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Application of topological optimization methods in wheelchair design

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Summary. The work was carried out to topological optimize the supporting elements of an electric wheelchair construction, as it is the model most frequently used by the disabled and people unable to move on their own. The form of frame wheel chair, that meets the configured criteria to reach the assumed value of the target function has created. The reduction of weight in the new design, the reduction of stress level and than threefold improvement the safety factor have been achieved. The presented method is very promising and should be supplemented with tools supporting the optimal selection of regular shapes of structural elements replacing the generated shapes in the future.

Key words: topological optimization, electrical wheelchair, computer aided design, finite elements method, stress, safety factor

INTRODUCTION

Nowadays, one can find a great variety of construction solutions for electric wheelchairs. An electric drive has many advantages and is frequently used in wheelchairs, although its disadvantage is the necessity to install heavy batteries in the construction of the machine. This, however allows to diversify solutions for the constructions of wheelchairs with numerous auxiliary functions. Due to usage of mobile batteries, an electric wheelchair is a relatively heavy machine, which significantly affects its movement range. There is a documented need to reduce the weight of a cart, which results not only from its operating conditions, but also from the health and ergonomics of patients. The smaller the weight, the easier it is to handle and move the wheelchair [2, 7].

WHEELCHAIRS WITH AN ELECTRIC DRIVE

There are numerous design solutions for wheelchairs, depending on their various applications. These include [8, 11]:

- wheeled carts (tricycles),
- carts with crawler system,
- carts with a multi-wheel assembly[16],
- stair-climbers,
- carts with walking mechanism [4,18],
- carts for special applications [17],
- etc.

The work was carried out to optimize the supporting elements of an electric wheelchair construction, as it is the model most frequently used by the disabled and people unable to move on their own.

Fig. 1. 3D model of electric wheelchair (www.grabcad.com)

The key supporting element of the cart is an aluminum frame to which other operating components are attached. Inside the frame there are batteries and motors from which the drive is transferred to the front wheels. A seat with handrails on which the controls are placed is attached to the top of the frame.

The supporting frame is made of square tubes with a cross section dimension of 20x20x2mm, a base plate made of 20mm thick sheet and two side panels also made of 20mm thick sheet with a hole for a shaft and a bearing.

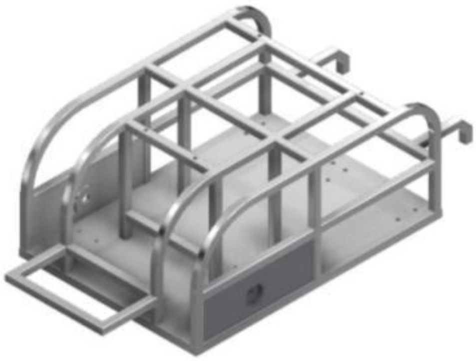


Fig 2. Digital model of an exemplary wheelchair frame

The work space has been prepared to allow for an optimal shape in space that does not exceed the overall dimensions of the base frame [12]. Therefore, the space within the latticed elements has been completely filled with material.

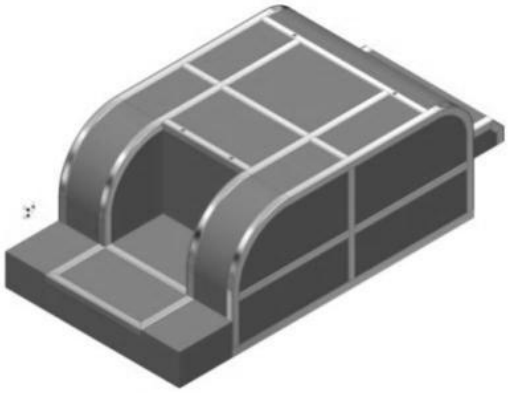


Fig. 3 Design space

The frame has been modified in relation to the one used in the actual construction. This was dictated by the need to prepare a model that could be used in topological optimization and, at the same time, provide space for the assembly of its equipment and all necessary parts. The part of space (floor), which is intended for installation of the equipment components, has been excluded during the search.

