A Systematic Material-oriented Design Approach for lightweight components and the CFRP motor wheel case study

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Supplementary Information

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SI1 - Design Concepts evaluation form

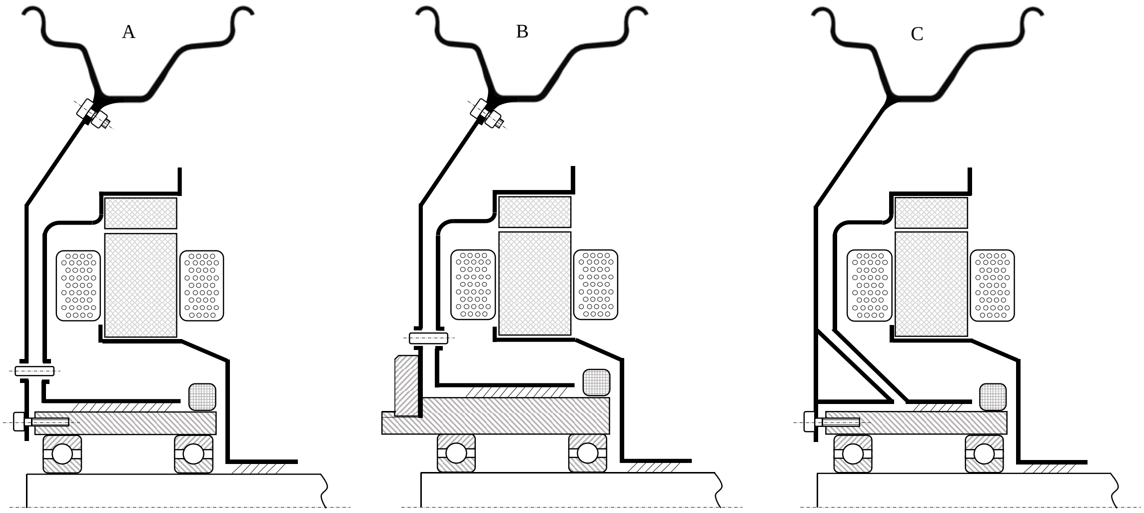
In the following pages is reported the form adopted for the evaluation of the design concepts. Five experts in the field of composite materials, outside the research group, were interviewed for the motor wheel project. The experts had to evaluate the design concepts, and they assigned a score to each sub-objective, using the scale of scores suggested in VDI 2225. The sub-objectives have been here reported without weights, in order not to influence the experts' judgments. The results of the evaluation process are reported in Table 1.

Title: Design Concepts Evaluation Step
Use: Conceptual Design Process

Document Revision Number: 3
Date: 2019-08-29

Expert ID:
Date of completion:

Design Concepts to be evaluated:



Evaluation criteria:

Level	Very good	Good	Adequate	Just tollerable	Unsatisfactory
Score (VDI 2225)	4	3	2	1	0

Evaluation Table:

Solution A

ID	Attribute	Score	Comments
O_{111}	Low Weight		
O_{112}	High Safety		
O_{113}	High Reliability		
O_{121}	Simple Manufacturing		
O_{122}	Simple Maintenance		
O_{123}	Easy Installation		

