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THE CAD TOOL IN MANAGING THE DESIGN PROCESS OF MACHINERY AND EQUIPMENT AS A ROAD TO INDUSTRY 4.0

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Purpose: The work aims to emphasize the importance of using the CAD tool in managing the design process of a selected mechanical device. The research includes comparing selected parameters from the use of innovative materials with traditional construction materials, such as steel, aluminium, or plastics.
Design/methodology/approach: As part of the research, a 3D model of the body of the selected device was designed and an analysis was carried out tightened by this element from commonly used materials and innovative construction material, which is carbon fibre. The use of the CAD tool allowed us to identify the benefits and restrictions resulting from the implementation of innovative material at the stage before production. In addition, the impact of carbon fibre structure on the distribution of stress and its strength properties in various operating conditions was analyzed.
Findings: The purpose of the work was to examine key parameters for the operation of the selected device without incurring real production costs. The obtained results gave a basis for analysis in the field of introducing and effective use of carbon fibre as a material used to build a given device.
Research limitations/implications: The main obstacle to the wider use of carbon fibre is its high price. This is related to both production costs and limited accessibility on the market. The price of carbon fibre elements significantly exceeds the cost of components, steel or aluminium. It has been shown how a tool such as CAD can lead to a reduction in production costs already at the design stage.
Practical implications: Research results are the first scientific approach indicating the possibility of using innovative materials in construction applications other than the automotive industry. By defining its efficiency and profitability. In addition, they confirm the need for further research on the processes of optimizing the cost of designing data of machinery and devices using a tool such as CAD in response to Industry 4.0 challenges.
Originality/value: The originality of the study lies in the innovative approach to the use of CAD software in managing the design process of individual parts of agricultural machines in order to reduce production costs.
Keywords: management of the design, analysis and research process, CAD tool, Industry 4.0.
Category of the paper: Scientific work.

1. Introduction

Promoting the idea of Industry 4.0 and the constant need to improve existing technological processes to increase the importance of management of the design process itself. One of the sectors of the economy that felt the effects of such changes is the garden equipment market. More and more often machines and devices are designed in such a way as to have their "digital twin" (Bołoz, 2020). For example, mushroom manufacturers implement ERP systems to improve the management of all company resources management, aimed at optimizing all processes of a given company. In particular, the accent is laid on the production module, implementing changes, they use min. The same components in several selected machines strive to minimize production costs.

In addition to organizational innovations, innovation in the material area is more and more often sought in this sector. One example is the use of carbon fibre. Considering that, as indicated by the observations of market reality, carbon fibre composites are widely used in industries such as motoring, aviation or sports industry, where the strength and reduction of mass are crucial (Kalinowski, 2024). However, despite its innovation, the potential of carbon fibre in the gardening industry remains relatively indefinite. At the same time, forgetting that the crucial for the management process of the cost aspect can be identified thanks to the use of tools such as CAD at the design stage.

The work aims to conduct simulation tests regarding the possibility of using carbon fibre as an innovative construction material in the construction of machinery and gardening equipment using the CAD tool already in the design process. The work focuses on showing the advantages of carbon fibre composite in the construction of gardening machines and analysis of the example of a specific element of the device (Bołoz, 2020). The use of this tool already at the design stage creates grounds for assessing its properties compared to traditional materials, taking into account the challenges related to the current management of the design process. The presented considerations are designed to answer the question of whether carbon fibre can be an attractive alternative to traditional materials and what benefits and limitations result from its use in gardening devices. The results presented in the work can contribute to a better understanding of the essence of the use of tools such as CAD in managing the design process of selected machines and devices.

2. Literature review

As indicated by the literature on the design process management should also take into account, apart from economic aspects, technological aspects, including material aspects.

