Generating different constructional solutions on the hubless wheel example

D Šotola¹, Ž Ivandić¹ and I Grgić¹

¹Josip Juraj Strossmayer University of Osijek, Mechanical Engineering Faculty of Slavonski Brod, Trg Ivane Brlić Mažuranić 2, 35000 Slavonski Brod, Hrvatska

E-mail: dsotola@sfsb.hr

Abstract: In this paper, we present evaluations of power and motion variants on the example of a motorcycle. The choice of the optimal variant is enabled by setting goals, forming a morphological matrix and evaluating particular variants. The selected characteristic elements and their combinations will give us the most appropriate solution. For the evaluation, some basic features of the motorcycle were selected with an emphasis on the hubless wheel for the further constructional and numerical models. At the end of the paper, the constructional assemblies of the hubless wheel with emphasis on design are given.

1. Introduction
The wheel has been known for hundreds of years in the same form, but with the development of the constructional solutions and industrial design, new wheel forms have been developed. Innovative ideas led to the development of a new wheel concept which is called a hubless wheel. A hubless wheel (also known as a rim-rider or centerless wheel) is a type of wheel with no centre hub, to be precise the hub is as large as the wheel itself and the axle is hollow. The beginnings of this wheel design are already encountered on bicycles and monowheels throughout the history which can be seen in the following pictures.

Figure 1 shows the first monowheel model from 1869 where the seat for the rider is connected with pedals to a small wheel, which was in turn connected to the outside wheel. Motion is created by the rider who pedals the small wheel and that drives the large wheel [1]. In 1904 Garavaglia presented the first...
motor-driven monowheel engine. The big tyre with its rim fitted internally with ball-bearings, upon which the fixed frame sits. It supports both the driver and the petrol engine; the rim of the tyre is moreover toothed on the side and engages with the pinion of the engine. In sum, the mobile wheel rolls around the built-in fixed engine, and of course, around the driver [2].

In 1989 Franco Sbarro patented a new hubless wheel which was used to manufacture three motorcycles. This new and improved design is the foundation of today’s hubless wheels. The orbital wheel comprises two components: A rotating part including the tyre, a centre-free rim and a brake ring and a fixed part lies around the inner ring of the bearing to which are set linking triangles, steering rod and brake gripper. To produce this wheel, he needed a very large-diameter wheel bearing. Franco Sbarro asked a Swedish company specializing in bearings, SKF [3]. The bearings are the non-standard which greatly increases their manufacturing costs thereby affecting the production of the entire wheel. Due to the high costs, we wanted to design three variants of the solution through the structural design of the product and choose the optimal one. Besides, the last few years the concept of hubless wheel has already been implemented into different aspects of life such as transportation [6], ocean engineering [7], bridge inspections [8] and medicine [9].

2. Requirement lists and morphological matrix

Requirement list is an internal list of requirements and wishes provided for the development of a product. The success of the design project can be judged using the specification listed in the requirement list. The following general method of compiling a requirements list can be recommended: Identifying the requirements, arranging the requirements in a clear order, entering the requirements list on standard forms and circulating among interested departments, licensees, directors, etc., examining objections and amendments and, if necessary, incorporating them into the requirements list [4]. A full list of requirements is shown in Table 1.

It is necessary to create a function structure in order to combine meaningful and compatible combination of functions and subfunctions which may be varied to satisfy the overall function. The function becomes independent of any particular solution. An overall function is then divided directly into identifiable subfunctions. It is usually possible to link subfunctions in various ways and hence to create variants. To that end it is useful to make a block diagram (black box) as shown in Figure 4.

Morphological matrix is a systematic combination method used to explore the complete set of possible relationships within any multi-dimensioned problem that can be decomposed into its constituent sub-problems. To be precise, the matrix is a table where the first vertical column consists of the general characters and attributes of the solved subject which are relevant to the problem and are indicating what the subject has to be, whereas the horizontal row shows the special features regarding each general attribute. In engineering design, the morphological matrix is used as a tool to support conceptual design
because it facilitates a visual exploration of the identified design space [4], [5]. Morphological matrix is also used within the conceptual design as the basis for exploration of the design space, where the functions represented in the functional decomposition are listed against the means to achieve each of those functions. Representation of the morphological matrix is illustrated in Table 2 with the functions listed along the column and the means listed along the corresponding rows.

