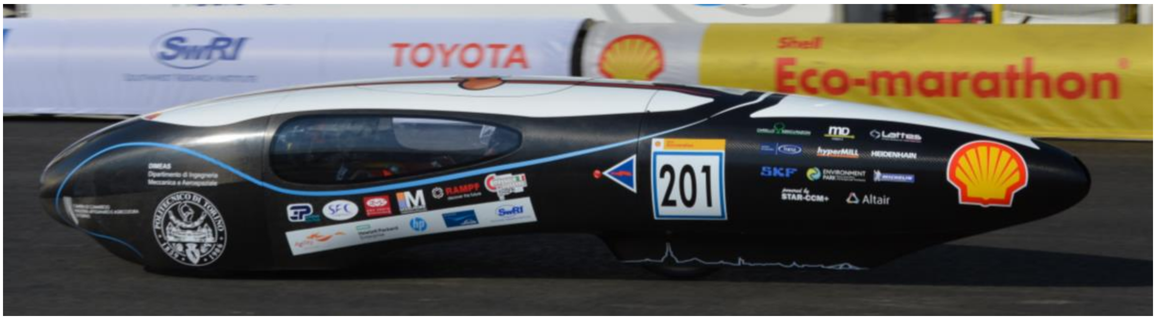


Figure 1: The vehicle prototype IDRAkronos at Shell Eco-marathon.

2 METHODOLOGY

2.1 Constraints

The IDRAkronos vehicle prototype has two front steering wheels and one rear driving wheel and the overall mass of the vehicle system (including driver) is 100 kg.

Regarding the wheel in particular the design constraints are:
- Dimensions: 16"
- Duct dimensions: Michelin tire especially made for the competition
- Inflation pressure: 5 bar
- Hub and upright, linked to the attachment points of the steering arms
- Caster, Toe-in, King-ping angle equal to zero.

Regulation of the competition defines a radius of 8 m for the smallest curve that the vehicle must be able to do. Furthermore, it recognizes the race worst load case as the vehicle rollover with this curve at 30 km/h. The multibody vehicle dynamic model of the vehicle states the applied forces on radial and axial direction. The forces related to the tracks are reported in Tab. 1.

Year	*Track*	*Radial Force [N]*	*Axial Force [N]*
2015	Rotterdam	500	250
2016	London	650	350

	+30%	+40%

Table 1: Force values for different tracks.

2.2 Topology Analysis

Topological optimization has been recognized a valid approach to guide the design phase for a large part of automotive components, e.g. [5], and in particular for wheel rims [6-10]. The presented optimization was performed using the Altair HyperWorks software and especially the linear solver Optistruct. The topology analysis allowed understanding the optimal distribution of material in relation to the type and extent of the applied loads, through an iterative calculation process that requires the constraints and loads, imposed by the designer, as input. The results of optimization have been reprocessed through a phase of post-processing which has led to the definition of the CAD model of the rim. Then it was possible to add the non-structural construction details (support for the transmission crown, hole for the tire valve).

2.3 FEM Analysis

The structural strength of the 2015 rim release was verified applying the radial load in two cases:
- case 1: Y Configuration (Fig. 2(a)) with the radial force discharged on a single race;
- case 2: Δ Configuration (Fig. 2(b)) with the radial force discharged on two races.

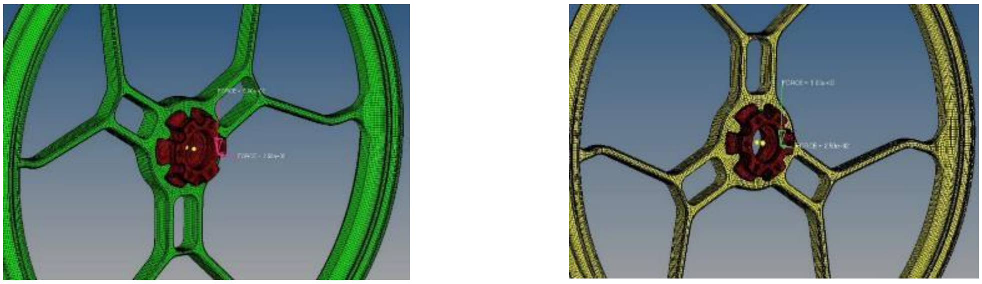


Figure 2: FEM static analysis of the rim in different radial loads: (a) case 1 Y, (b) case 2 Δ.