Carbon composites, which are formed by sinking carbon fibres in a polymer warp, are a material with exceptional mechanical properties, which means that they have great potential, e.g. in the construction of modern mowers. They are characterized by very low mass and very high mechanical strength (Drobny, Hetmańczyk, 2012). Corrosion resistance is another advantage that makes carbon composites perfectly cope in difficult garden conditions, where devices are exposed to moisture, rain or chemicals. The density of the carbon composite is on average 1750 kg/m³, which makes it a material much lighter than steel (7500–7900 kg/m³) and aluminium (2700 kg/m³) (Long et al., 2021). Young Module Carbon Fiber has a power of 253 GPa, while the composite reinforced with carbon fibre has 145 GPa, which gives it an advantage over traditional materials in the field of stiffness and resistance to deformation (Gębarowska, 2025). The carbon composite is on average six times more durable than steel, while at the same time reduces weight four times. The coal coefficient of coal composites is about 0.1-0.2, which means that they show minimal lateral deformation under load (Fejdyś, Łandwijt, 2010). In addition, carbon composites, although very resistant to stretching, are less resistant to point damage, such as impacts that may occur during intensive work in the garden (Kubiński, 2012). Despite these restrictions, in the opinion of the authors, carbon composites can be an interesting alternative to traditional materials such as steel or aluminium, especially in technologically advanced gardening devices for demanding users (Klas, 2024). Therefore, from the strict process approach, it seems an important issue to learn all the advantages and disadvantages of this material at the design stage by starting the final production.

In short, carbon fiber parts are among the most technologically advanced elements in the high-tech industry aligned with the idea of Industry 4.0. Their production requires precision, advanced materials and modern processes. The fourth industrial revolution, also known as Industry 4.0, is essentially a digital thread from start to finish, from idea to production. No company fully grasps what Industry 4.0 is and how it works, but it is certain that it consists of many interconnected elements. Only then will the concept of Industry 4.0 be effective and practical in the workplace, and CAD software is an important part of this process. CAD software has all the advantages to meet the growing demand for intelligent design and digital transformation and to help engineers in the next stages of digital technology development and implementation in practice of such advanced materials as carbon fibers.

3. Material and methods

3.1. Research Program

The research part analyzed the possibilities of making a mower body pushed from the carbon fibre composite. Traditional materials such as steel, aluminium and plastics were compared, which can bring the benefits of carbon fibre. To assess the potential of this modern material in the construction of horticultural machinery, data was analyzed from entities dealing with the service of such devices, it was subjected to detailed analysis and the conclusions were formulated on the possibility of improving the structure by introducing carbon fibre composites.

The next stage of the research part was the use of the CAD Autodesk Inventor tool in the design process of the mower body model. The stress analysis module (MES - Finite Element) was used to examine the properties of materials currently used in the construction of gardening machinery and compare them with carbon fibre composite. The analysis allowed the assessment of the body's behaviour in the conditions of static forces, as well as dynamic, such as vibrations formed during engine operation. The obtained results allowed us to estimate the costs of producing elements from various materials and compare them for the profitability of implementation into serial production- without incurring unnecessary costs for creating pre-production models.

For the analysis, a part of the gardening machine was chosen, which is the mower body due to its key role in the functioning of gardening machines. The machine body is an element connecting all components of the device, which is why the selection of the right construction material in this case is crucial. The choice of this element for analysis was not accidental. Considering that one of the largest manufacturers of this category of machines is considering the use of 3D printed parts from carbon fiber to personalize its product in accordance with the idea of Industry 4.0.

3.2. Source data for the analysis of the research problem

From data from one of the Polish service companies specializing in the sale of garden parts and devices. It follows that one of the most common faults concerns the rupture of the mower housing (Fig. 1).

Figure 1. Damage to the mower body as a result of dynamic loads.

Source: own study.

According to data analysis, long-lasting vibrations, to which gardening devices are exposed, can cause local cracks, which over time transform into greater structural damage. The microcracks in the material tend to deepen, which ultimately leads to permanent damage.

One of the main causes of this phenomenon is insufficient fatigue strength of the material, which is particularly important for elements exposed to intensive dynamic loads.

3.3. Modeling and analysis of the MES element in Autodesk Inventor

The mower body itself was designed in Autodesk Inventor (Fig. 2) as a faithful mapping of the existing mower model. Before starting the design, a careful selection of the appropriate reference model was made, whose three-dimensional reproduction allows for precise analysis of the impact of the proper selection of material on the durability and strength of the structure. The purpose of this approach was to ensure reliable and real results during future strength simulations, which is crucial in the process of assessing the properties of materials and their applications in technical constructions without incurring unnecessary costs for creating pre-production models.