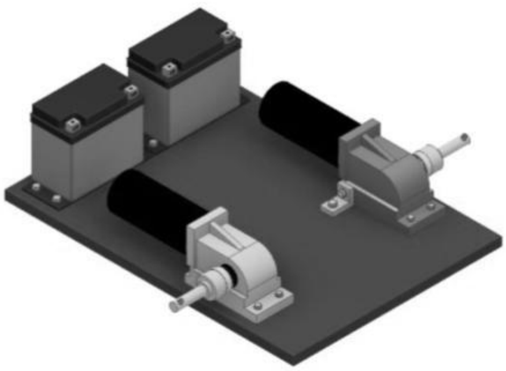


Fig. 4. Inner accessories of a wheelchair mounted on the base plate

The objects which, due to the specifics of topological optimization and the assurance of proper placement in the design space form the inner accessories of a wheelchair, have been converted together with the base plate into a unitary solid. Thanks to this, it was possible to perform the material removal operation by performing the logic operation of the difference between two solids.

Since the base plate plays an important part in the optimization, the design space was replenished with the base material. The model prepared so already contains only a volume of material that can be freely used in search of an optimum shape. The final geometry of the work space in the style of a transparent object with visible edges is presented in the figure below [19].

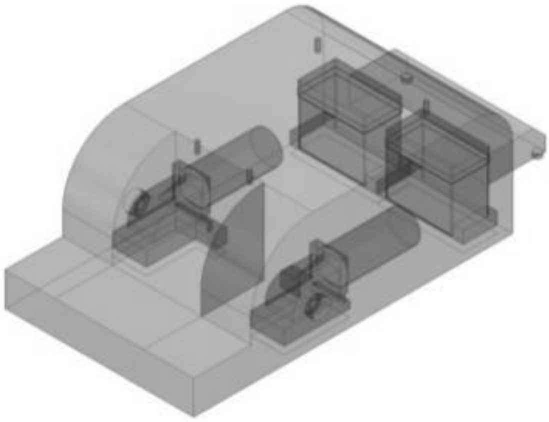
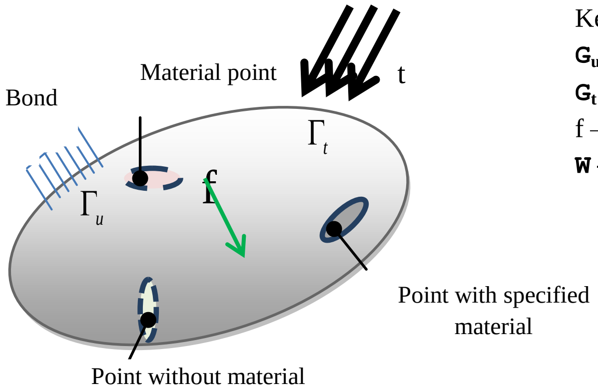


Fig. 5. Final geometry of work space for use in optimization

TOPOLOGICAL OPTIMIZATION

The topology optimization gives an answer to the question of how to arrange a material intended to create a given structure in a certain space so that the shape of the structure was optimal under given boundary conditions and for a given load. The optimization process involves searching for maximum or minimum value of a function or functional of a target which satisfy a certain number of constraining conditions [3,14].

What should be considered is a mechanical element as an object of an space of Ωmat that belongs to a design space with a greater range of Ω. The design space Ω is chosen to allow for specifying the loads and boundary conditions and creating at the same time the base area [1].



Key:
G_u – bonds,
G_t – outer loads,
f – inner forces,
W – material area.

Fig. 6. Generalized problem of shape design by finding the optimum distribution of material in a two dimensional space [4]

Searching for the construction topology should focus on finding the optimal arrangement of a given isotropic material in space, that is to say, which points of this space should be occupied by the material and which not. By limiting the spatial scope to the design space Ω, the optimal subspace Ωmat consisting of points occupied by the material should be found.

The problem of the topological optimization task for minimization can be written as follows:

$$\min_{\Omega} f(\eta),$$

with restrictions:

$$\underline{g_j} < g_j(\eta) \le \overline{g_j}, \quad j = [1,2,\ldots,M],$$

where:
$h=[h_1, h_2,\ldots,h_N]$ – is a vector of decision-making variables (pseudo-density of finite elements),
g_j – jest j-tym restriction (state parameter),
$\underline{g_j}$, $\overline{g_j}$ - upper and lower values of restrictions,
V – weight of structure,
M – number of restricting conditions.

According to the above, an optimization procedure was performed, the end of which occurs when the structure reaches the assumed mass or when value of the state parameter g_j is exceeded. The following figure shows the effect of applying the topological optimization procedure.

