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Conceptual Design with Strength Analysis Based on the FOPS Test for a Tubular Cover Dedicated to the Kubota M135GX-IV Tractor

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An agricultural tractor equipped with appropriately rated guards can often replace specialized forestry machinery. Currently, few authorized dealers on the Polish market offer tractors adapted to harsh forest conditions, so this work involved designing a tubular guard for the Kubota M135GX-VI agricultural tractor. The aim of this work was to develop a conceptual design for a tubular guard, together with a strength analysis based on FOPS procedures, dedicated to the KUBOTA M135GX-IV agricultural tractor. To properly design the tubular guard, applicable standards and regulations regarding the construction of cabs and tubular guards for agricultural and forestry machinery were first analyzed. Subsequently, the available solutions were analyzed and two original concepts were developed. These concepts were evaluated based on the adopted criteria, selecting the variant with the highest score. Furthermore, the most advantageous variant was subjected to a strength analysis using the finite element method (FEM) in accordance with the FOPS procedure. The test results showed that all nodes included in the developed concept met the strength requirements.

Keywords: Forestry machinery, Tubular cover, FOPS, Strength analysis, FEM

1 Introduction

Considering the share of forests in the total area of the country, Poland is among the European leaders. Immediately after World War II, forest cover amounted to one-fifth of the country (20.8% in 1946), while currently it has increased by half and amounts to 29.6% (data from 2021) [1]. The simultaneous, intensive development of cities and communication routes is driving a growing demand for machines adapted to work under tree canopies, in forests, and woodlands. Manufacturers of agricultural tractor accessories, meeting market expectations, offer equipment that ensures operator safety and minimizes machine damage in the event of an accident. One example is a tubular guard, which guarantees safety and protects the operator from falling objects and is FOPS (Falling Objects Protective Structures) certified [2]. Agricultural tractors equipped with additional forestry equipment are increasingly used for forestry work, including harvesting, loading, and forwarding [3, 4, 5, 6]. Their versatility makes them suitable for small-scale forestry work, especially in private and fragmented forest areas [7]. The low investment cost of agricultural tractors makes them a popular choice for basic transport of forest products, especially in regions with limited financial resources [8, 9]. Currently, few companies on the Polish market offer tractors adapted for forestry work due to the restrictive standards defined by OECD codes [10] and Regulation (EU) No. 167/2013 of the European Parliament and of the Council specifying the regulations that must be met for a vehicle to participate in public transport and regarding the safety of agricultural and forestry tractors. The Organization for European Economic Co-operation (OECD, Paris, France) formulates testing procedures for individual machines or safety devices [10]. Falling Object Protective Structures (FOPS) are critical safety devices designed to protect construction machinery [11], material handling equipment, and forestry machinery [12, 13], as well as agricultural tractors adapted for forestry work. A subsequent study emphasized that a wheel loader always operates in a hazardous environment and a protective structure meeting FOPS requirements is a necessary condition to protect the safety of the operator working in the loader [14]. The standard test procedure for falling object protective structures (FOPS) was initially regulated by the PN EN 13627 standard [15], which was subsequently withdrawn and replaced by the PN EN ISO 3449 standard [19]. This standard requires full-scale destructive testing to ensure compliance, which includes an assessment of the protective structure's ability to absorb energy when heavy objects fall onto the operator's cab [16]. The procedure is designed to be rigorous and comprehensive, ensuring that the FOPS structure can effectively absorb energy and thus

protect operators from fatal injuries caused by falling objects, such as tree limbs [16, 17, 18]. The standard FOPS testing procedure includes a full-scale destructive test to verify its strength and effectiveness [19]. However, the FOPS destructive testing procedure is very expensive and inappropriate for custom-made or individually manufactured FOPS structures [17]. An alternative approach involves the use of numerical simulations and mathematical modeling to validate the design and performance of the FOPS structure [17]. Numerical simulations eliminate the need for expensive physical testing, making them ideal for custom FOPS structures [17, 20]. FEM simulations have shown good correlation with experimental results, confirming their effectiveness in FOPS design [16]. Another example was the use of the finite element method (FEM) to analyze the die geometry in the extrusion process and the elongation factors influencing energy consumption [21], or the analysis of the load on the supporting structure of the bus roof with gas tanks [22]. Furthermore, numerical methods including FEM allow for the optimization of design parameters, leading to more efficient and effective protective structures [17, 23]. To reduce the number of prototypes and associated costs, numerical simulations using finite element analysis (FEM) are used. These simulations help predict the performance of FOPS structures in various impact scenarios and refine the design prior to physical testing [16, 24, 25]. FOPS design focuses on energy absorption and dissipation. Some designs incorporate impact energy dissipation elements between the chassis and the protective structure to absorb most of the impact energy, thereby reducing cabin structure deformation [25]. One of the main challenges in FOPS design is estimating the load magnitude exerted by falling objects. This requires a thorough understanding of impact forces and energy levels, which can vary significantly depending on the structure and conditions [26, 27, 28]. For complex structures, probabilistic methods can also be used to account for model uncertainties, particularly in the connections within the structure [29]. Finite element analysis (FEM) is commonly used to simulate FOPS performance prior to physical testing. This method helps predict the behavior of the structure under various loading conditions, enabling design optimization and appropriate material selection [11, 16, 18]. By following these steps and considerations, the tubular guard of the KUBOTA M135GX-IV agricultural tractor can be effectively adapted to FOPS procedures, ensuring the safety and protection of operators from falling objects. The aim of this work was to develop a conceptual design of a tubular guard, along with a strength analysis based on FOPS procedures, for the KUBOTA M135GX-IV agricultural tractor. This tubular guard design will enable the tractor to operate in high-risk conditions, such as under tree canopies.