Table 1. Requirements list for a hubless wheel.

| Number | Requirement                                | Requirement or Wish |
|--------|--------------------------------------------|---------------------|
| 1      | Geometry                                   |                     |
|        | Wheel dimensions                           | W                   |
|        | Hubless design                             | R                   |
| 2      | Kinematics                                  |                     |
|        | Achieved rotation of the wheel and transmission | R               |
|        | The direction of movement forwards          | R                   |
|        | Accepting axial forces                      | R                   |
|        | Reliable braking system                     | W                   |
| 3      | Forces                                     |                     |
|        | Construction of wheels designed to withstand the weight of a motorcycle with a passenger (6 kN) | W               |
|        | The smallest possible weight of the wheel construction capable of supporting the required load | W               |
|        | Stability (low center of the gravity)       | R                   |
|        | Aerodynamics                               | W                   |
| 4      | Energy                                      |                     |
|        | Achieved transmission of power and motion either by chain, belt or universal joint | R               |
|        | The possibility of installing the engine in the wheel | W               |
| 5      | Material                                    |                     |
|        | Use of light alloys                         | R                   |
|        | Corrosion resistance                        | R                   |
|        | The possibility of using polymer materials   | W                   |
| 6      | Ergonomics and Safety                       |                     |
|        | Protection of rotating parts                | W                   |
| 7      | Production                                  |                     |
|        | Use of widely available materials           | R                   |
|        | Assembly with screw joints                  | W                   |
|        | Accuracy, tolerance of faying surface       | R                   |
| 8      | Assembly                                    |                     |
|        | Easy assembly on fork and frame             | R                   |
| 9      | Handling and maintenance                    |                     |
|        | Easy maintenance                           | R                   |
|        | Simple replacement of spare parts considering compactness of the construction | R               |
|        | Protection of rotating parts due to the entry of impurities and to prevent continual lubrication due to washing | R               |
|        | The use of standard spare parts             | R                   |
| 10     | Costs                                       |                     |
|        | Justified price considering the complexity of the manufacturing | R               |
|        | Low price of spare parts                    | R                   |
| 11     | Aesthetics                                  |                     |
|        | Assembly design that follows the contour of the tire | R               |
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**Table 2. Morphological matrix for hubless wheel.**

| Partial functions                                      | Solution matrix                                                                 |
|--------------------------------------------------------|---------------------------------------------------------------------------------|
| **Wheel support**                                      |                                  |                                  |                                  |
| Unilateral (left)                                      | Unilateral (right)                | Bilateral                        |
| Position of the wheel support                          | Top                               | Middle                           | Bottom                           |
| Top                                                    | Middle                            | Right                            |
| Position of the rotating part in relation with power and motion assembly | Left (not in the center of gravity) | Center (in the center of the gravity) | With support for shafts (Milling sunk faying surface for shafts) |
| Simple (for two bearings of non standard dimensions)    | With threaded support for bearings | Fixied bearings with screwed joint at 12 places                                |
| Rotation between the movable and stationary wheel frame| Using two bearings (non standard dimensions)                                   | Bearing + UHMWPE (ultra high molecular weight polyethylene)                    |
| Using 6 shafts (with 2 standard bearings for rolling)  |                                  | 210/50 R17                       |
| Rotating element                                       | Bearing                           | Bearing + PTFE (teflon)           | The combination of the gear transmission and universal joint |
| Bearing                                               | Bearng + UHMWPE (ultra high molecular weight polyethylene)                     |
| Wheel dimensions                                       | 210/50 R26                        | 280/35 R18                       | Plastic rings (transparent)      |
| 210/50 R26                                             | 280/35 R18                       | 210/50 R17                       |
| Transmission                                           | Chain drive                       | Belt drive                       |                                  |
| Safety protection of rotating element                  | Without protection                | Aluminium rings                  |                                  |
| Braking system                                         | One side disc breake              | Double disc breake               |                                  |
3. Objectives tree
The objectives have been set out on four levels of decreasing complexity and provided with weighting factors. The evaluation proceeds step-by-step from a level of higher complexity to the next lower level [4].

![Objectives tree diagram]

Figure 5. Objectives tree.
In Figure 5 we can see weightings are based on factors ranging from 0 to 1 and the sum of the factors of all evaluation criteria must be equal to 1 so that a percentage weighting can be attached to all of the sub-objectives. The sum of the weighting factors for any level must always be equal to (1).

\[ w_i = 1.0 \]  

(1)

4. Evaluation chart and 3D model of hubless wheel

The next step is the assessment of values and hence the actual evaluation. The following evaluation method is in accordance with the standard VDI 2221 [4]. These values derive from weighting factors calculated in objectives tree shown in Figure 4. and afterwards each variant is given a mark from 1 to 5 for every criterion, and are thus more or less subjective [4]. When the sub-values for every variant have been determined, the overall value must now be calculated according to (2), (3):

\[ OV_j = \sum_{i=1}^{n} v_{ij} \]  