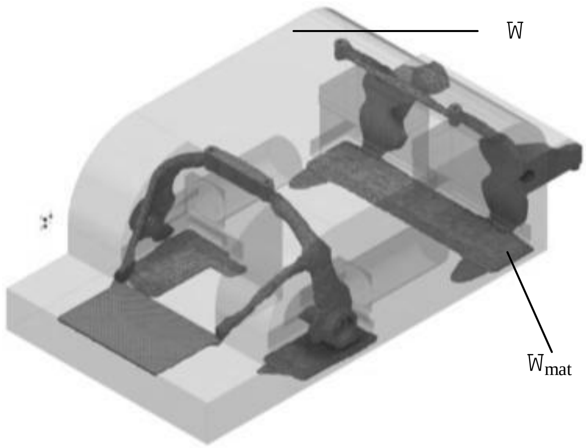


Fig. 7. Example of a applying the topological optimization

THE TOPOLOGICAL OPTIMIZATION OF A WHEELCHAIR FRAME

A ready-made model was downloaded from the cloud-based free online social portal (www.grabcad.com) which allows users to share their CAD modeling work. This model has been fully made available by Marcin Wojtowicz.

The object of the model that was used to solve the optimization task was the aluminum supporting frame. The position of this frame in the model is shown in Figure 9.

Fig. 8. Digital model of a wheelchair with frame

The main load for the frame comes from a disabled person weighing up to 200kg. However, it does not directly affect the analyzed frame as it is carried by the chair and its support structure, which are both attached to the frame by a bolted joint.

To determine the resultant forces and moments, a simulation-based analysis which implemented the finite element method of a part of a wheelchair which is located directly above the frame has been carried out. The model of this part, the loads applied to it and the bonds are shown in Figure 9.

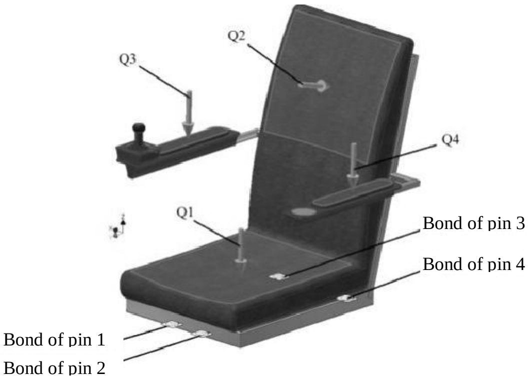


Fig. 9. Scheme of loads for a chair mounted on a wheelchair frame

In addition, the loads affecting directly the frame have been taken into account:
- load due to battery mass (2x300N),
- load due to mass of electric drives (2x170N),
- gravity force.

The model includes also material features and configurations generated by the CAD bonds within the contacts.

The next step was to set up a generator's shape that enables to specify the optimization type, the criteria describing the limits and the resolution of the grid. Then the maximization of the rigidity was specified in the system. Accordingly, the shape generator was set to provide the maximum rigidity of the part with using the specified amount of material.

In addition, the system needed to define the criteria for the sought mass of the optimized element, the minimum element size and the grid resolution. As a result, a grid with 1 308 692 elements and 1 842 711 nodes was generated [20].

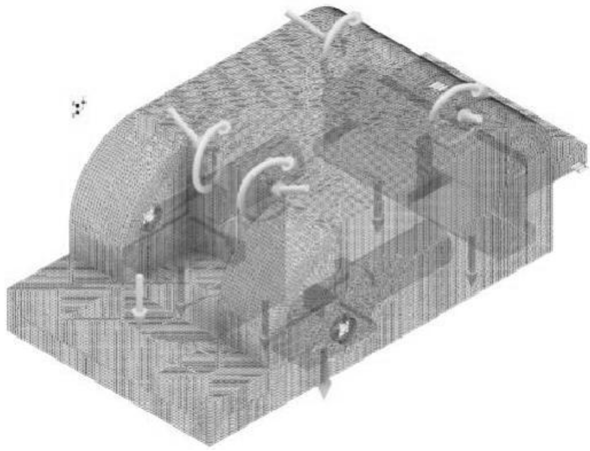


Fig. 10. View of the workspace grid

The shape generator after multiple iterations has created a form that meets the configured criteria to reach the assumed value of the target function.