Title: Design Concepts Evaluation Step **Use**: Conceptual Design Process	**Document Revision Number**: 3 **Date**: 2019-08-29
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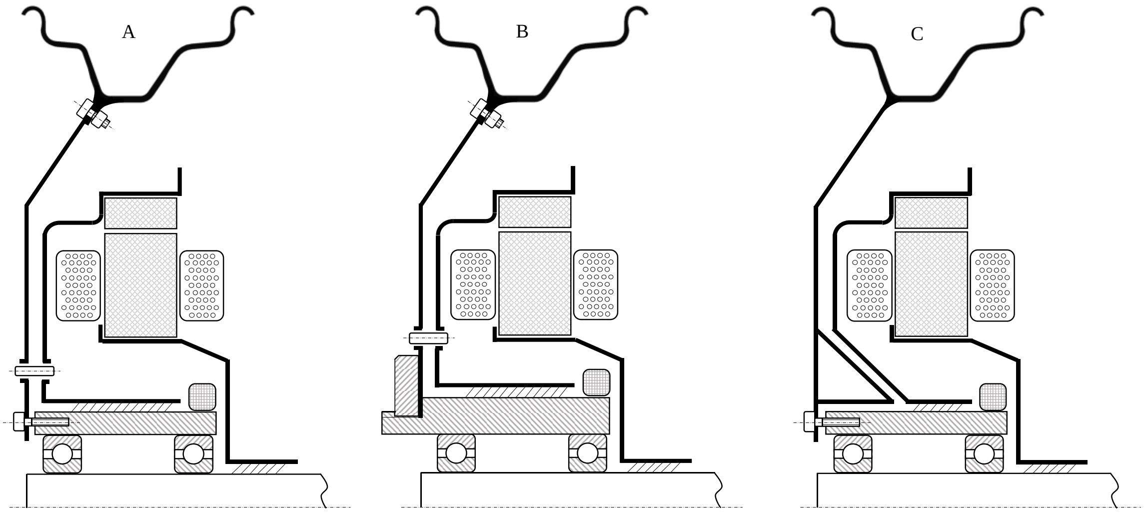
Design Concepts to be evaluated:



Evaluation criteria:

Level	Very good	Good	Adequate	Just tollerable	Unsatisfactory
Score (VDI 2225)	4	3	2	1	0

Evaluation Table:

Solution B

ID	Attribute	Score	Comments
O_{111}	Low Weight		
O_{112}	High Safety		
O_{113}	High Reliability		
O_{121}	Simple Manufacturing		
O_{122}	Simple Maintenance		
O_{123}	Easy Installation		

Title: Design Concepts Evaluation Step **Use**: Conceptual Design Process	**Document Revision Number**: 3 **Date**: 2019-08-29
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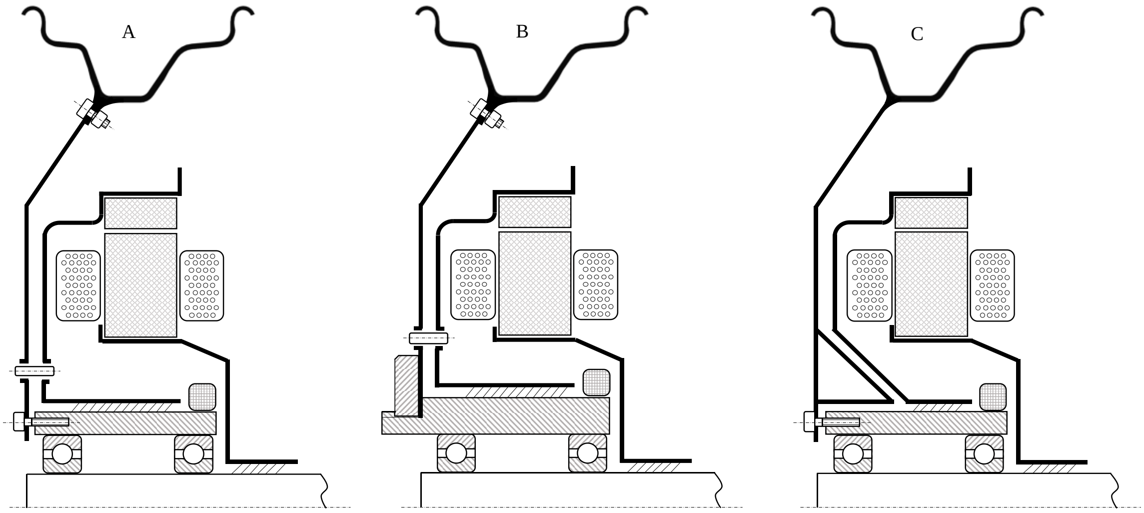
Design Concepts to be evaluated:



Evaluation criteria:

Level	Very good	Good	Adequate	Just tollerable	Unsatisfactory
Score (VDI 2225)	4	3	2	1	0

Evaluation Table:

Solution C

ID	Attribute	Score	Comments
O_{111}	Low Weight		
O_{112}	High Safety		
O_{113}	High Reliability		
O_{121}	Simple Manufacturing		
O_{122}	Simple Maintenance		
O_{123}	Easy Installation		

SI2 - Wheel disk stacking sequence

Optimized lamination of the wheel disk, obtained by the proposed method, is reported in Table S1. For each lamination step and sub-step (if present), material, number of plies and orientation are reported. The orientation of the different plies is referred to the reference system of Fig. 8.

Table S1 *Laminate stacking sequence for the wheel disk*

Step	Sub-step	Material	Number of plies	Orientation
WD-L1		PW T800	1	0°
WD-S1		UD M46J	3 (x5)	Radial
WD-L2		PW T800	1	144°
WD-S2		UD T1000	4 (x5)	Radial
Inserts	Reinforce	PW T800	2 (x5)	±45° Radial
	Concentrator	Rubber	1 (x5)	/
WD-L3		PW T800	1	288°
WD-D1	D1.1	PW T800	1	0°
	D1.2	PW T800	1	216°
	D1.3	PW T800	1	72°
	D1.4	PW T800	1	288°
	D1.5	PW T800	1	144°
WD-S3		UD T1000	4 (x5)	Radial
WD-L4		PW T800	1	72°
WD-S4		UD M46J	3 (x5)	Radial
WD-D2	D2.1	PW T800	1	0° [+45°]
	D2.2	PW T800	1	144° [+45°]
	D2.3	PW T800	1	288° [+45°]
	D2.4	PW T800	1	72° [+45°]
	D2.5	PW T800	1	216° [+45°]
WD-D3	D3.1	PW T800	1	0°
	D3.2	PW T800	1	216°
	D3.3	PW T800	1	72°
	D3.4	PW T800	1	288°
	D3.5	PW T800	1	144°
WD-L5		PW T800	1	216°

SI3 - Rim stacking sequence

Optimized lamination of the rim, obtained by the proposed method, is reported in Table S2. For each lamination step and sub-step (if present), zones of application, material, number of plies and orientation are reported. The orientation of the different plies is referred to the reference system of Fig. 9.

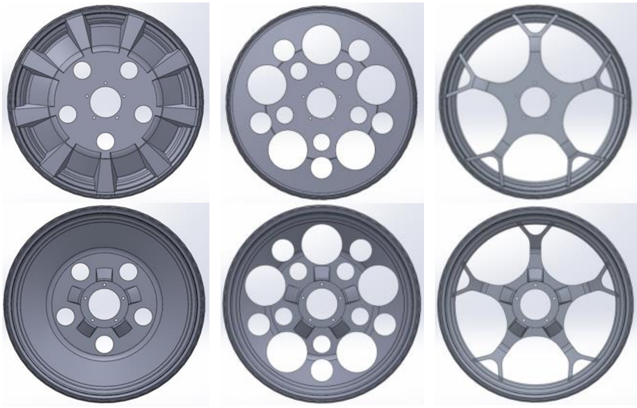
Table S2 *Laminate stacking sequence for the rim*

Step	Sub-step	Zones	Material	Number of plies	Orientation
R-F1		1,2,3,4,5	PW T800	1	0°
R-U1	U1.1	3,4,5	UD T1000	3	90°
	U1.2	4,5	UD T1000	3	90°
R-F2		2,3,4,5	PW T800	1	45°
R-U2	U2.2	4,5	UD T1000	2	90°
	U2.3	5	UD T1000	4	90°
R-F3	F3.1	2,3,4,5	PW T800	2	0°
	F3.2	3,4,5	PW T800	1	0°
	F3.3	4,5	PW T800	2	0°
R-U3		1	UD T1000	2	0°
R-F4		1,2,3,4,5	PW T800	2	0°

SI4 - Aluminum wheel design

As a comparison to CFRP wheel, an aluminum wheel has been designed. For the design of the aluminum wheel, the same conceptual design solutions, identified for the CFRP one, have been adopted. In particular, a cylindrical surface for the wheel centering sub-function (solution (1B) of the morphological matrix, Fig. 4), bolted connections for the wheel fixing (solution (2A), Fig. 4) and interlocking noses for the torque transmission (solution (3C), Fig. 4) were adopted. All the proposed solutions are in accordance with the geometrical constrains defined in Fig. 3.