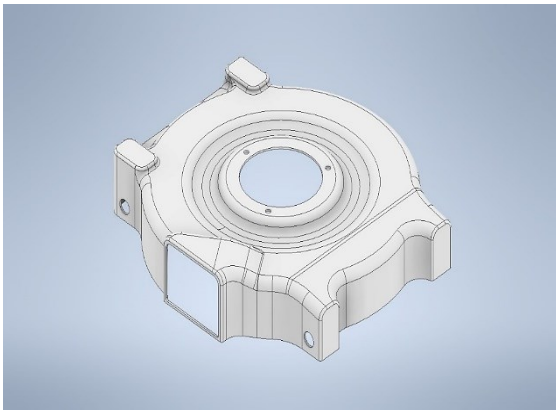

Figure 2. Model of a pushed mower body made in Autodesk Inventor - isometric view.

Source: own study.

The body of the body is based on a thorough reproduction of the geometry of the original structure, taking into account all the details, such as dimensions, shape, mounting holes and reinforcing ribs. It is important to emphasize that all analyses are performed in the design environment without incurring costs for field research on pre-production prototypes.

4. Results and discussion

4.1. Modeling and analysis of the MES element in Autodesk Inventor

The first step to creating a stress analysis for the pushed mower body structure is to determine the bonds. The designed body uses stationary bonds in places where the holes are found through which the wheel axles pass (Fig. 3). These bonds simulate stable body adhesion. In the analyzed model, the mower in the places of the holes is found for mounting wheels, which are still relative to the body.

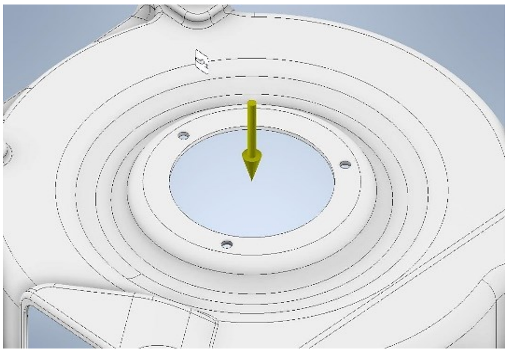

Figure 3. Model of a mower pushed with solid bonds.

Source: own study.

For comparison of building materials used for the construction of gardening machinery and equipment with a carbon composite, the stress analysis module available in the CAD tool in Autodesk Inventor was used.

It was assumed that the weight of the engine is 10 kg, which corresponds to 100 N (when accelerating the gravity acceleration value g = 9.81 m/s^2). To take into account the dynamic loads resulting from engine vibrations during operation, a 1.5 dynamic factor was adopted for static analysis, which increases the value of the inclusion force to 150 N. Such a procedure simulates additional overloads that may occur in the actual operating conditions of the device. The value of 220 mm on the Y axis in the remote force editing window means that the point where the remote force works is moved by 220 mm along the Y axis relative to the reference point in the model. The value of the 1.5 factor was used to estimate the additional dynamic load. In real operating conditions, the engine generates vibrations that increase the temporary load of the structure. Because the Autodesk Inventor program only analyzes static loads, the addition of a coefficient allows you to simulate such overloads. Gear ratio 1.5 means that the value. The load has been increased by 50% about the static load, i.e. to the principles used in the strength of the structure. The project uses optimal mesh settings shown in Fig. 4.

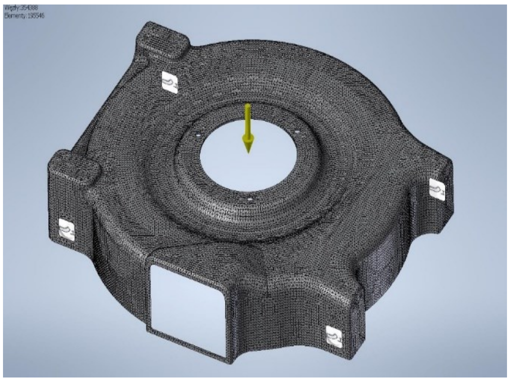

Figure 4. View of the component mesh on the pushed mower model.

Source: own study.

The last step before joining the simulation was the choice of material for the analyzed model. As part of the research, a stress analysis of the designed pushed mower body was carried out, using four different materials: steel, aluminium, plastic (ABS) and carbon fibre composite.

Due to the nature of the design, focusing on the endurance analysis of the body, the mechanical and strength properties of the material are of key importance. Thermal properties were omitted as no impact on the simulation.

4.2. Assessment of simulation results

Von Mises's stress is a value that allows you to predict when the plastic material begins to deform permanently. The von Mise’s stress value is calculated from the formula (Nikulin, 2016):

$$\sigma_{von\ Mise's} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]} \tag{1}$$

where: $\sigma_1, \sigma_2, \sigma_3$ – main stresses.