The structural verification of the 2016 rim release carried out linking the hub and applying forces on the channel, considering the non-deformable tire and an estimated contact area between rim and tire.

3 RESULTS

3.1 Topology Analysis

The starting design was obtained by the revolution of the channel and the hub (Fig. 3(a)). Importing the CAD into FEA (Finite Element Analysis) environment, a two-dimensional mesh was generated on the section keeping divided the channel and the hub (Fig. 3(b)). By revolution, this was transformed into a 3D mesh of tetra elements.

The channel (purple) and the hub (green) are defined according to the characteristics of Michelin tire and the wheel hub geometry. In the central region (yellow) were obtained 3 races subjects of the topological optimization through the design variables (DESVAR).

The computational time for the optimization iterative analysis linearly depends on the number of elements, therefore it was necessary to optimize the following parameters:
- Mindim: minimum dimension of an element.

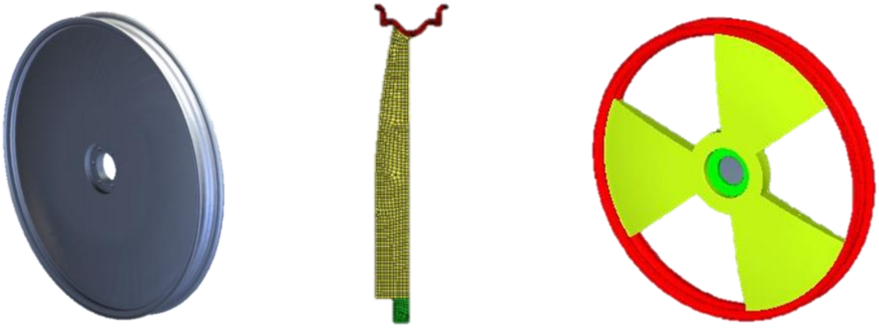


Figure 3: The first design of the rim and the channel.

- Cyclic pattern grouping: request for an axisymmetric distribution, in this case 3 for 3 races.
- Draw direction: preferred direction of extrusion (wheel axis) to ensure the machining by milling.

The effect of disabling the "draw direction" parameter can be observed in the Fig. 4. In fact, the result of the simulation without this function would present considerable problems in manufacturing by machining processes.

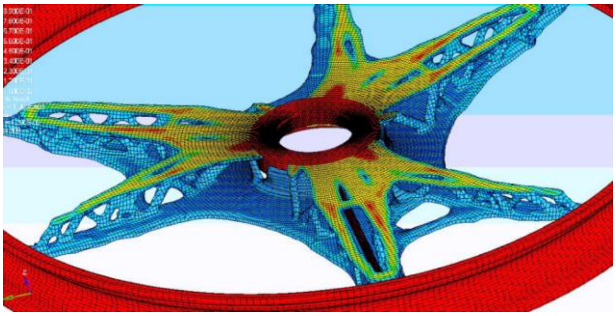


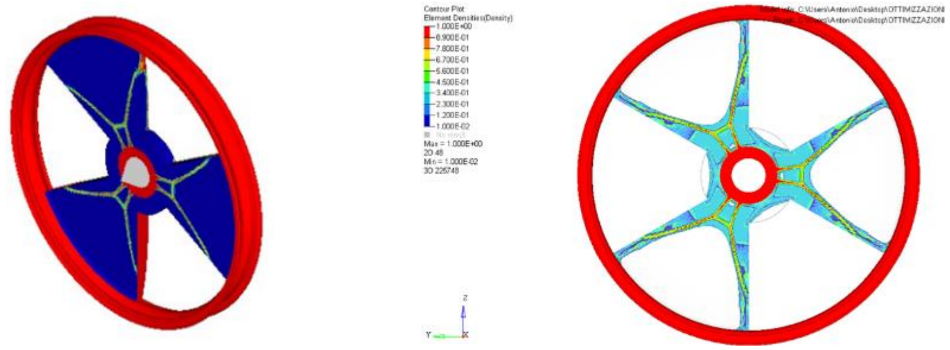
Figure 4: Effect of the "draw direction" parameter.