(2)

\[ OWV_j = \sum_{i=1}^{n} w_i \cdot v_{ij} = \sum_{i=1}^{n} w v_{ij} \]  

(3)

If the absolute rating of a variant has to be established, then the overall value must be referred to an imaginary ideal value which results from the maximum possible value as follows (4), (5):

\[ R_j = \frac{OV_j}{v_{max} \cdot n} = \frac{\sum_{i=1}^{n} v_{ij}}{v_{max} \cdot n} \]  

(4)

\[ WR_j = \frac{OWV_j}{v_{max} \cdot \sum w_i} = \frac{\sum_{i=1}^{n} w_i \cdot v_{ij}}{v_{max} \cdot \sum w_i} \]  

(5)

Evaluation results for three variants of hubless wheel design are given in Figure 6.

| Number of criteria | Designation of criteria | Level | $\beta_i$ | Content of criteria | Variant 1 | Variant 2 | Variant 3 |
|--------------------|-------------------------|------|--------|-------------------|--------|--------|--------|
|                    |                         |      |        |                   | $v_1$  | $w_{v1}$ | $v_2$  | $w_{v2}$ | $v_3$  | $w_{v3}$ |
| 1                  | $C_{111}$               | 4    | 0.009  | The transmission of power and motion | 4.00   | 0.396  | 4.00   | 0.396  | 5.00   | 0.405  |
| 2                  | $C_{112}$               | 4    | 0.0504 | The use of standard parts          | 2.00   | 0.101  | 4.00   | 0.202  | 4.00   | 0.202  |
| 3                  | $C_{113}$               | 4    | 0.0306 | Dimensional features              | 4.00   | 0.122  | 3.00   | 0.092  | 5.00   | 0.133  |
| 4                  | $C_{121}$               | 4    | 0.0316 | Reliable braking system           | 4.00   | 0.206  | 5.00   | 0.258  | 5.00   | 0.258  |
| 5                  | $C_{122}$               | 4    | 0.0684 | Accepting radial and axial forces | 5.00   | 0.342  | 4.00   | 0.274  | 5.00   | 0.342  |
| 6                  | $C_{131}$               | 4    | 0.025  | Low weight in state without load | 2.00   | 0.050  | 2.00   | 0.050  | 4.00   | 0.100  |
| 7                  | $C_{132}$               | 4    | 0.035  | Stability                         | 4.00   | 0.140  | 3.00   | 0.105  | 4.00   | 0.140  |
| 8                  | $C_{133}$               | 4    | 0.04   | Bearing power (motorcycle + rider)| 4.00   | 0.160  | 3.00   | 0.120  | 4.00   | 0.150  |
| 9                  | $C_{1210}$              | 3    | 0.0875 | Proper selection of materials     | 5.00   | 0.458  | 4.00   | 0.350  | 4.00   | 0.350  |
| 10                 | $C_{1220}$              | 3    | 0.07   | Proper lubrication                | 5.00   | 0.350  | 4.00   | 0.280  | 4.00   | 0.280  |
| 11                 | $C_{1230}$              | 3    | 0.0923 | Easy maintenance                  | 5.00   | 0.465  | 3.00   | 0.278  | 4.00   | 0.370  |
| 12                 | $C_{1211}$              | 3    | 0.21   | Assembly design that follows the contour of the tire | 4.00 | 0.840 | 4.00 | 0.840 | 5.00 | 1.050 |
| 13                 | $C_{1212}$              | 3    | 0.14   | Working safety                    | 3.00   | 0.420  | 4.00   | 0.560  | 5.00   | 0.700  |

\[ \sum = 1 \]

| The overall value | \( OV_j \) | \( OWV_j \) | \( OWV_j \) | \( OWV_j \) |
|-------------------|--------|--------|--------|--------|
| 51.00             | 4.03   | 47.00  | 3.80   | 58.00  | 4.60   |

| The overall value regarding real solutions | \( R_j \) | \( WR_j \) | \( WR_j \) | \( WR_j \) |
|-------------------------------------------|--------|--------|--------|--------|
| 0.78                                       | 0.81   | 0.72   | 0.67   | 0.89   | 0.92   |

Figure 6. Evaluation chart.
The data from Figure 6 shows that variant 3 is selected as an optimal solution which will be shown in following figures. Conceptual 3D design of the chosen variant is created in software Solidworks. In terms of industrial design, special attention was paid to the aesthetic appearance and ergonomic properties of the wheel. The final product emerged from engineer’s requirements and wishes that had been confirmed as the optimal ones (Figure 7). The main parts of the hubless wheel assembly:

- Spacer washer
- Deep groove ball bearing 6001-2Z
- Roller bushing
- Special allen screw M12x40 mm
- Inner rim
- Outer rim R26
- Tire 210/50 R26
- Plastic protections

All components of the hubless wheel are shown in Exploded View in Figure 8. The tire is mounted on the outer rim, and on the left side, there are faying surfaces for the sprocket that is fastened to the outer rim by screws. Outer and inner rim is at an angle to ensure radial and axial forces have been taken over.