According to von Mise’s theory, plastic material begins to deform permanently at a point where the reduced stress reaches the value of the material stress limit. Most often, the boundary of plasticity is taken as a stress limit. The essence of this phenomenon was presented (Fig. 5).

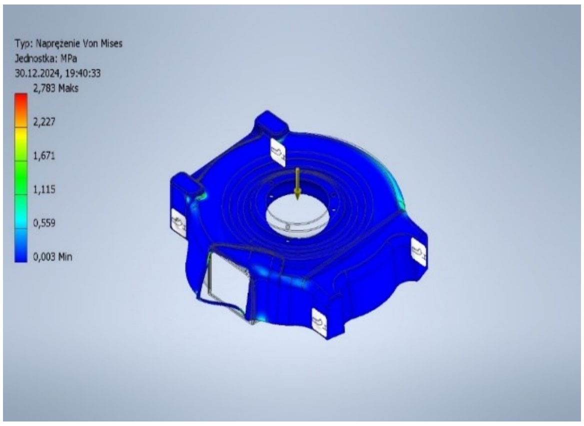

Figure 5. Distribution of von Mises stresses for a mower made of carbon fibre.

Source: own study.

According to the analysis von Mises's stress for all tested materials is in the range of 2.6-2.8 MPa. These values are much lower than the plasticity of each of the analyzed materials, which means that the mower body does not undergo permanent deformations under the pressure of the working engine, regardless of the material used. The similarity of the results is because von Mises's stress is largely dependent on the geometry of the structure. In this case, the mower body has been designed in such a way as to evenly distribute the loads and move them efficiently. Thanks to this, the stresses remain low for each of the materials, which confirms the properly selected structure. The lowest von Mises stress value (2.681 MPa) was achieved for ABS plastic. This material, despite the lowest elasticity module among the analyzed materials, is characterized by good tensile strength, which allows for effective load transfer static. At the same time, his ability to suppress vibrations can be beneficial in applications with vibrations, which in the case of a mower can have practical significance. The safety factor is a parameter determining the degree to which the permissible load or stress of the material must be exceeded to damage. The safety factor determines the pattern (Pokojski, et.al., 2022):

$$\delta = \frac{R_m}{K_r} \tag{2}$$

where:
δ – safety factor,
R_m – tensile strength (maximum stress),
K_r – permissible stress.

The role of the security factor is to ensure the reliability and safety of the structure by taking into account potential and unforeseen situations, such as design errors and the heterogeneity of materials. Executive inaccuracies or changes in working conditions. The value of the safety factor equal to 1 determines the moment when the actual stress reaches the permissible limit of the material. For this reason, this factor should be greater than 1. In this case, the structure has a reserve of strength, which ensures that the material will not be damaged even in the case of unforeseen loads. Figure 6 shows the safety distribution of the carbon fibre mower body.

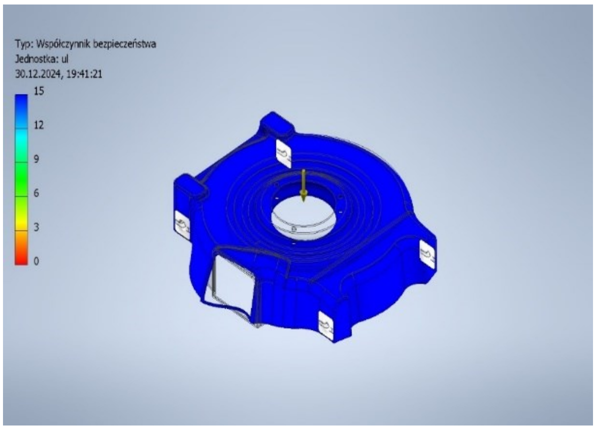

Figure 6. Distribution of the safety factor for the carbon fibre mower body.
Source: own study.

The value of the safety factor reaches the lowest value in the case of ABS plastic. The minimum value is 7.46. This means that in the most burdened design, the actual stress is only 1/7.46, i.e. about 13% of the maximum permissible material strength. The displacement of stress analysis describes the change in the location of each point of the object under the influence of loads. In the structure of the mower body, displacement is one of the key parameters that, visibly shows the differences between the analyzed materials.