The solution required 33 iterations before going to convergence with the following results:
- Displacement: maximum value of 0.5 mm.
- Mass: the goal of the optimization.

OptiStruct solved the topological optimization problems using the density method, also known as SIMP (Solid Isotropic Material with Penalisation) method. A value of the material density is assigned to each element between 0 (blue) and 1 (red) based on the fact that element is void or solid. Through a filter, it was possible to remove the elements under a predetermined value. The results obtained for a filter value of 0.9 and 0.5 are shown in Fig. 5(a) and Fig. 5(b), it is possible to see that the area around the hub requires a reinforcement, in particular of three structures in the shape of an "H". The areas in blue can be lightened to reduce volume and therefore the mass of the component.

3.2 CAD modeling

For each race of the rim, the material was removed following the guidelines of the topological analysis. Particular attention was given in the interface areas with the hub and the channel (Fig. 6). The presence of edges not adequately connected, in fact, constitutes a critical issue to the stress concentration.



a) b)

Figure 5: Topological optimization by SIMP method: (a) filter value 0.9, (b) filter value 0.5.

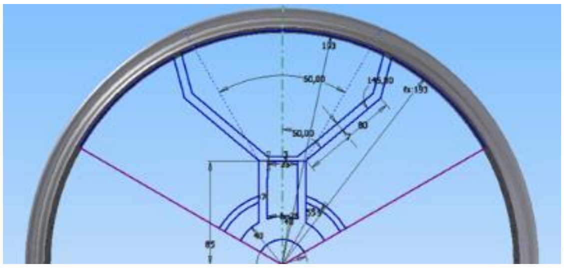


Figure 6: Race geometry on CAD.

The design of the rim realized for the SEM2015 is represented in Fig. 7(a) and Fig. 8(a).

To increase the stiffness, in order to support the new loads in the SEM2016 track, it was initially decided to increase the interface area between race and channel and to insert a cross bar for each race in the area closest to the hub (Fig. 7(b) and Fig. 8(b)). The changes shown that the hub area is not particularly influential for the stiffness, so it was decided to remove the cross element on the spokes. To optimize the location of the hub group, the thickness was reduced by 2 mm only in the hub zone. In this way, the thickness increases going from the center of the rim to the channel, giving also a good flexural strength of the races (Fig. 7(c) and Fig.8 (c)).

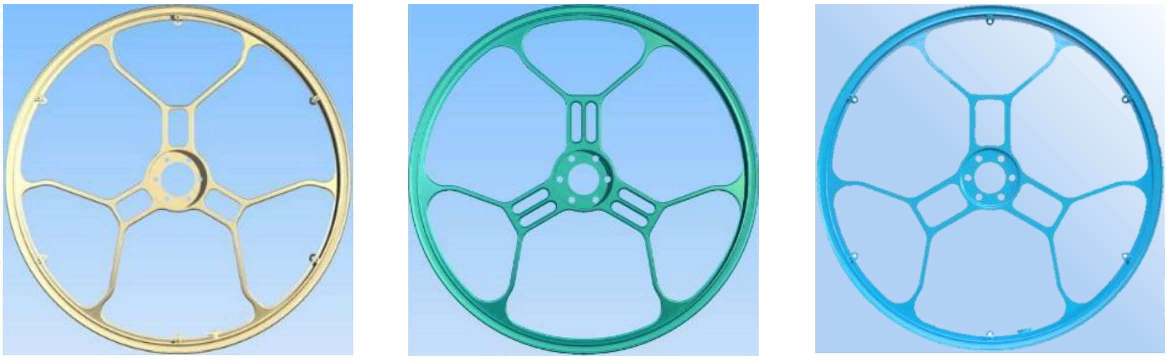


Figure 7: Different releases of the wheel rim: (a) 2015, (b) 2015_Review, (c) 2016.