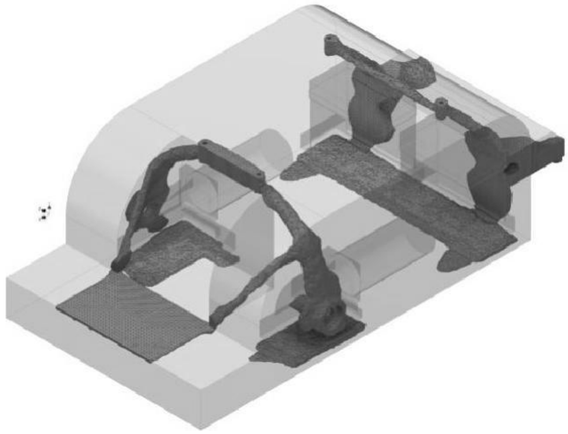


Fig. 11. Results obtained in the shape search attempt (isometric view).

On the basis of the digital object obtained through simulation, a formal model was prepared, consisting of regular shapes available in the 3D CAD model. The modeling process was conducted in such a way, that the theoretical solid was as closely tied to the actual shape as possible.

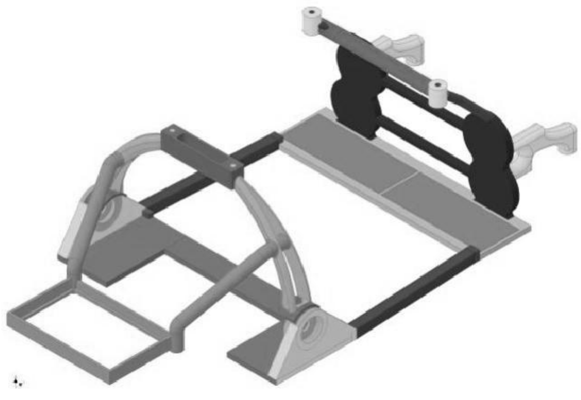


Fig. 12. Geometry of the new frame model obtained in the topological optimization process

VERIFICATION OF OBTAINED CALCULATIONS

MES calculations of existing and newly designed frames were conducted. The purpose of the planned calculations was to compare the structure in terms of the volume of transferred stresses and the rigidity of the structure. The basic comparison criterion was the weight of the structure since, according to the initial assumption, the aim was to reduce the weight of a wheelchair frame, which directly passes on a reduction in weight of the whole structure while retaining its rigidity and strength. The boundary conditions for both forms of frames were determined as shown in the figure below.

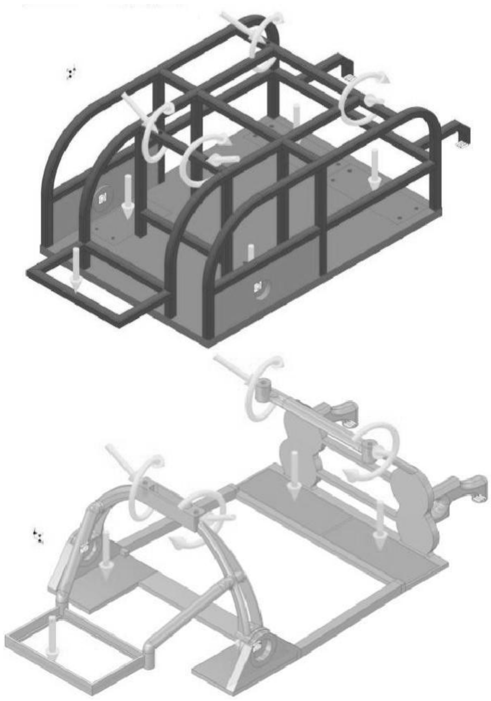


Fig.13. Model of boundary conditions for an old frame (existing construction) and for a new frame

In the process of discretization of the analysis area, an identical configuration of the grid generator was set for both cases of the digital model of the structure.