The results of stress analysis indicate that the body made of steel, due to the high Young module, which is a measure of material stiffness, showed the least susceptibility to deformation caused by the pressure of the working engine. The displacement result equal to 0.008815 mm confirms the high stiffness of the material and its resistance to deformation under the influence of loads. In the case of aluminium, which has a smaller elastic module than steel, the displacement is 0.02656 mm, which is a result more than twice as high as in the case of steel. Finally, the body made of aluminium provides sufficient stiffness and ensures a good weight ratio to stiffness. The body made of ABS plastic is moved much more than bodies made of other materials. It is 0.8026, i.e. a value almost a hundred times higher than the displacement of steel. This result clearly shows that this material is susceptible to deformation and despite its low mass and attractive price, it is not able to match the materials construction such as steel or aluminium. Carbon fibre is characterized by a high Young module with a very low mass. Its displacement calculated by stress analysis is 0.01326, which is a slightly higher result than in the case of steel, which in this comparison was the best. Compared to other materials, the carbon fibre composite used in the structure of the mower body showed a displacement about twice as small as in the case of aluminium and about 60 times smaller than the plastic body (Fig. 7).

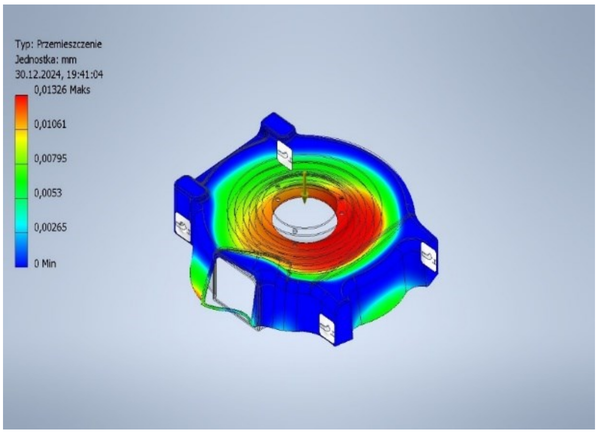

Figure 7. Distribution of displacement for a carbon mower.

Source: own study.

The high level of Young Module with the Carbon Fiber composite makes this material combine lightness with very good deformation resistance. This result confirms that carbon fibre is a great alternative to traditional materials. It is important to emphasize that all mentioned data was obtained at the design stage, which indicates a rational approach to the implementation of new material solutions.

5. Conclusion and discussion

In the modern competitive market, a strong need to implement the latest concepts and management methods is noticed. Innovations in the activities of enterprises should relate not only to the organization of production or management systems but also include ways of implementing individual modules, including the design module mode. In the era of the ongoing Industry 4.0 revolution, no one should have doubts that the culmination of the machine design process is visualization and optimization using specialized CAD software. As part of the last stage, a 3D element of the element is prepared, which can be used to produce a given component or part. At this stage of summaries, it should be remembered that the implementation of the project itself, for example, is a key, but still preliminary stage of production. Based on tests, it is possible to modify the element and optimize its parameters before starting the production cycle. Importantly, without unnecessary costs related to the construction of many prototypes. Observations of market reality indicate that carbon fibre composites have great potential as a modern construction material in the production of gardening machines and equipment. The analyses presented show that carbon fibre is characterized by an excellent ratio of mass to stiffness. This is especially important for devices that require manual service because the smaller mass greatly facilitates their use. In addition, carbon fibre, unlike steel and aluminium, is a corrosion-resistant material. ABS material, although also resistant to corrosion and the lightest of the analyzed materials, however, shows much less stiffness. This property makes this material more susceptible to deformation and cracks, which limits its use in constructions requiring durability and stability.

It is important to emphasize that the main obstacle to the wider use of carbon fibre is still its high price. In particular, in the segment of gardening machines, where this parameter plays a key role, this can be a significant limitation. The presented research can be a response to this postulate. In practice, CAD data ensures higher product quality at lower development costs and increased efficiency, which enables faster production and time to market. By using CAD data, engineers will spend less time designing products or parts due to the wide availability of knowledge, materials and suggestions. Thus, the cited analyses can be an important postulate supporting the key role of CAD tools in managing the design process of machinery and equipment as a path to Industry 4.0.

To sum up, the presented considerations certainly do not fully exhaust the essence of research issues. Further research on the subject should focus on answering the question of whether the CAD tool will allow the structure of the full process, and design processes and will promote examining the full potential of carbon fibres. In this sector of machines and devices, or will be only a tool verifying the possibilities of Implementation and replacement of current materials with these new ones with the corresponding requirements for Industry 4.0.

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