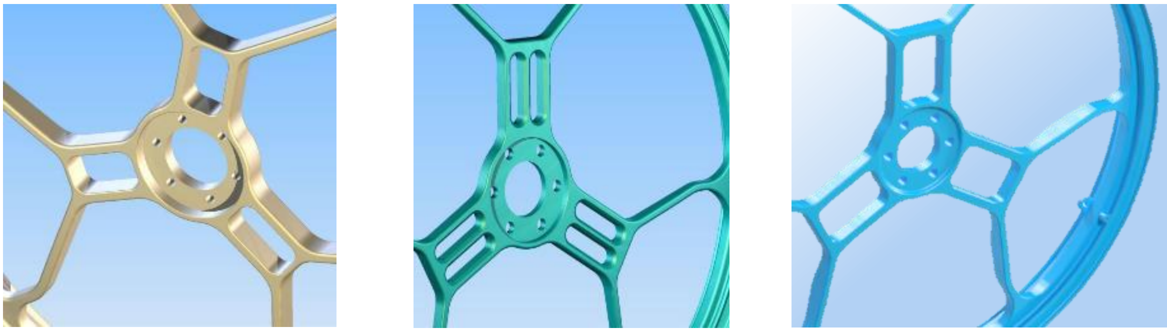


Figure 8: Particular of the wheel rim releases: (a) 2015, (b) 2015_Review, (c) 2016.

3.3 FEM Analysis

The contact between the rim, the hub and the nut was simulated, through a suitable mesh and not with a spider of rigid elements. In this way, the results are more realistic without excessively increasing the computational time, because of linear static analysis without iterative processes. The mesh of a portion of the component was performed on a circular pattern (Fig. 9). To obtain a homogeneous FEM model after the step of mirroring, the nodes in the contact parts have been re-indexed to be coincident.

Figure 9: Circular mirroring for FEM analysis of the wheel rim.

The linear static analysis results for the 2015 Release wheel rim are plotted in terms of displacements and stresses for case 1 and case 2, respectively in Fig. 10 and Fig. 11.

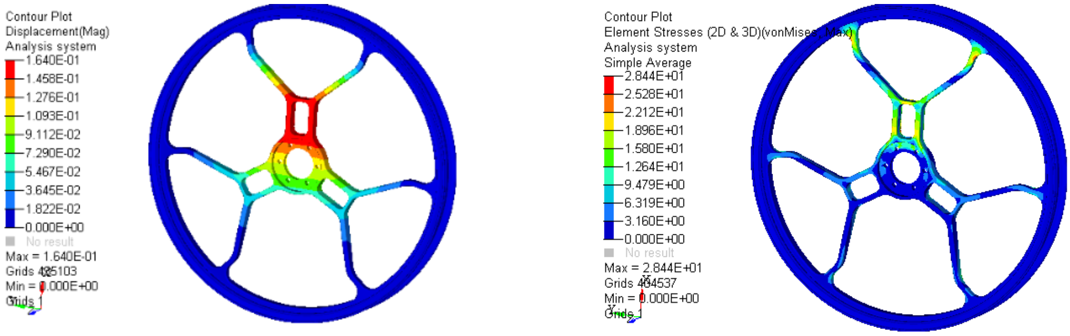


Figure 10: FEM results for case 1 (Y configuration) – 2015 Release.

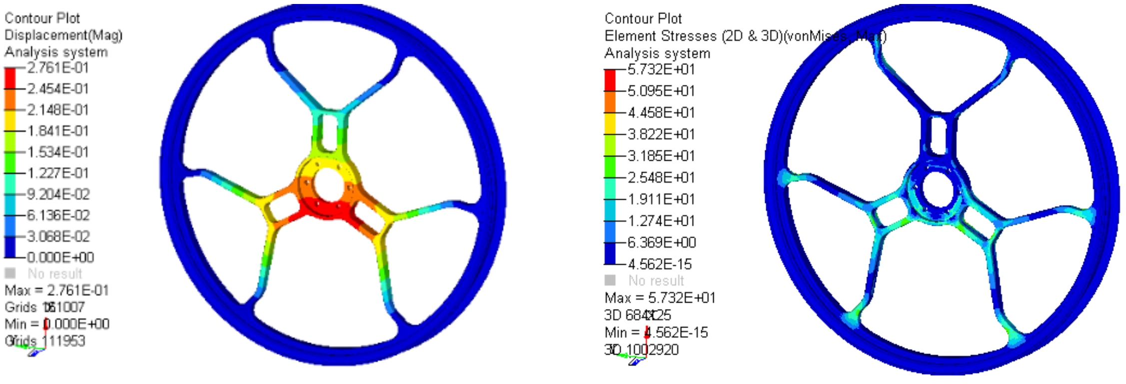


Figure 11: FEM results for case 2 (Δ configuration) – 2015 Release.