As reported in Fig. S1, three geometries have been proposed: (a) a lenticular wheel with spokes, (b) a lighten lenticular wheel and finally (c) a 5-spoke wheel. For this case study, the main constraint was the machinability of the component.

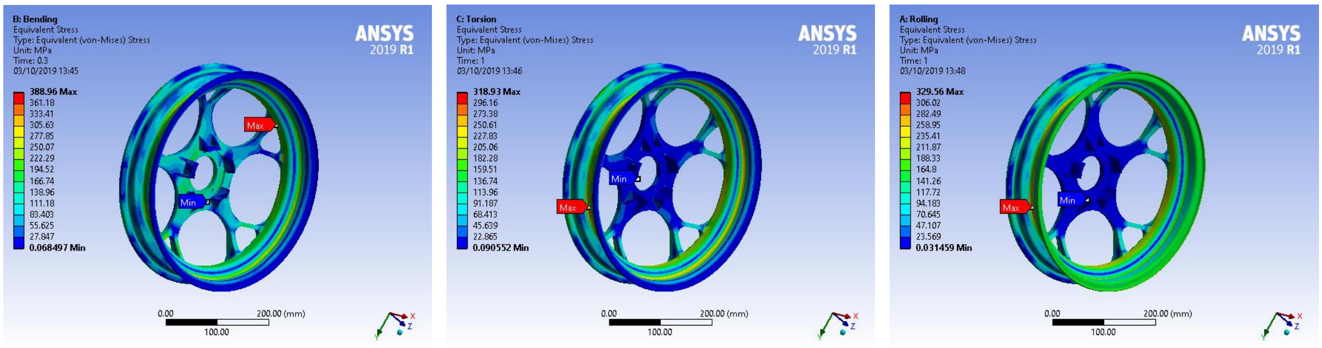


(a) (b) (c)

Fig. S1 *Proposed geometries for the aluminum wheel: a) lenticular wheel with spokes, b) lighten lenticular wheel and c) 5-spoke wheel*

The weights of the proposed geometries were 4.28 kg, 5.5 kg and 2.86 kg for solution (a), (b) and (c) respectively. Each geometry was analyzed by means of FEM using the same loading conditions adopted for the CFRP wheel. For the particular racing application, a 7075-T6 aluminum was used for the simulations (Rs = 467 MPa, Rm = 524 MPa, E = 70 GPa, ν = 0.3). Both lenticular structures (a) and (b) resulted to be particularly unstressed, indicating that the material was not actually fully exploited. On the contrary, the spoked solution was the one that best exploited the material's properties. In fact, in contrast with the composite wheel, the aluminum spoked solution has allowed to increase at the same time the stiffness and the resistance of the wheel disk. The main disadvantage of this solution is the need to introduce a frontal cover to reduce aerodynamic losses, which add unneeded weight to this solution.

In Fig. S2 are shown the equivalent stress distributions, calculated according to Von Mises criteria, for solution (c). The results are reported for the three loading conditions defined in Section 5: (i) bending, (ii) torque and (iii) rolling, combined with the inflating pressure. The worst loading condition was found to be the bending, mainly for the contribution of inflating pressure. In this configuration a minimum safety factor of 1.2 against yielding was obtained.



(a) (b) (c)

Fig. S2 *Von Mises equivalent stress distribution of the 5-spoke aluminum wheel under prescribed load cases: (a) bending, (b) torque and (c) rolling, combined with inflating pressure*