![Figure 7. Hubless wheel assembly.](image1)

![Figure 8. Exploded view of hubless wheel.](image2)

The inner rim is the static part of the wheel on which bearings with screws are assembled. Screw assemblies are the most important part through which the outer rim rotation is performed. There are 12 allen screws on each side with associated ball bearings, roller bushings and spacer washers. Each allen screw which has a faying surface for two ball bearings of dimensions 12x28x8 mm on which roller bushing is fitted. SKF Single row deep groove ball bearing with two metal shields 12mm inside x 28mm outside x 8mm width, also known as 6001-2Z. Spacer washer is built-in between the screw assembly and inner rim. These parts are more precisely shown in Figures 9 and Figure 10. Roller bushing made of UHMWPE (ultra high molecular weight polyethylene) with the self-lubricating feature is attached on ball bearings and through them, the motion of the outer rim is achieved. Screw assemblies with bearings

![Figure 9. View of inner rim with the corresponding parts.](image3)
are sealed with plastic protections due to the entry of dirt and water. Protections can be made of transparent plastic in order to always be able of seeing the status within the drive assembly. Working principle is quite simple - the outer rim rotates on roller bushings creating motion that is transferred to the road.

5. Conclusion
By searching and analysing existing solutions from the hubless wheel history, we have created a new conceptual solution that would certainly have an impact on product price reductions and enable wider wheel usage. The problem of Sbarro's wheel was the bearing of non-standard dimensions and it's high production cost which we standardized by our conceptual solution with standard bearings 6001-2Z. The hubless wheel has several advantages. First, better accuracy in steering due to the use of the new front and rear wheel axles, with their large diameter bearings providing a high degree of resistance during tilt, and with the layout of the ball joints reducing the angle allowance. Secondly, lower centre of gravity improves driving comfort and adherence. Thirdly, decreased weight – obviously, without spokes and central solid hub, weight has to decrease. Finally, better braking leverage. Some of the disadvantages are difficult manufacturing, higher exposure to the environment and thus higher chances of failure or wear out, difficult assembly and high costs of production. The numerical analysis of this hubless wheel, both statical and dynamical, will be presented in our following articles after thorough future research. We will consider the bearing as one of the main parts of the wheel and perform control of bearing life and durability. Finally, if necessary, optimizing the wheel design can be done to get the ultimate production product.

References
[1] Sahu M, Shaikh N, Jadhao S and Yadav Y 2017 A Review of One Wheel Motorbike, International Research Journal of Engineering and Technology 4(3) 1141-1147
[2] Deliu G and Deliu M 2009 Monowheel Dynamics, International Conference on Economic Engineering and Manufacturing Systems, Brasov, Romania, November 26-27, pp. 245-248
[3] Sbarro F, Another Vision of Car 2000, http://sbarro.phcalvet.fr/ (accessed on January 2018)
[4] Pahl G, Beitz W, Feldhusen J and Grote K-H 2007 Engineering Design – A Systematic Approach, Springer-Verlag London
[5] Ulrich K T and Eppinger S D 2012 Product Design and Development, McGraw Hill
[6] Martinelli P, Williams A, Larive O and Coibion N 2015 Hubless Self-Balancing Human Transporter, United States Patent and Trademark Office US 9,010,474 B2
[7] Song B-W, Wang Y-J and Tian W-L 2015 Open Water Performance Comparison Between Hub-Type and Hubless Rim Driven Thrusters Based on CFD Method, Ocean Engineering 103 55-63
[8] Yamada M, Nakao M, Hada Y and Sawasaki N 2017 Development and Field Test of Novel Two-Wheeled UAV for Bridge Inspections, International Conference on Unmanned Aircraft Systems ICUAS, Miami, USA, June 13-16, pp. 1014-1021
[9] Olsson C 2017 Hubless Wheel Motor, United States Patent and Trademark Office US 2017/0063196 A1

Figure 10. Magnification view of allen screw, roller bushing, bearings and spacer washer.