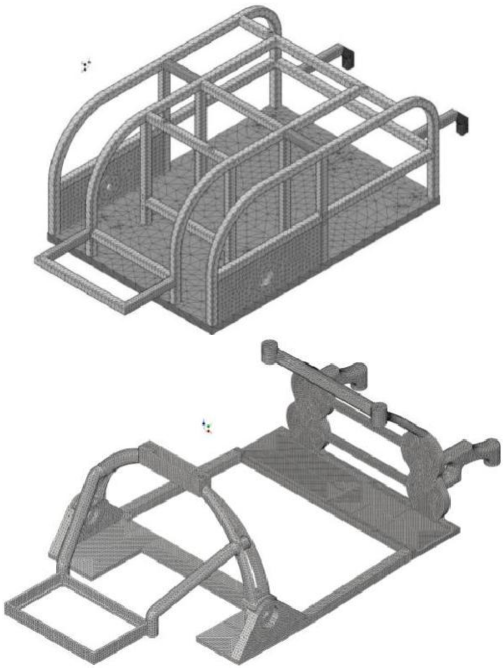


Fig. 14. Discretization of digital model analysis area

Continuing, the stress, deformation and digital map of the safety factor were calculated then. Figure 16 shows the stress distributions for both digital models of wheelchair frame. Table 1 compares the results of the calculations for maximum stress, deformation and minimum safety factor.

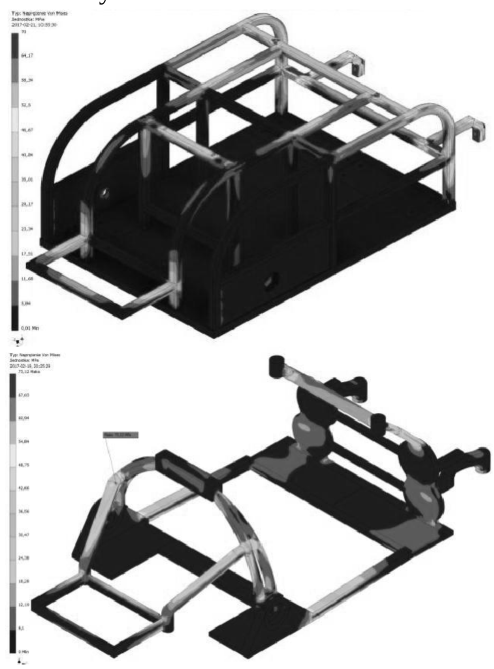


Fig. 15. Stress distribution in structural models

Table 1. Comparison of frames simulation results

Calculated value	Basic model of frame	Model of frame after optimization
Weight	24,66 kg	8,92 kg
Maximum stress reduced (Huber's hypothesis)	233,40 MPa	73,12 MPa
Maximum displacement	2,50 mm	5,10 mm
Minimum safety factor	1,18	3,84

Comparing the designs of both frames has led to the following findings: the reduction of weight in the new design by 15.74 kg (64% of original weight), the reduction of stress level in the new design by 160 MPa, more than threefold improvement the safety factor. Due to the high value of the minimum safety factor (3.84), it is possible to implement design amendments involving the reduction of cross sections of a new wheelchair frame. Moreover, with the required minimum safety factor, the weight of the newly designed frame can be also effectively reduced.

CONCLUSION

The topology optimization is an effective design tool . After the wheelchair optimization, the weight of the support frame has been reduced with a significant reduction of stress in the concentration zone. The new construction provides a more even distribution of stresses, which has a positive effect on the duration of using the structure [5,6,9].

The suggested method requires high computing power of the computer system, which in the case of more complex and elaborate constructions, determines the application of the computing cluster [15].

As a result of using the topological optimization, the randomness from the modeling process, where the designer constructing the shape of an object is exclusively devoted to his own experience and intuition - deficient features, especially for beginner engineers, has been eliminated.

The presented method is very promising and should be supplemented with tools supporting the optimal selection of regular shapes of structural elements replacing the generated shapes in the future [10, 13].