The estimated maximum displacements are still considered acceptable for this kind of application and they are localized in the outer zone near the hub for both configurations. The maximum stress does not exceed 30 MPa in case 1 and 60 MPa in case 2.

For the 2016 Release wheel rim, the results of the linear static FEM analysis shown in Fig. 12, indicate a maximum displacement of 2.56 mm of the channel and a maximum stress of 100 MPa only near the holes on the hub zone. This local effect is due to the loading with a spider constraint.

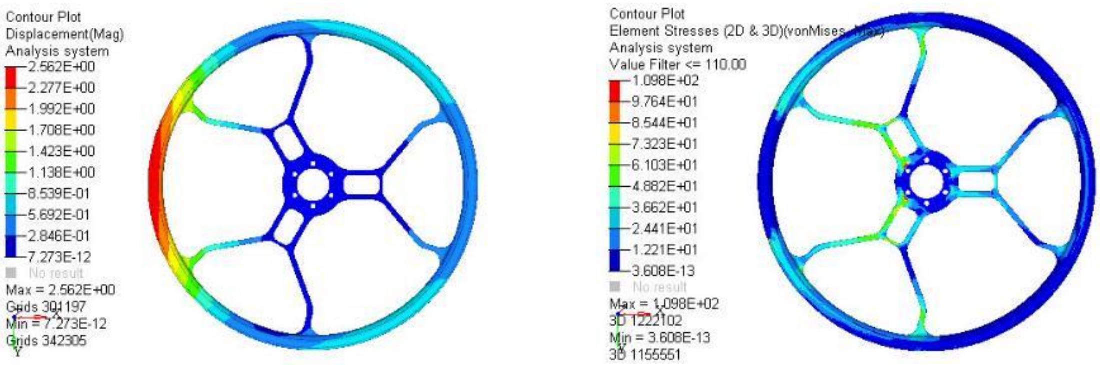


Figure 12: FEM results – 2016 Release.

For the comparison between 2015 and 2016 release of the wheel rim, the hub was linked and the channel was loaded. The results of FEM analysis and the delta parameter, calculated with the London track new forces, are reported in Tab. 2.

Release	*Mass [g]*	*Max displacement [mm]*	*Max Stress [MPa]*	*Delta [g*mm]*
2015	1150	0,223	59	256
2015_Review	1170	0,267	86	312
2016	**1160**	**0,184**	**30**	**213**
	+10g	-17%	-50%	-17%

Table 2: Delta parameter for the FEM analysis evaluations for different release of the wheel rim.

The wheel rim for IDRAkronos prototype was designed for riding a competition. Considering the tests and the race laps made until now, the vehicle made approximately 300 km that correspond to $2x10^5$ wheel cycles. Furthermore, taking into account a fatigue limit of $1x10^8$ cycles, the component was subjected to 0,2% of fatigue cycles.

4 CONSTRUCTION AND VERIFICATION

An important aspect is the construction phase of the wheel rim (Fig. 13).

The study of [11] was taken into account for the experienced loss in the tubeless rim made in composite material. The chosen material is Aluminum alloy AL7075-T6, able to ensure high yield stress (520 MPa) and good workability. It was starting from a mass full disk of 23 kg, removing material up to 1.160 kg mass component. To preserve the performance of the finished component, the reduction of the residual stresses and strains after the milling phase was obtained with a relaxation of the material for few days before following operations.

Following the realization of the rim a metrology measure carried out to verify that the actual tolerances correspond to those required. This verification was successful, the rim was positioned on a test hub and during the rotation, it was measured oscillation of the channel lower than 0.03 mm.