REFERENCES

1. **Bołbotowski K, Knauff M., Sokół T, 2013**: Zastosowanie optymalizacji topologicznej w projektowaniu konstrukcji żelbetowych z wykorzystaniem modeli "Strut and Tie", Budownictwo i Architektura 12(1) (2013) 91-98.
2. **Branowski B.,** 1998: Wprowadzenie do projektowania, PWN.
3. **Bendsøe M. P., Sigmund O., 2003:** Topology Optimization – Theory, Methods and Applications. Springer Verlag.
4. **Britto W., Bezerra M. J., 2005**: Mechatronic design of a chair for disabled with locomotion by legs ABCM Symposium Series in Mechatronics - Vol. 5.
5. **Christensen J., Bastien C., Blundel M. V., Grimes O., Appella A., Bareham G., O'Sullivan K., 2012:** Generation of Optimised Hybrid Electric Vehicle Body in White Architecture from a Styling Envelope Global Journal of researches in engineering Vol.12 Iss.1 V.1.0.
6. **Dede L., Borden M. J., Hughes T. J. R., 2012:** Isogeometric Analysis for Topology Optimization with a Phase Field Model, Archives of Computational Methods in Engineering. 19(3): 427–465.
7. **Dietrych J., 1978:** System i konstrukcja, WNT.
8. **Dobrzyński G., 2012:** Synteza własności mechatronicznego wózka inwalidzkiego jako elementu systemu transportu osób niepełnosprawnych rozprawa doktorska Politechnika Warszawska Wydział Transportu, Warszawa.
9. **Eschenauer H. A., Olhoff N., 2001:** Topology Optimization of Continuum Structures, Journal of Applied Mechanics Reviews. 54(4): 372.
10. **Guest J. K., Prevost J. H., Belytschko T., 2004:** Achieving Minimum Length Scale in Topology Optimization Using Nodal Design Variables and Projection Function, International Journal for Numerical Methods in Engineering. 61(2): 238–254.
11. **Ito, T., 2009:** Simulation-Based Study Using a Stair Climbing Wheelchair, Modelling & Simulation AMS '09. Third Asia International Conference 537-542, 25-29.
12. **Jaskulski A., 2009:** Autodesk Inventor 2009PL/2009+ metodyka projektowania, PWN.
13. **Kirichenko I, Morneva M., Kashura A., Popov S., 2015:** Technological standardization, EKA Komisji Motoryzacji i Energetyki Rolnictwa XV_1/2015, Commission of Motorization and Power Industry in Agriculture, 29 – 35.
14. **Kutyłowski R., 2004:** Optymalizacja topologii kontinuum materialnego. Oficyna Wydawnicza Politechniki Wrocławskiej. Wrocław.
15. **Mrzygłód M., Michalik M., 2008:** Optymalizacja topologiczna z ograniczeniami naprężeniowymi konstrukcji pojazdu, PAK vol. 54nr7/2008, 429 – 432
16. **Quaglia, G.; Franco, W.; Nisi, M., 2015:** Evolution of Wheelchair.q, a Stair-climbing Wheelchair. In: The 14th **IFToMM** World Congress, Taipei, Taiwan.
17. **Varga J., Semjon J, 2015:** Proposal of Modular Robotic Arm from DSM Modules American Journal of Mechanical Engineering, vol.3, no.6: 281-284.

18. **Wellman P., Krovi V, Kumar V., Harwin W., 1995**: Design of a Wheelchair with Legs for People with Motor Disabilities IEEE Transactions On Rehabilitation Engineering, Vol. 3, No. 4.
19. **Deineka I, Riabchykov O., 2013:** Ratonal design modeling methods of complex surface workpiece creation, TEKA Komisji Motoryzacji i Energetyki Rolnictwa XIII_4/2013, Commission of Motorization and Power Industry in Agriculture, 59-68.
20. **Zagrajek. T., Krzesiński G., Marek P. 2006:** Metoda elementów skończonych w mechanice konstrukcji. Ćwiczenia z zastosowaniem systemu ANSYS, OWPW.

ZASTOSOWANIE METOD OPTYMALIZACJI TOPOLOGICZNEJ W PROJEKTOWANIU WÓZKA INWALIDZKIEGO

Streszczenie. W pracy dokonano optymalizacji topologicznej elementów nośnych konstrukcji kołowego wózka elektrycznego, modelu najczęściej wykorzystywanego przez inwalidów i osoby nie mogące poruszać o własnych siłach. Utworzono postać ramy wózka jezdnego spełniającą zdefiniowane kryteria, osiągając założoną wartość funkcji celu. Osiągnięto redukcję masy części w nowym projekcie zmniejszono wartość naprężeń w nowym projekcie oraz poprawiono wartość współczynnika bezpieczeństwa. Przedstawiona metoda jest bardzo perspektywiczna i w przyszłości powinna zostać uzupełniona o narzędzia wspomagające optymalny dobór regularnych kształtu elementów konstrukcyjnych zastępujących wygenerowane kształty.

Słowa kluczowe: optymalizacja topologiczna, wózek elektryczny, komputerowo wspomagane projektowanie, metoda elementów skończonych, naprężenia, współczynnik bezpieczeństwa.