Figure 13: Tolerance verification of the rim.

5 CONCLUSIONS

In the present paper a topological optimization approach has been studied referring to many literature works in which the resistance performance was maximized with respect to the geometry and therefore to overall mass of the component. This innovative method has been applied to the design of the wheel rim for the IDRAkronos vehicle prototype, starting from a previous release. A new parameter, called delta, was identified to compare the different releases of the CAD to evaluate the effectiveness of the topological optimization. The experience gained during this work allowed to "drive" the solver optimization towards the desired result, increasing the number of constraints and defining the parameters related to the topological variable. The results obtained with a FEM model, both in terms of displacement and in terms of stresses, widely comply with the specifications of the project without increasing appreciably the mass.

The topological optimization of the rim carried out the following results:
- a mass increase of just 10 g;
- a reduction of the thickness of the hub area to minimize packaging of the assembly;
- a reduction of delta parameter equal to 17%;
- a reduction of displacements and stresses, respectively of 17% and 50%.

Thanks to the experience gained in the topological optimization pointed out on the presented wheel rim, in future the same methodology will be used to design other automotive components.

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REFERENCES

[1] Airale, G.-A.; Carello, M.; Scattina, A.: Carbon fiber monocoque for a hydrogen prototype for low consumption challenge, Materialwissenschaft und Werkstofftechnik, 42(5), 2011, 386–392. https://doi.org/10.1002/mawe.201100793
[2] Carello, M.; Malvindi, A.; Multari, D.; Sanfilippo, P.: Cerchio in lega di alluminio per prototipo di veicolo a basso consumo, Il Progettista Industriale, 5, 2016, 48-51. http://www.commercialefond.it/wp-content/uploads/2016/08/l%E2%80%99artico-pubblicato-su-%E2%80%9CIl-Progettista-Industriale%E2%80%9D-di-Maggio-2016.pdf
[3] Carello, M.; Messana, A.: IDRApegasus: a fuel-cell prototype for 3000 km/L, CAD, Computer-Aided Design & Applications, 12(1), 2015, 56–66. https://doi.org/10.1080/16864360.2015.1077076
[4] Carello, M.; Scattina, A.: Structural design and experimental investigation of a carbon fibre wheel for low consumption vehicle, Advanced Structured Materials, 16, 2012, 521–535. https://doi.org/10.1007/978-3-642-22700-4_32
[5] Lee, D.-C.; Lee, J.-I.: Structural optimization concept for the design of an aluminium control arm, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 217 (8), 2003, 647-656. https://doi.org/10.1243/09544070360692041
[6] Zuo, Z.-H.; Xie, Y.-M.; Huang, X.: Reinventing the Wheel, Journal of Mechanical Design, 133(2), 2011, 024502. https://doi.org/10.1115/1.4003411
[7] Ahmad, M.-N.; Kamil, A.-I.; Muhamad, W.-M.-W.: Application of Shape Optimization Method on Steel Wheel Rim, Advances in Mechanical and Manufacturing Engineering, 564, 2014, 13–18. https://doi.org/10.4028/www.scientific.net/AMM.564.13
[8] Jape, R.-K.; Jadhav, S.-G.: CAD Modeling and FEA Analysis of Wheel Rim for Weight Reduction, International Journal of Engineering Science and Computing, 6(6), 2016, 7404-7411, https://doi.org/10.4010/2016.1756
[9] Anusha, R,; Tara Sasanka, C.: Analysis and Optimization of Alloy Wheel, International Journal of Innovative Research in Science, Engineering and Technology, 6(7), 2017, 15328-15336. https://doi.org/10.15680/IJIRSET.2017.0607370
[10] Das, S.: Design and Weight Optimization of Aluminium Alloy Wheel, International Journal of Scientific and Research Publications, ISSN 2250-3153, 4 (6), 2014, 1-12.
[11] Santin, J.-J.; Onder, C.-H.; Bernard, J.; Isler, D.; Kobler, P.; Kolb, F.; Weidmann, N.; Guzzella, L.: The World's Most Fuel Efficient Vehicle - Design and Development of Pac-Car II, vdf Hochschulverlag AG, ETH Zurich, 2007.