2 Materials and methods

The first step in developing the conceptual design was to identify mounting points for the proposed tubular guard. An additional challenge was to avoid interfering with the tractor's visibility and functionality (including the rear three-point linkage). Therefore, two alternative mounting points were identified, located near the rear axle (see Fig. 1a), as well as factory-made holes in the tractor's support frame for mounting a front loader (two points marked with a red circle, see Fig. 1b).
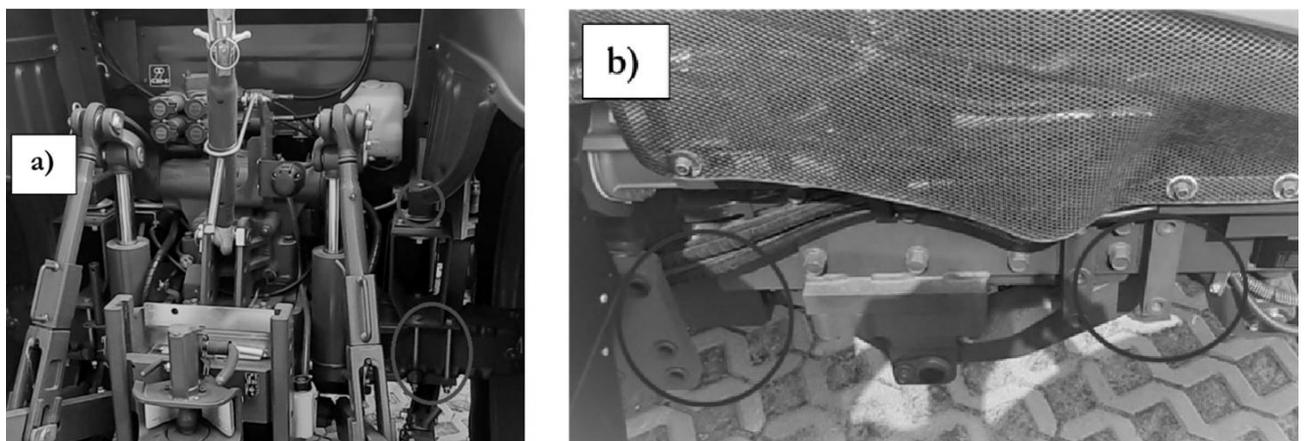

Fig. 1 *Mounting points of the conceptual design of the tubular frame on the KUBOTA M135GX-IV agricultural tractor (4 points marked with a red circle): a) two mounting points located at the rear axle, b) two points - factory-prepared holes in the supporting frame intended for mounting a front loader*

The second stage of conceptual design development was to propose and model two variants of the tubular hood concept dedicated to the KUBOTA M135GX-IV agricultural tractor.

Therefore, Variant 1 and Variant 2 were proposed, presented in Table 1. Variant 1 is constructed of thick-walled square profiles joined by welding. This variant is complemented by a sheet metal structure protecting the front of the tractor (mounted to the tractor frame) and chains to minimize the risk of branches or other objects entering the operator's cab. The presented tubular hood cover (Variant 1) also does not restrict the functionality of the vehicle's lights or access to the engine compartment required for daily maintenance. Variant 2 is modeled from thick-walled round tubes, also joined by welding. To comply with FOPS, variant 2 is supported in the same way as variant 1. The profiles connecting the mounting plate to the front cover (Table 1 -Variant 2-b) ensure easy dismantling.

Tab. 1 *Proposed variants of the tubular trailer concept for the KUBOTA M135GX-IV agricultural tractor: a) view of the entire structure, b) combined view of the front mounting system*

	Variant 1	Variant 2
a)		
b)		
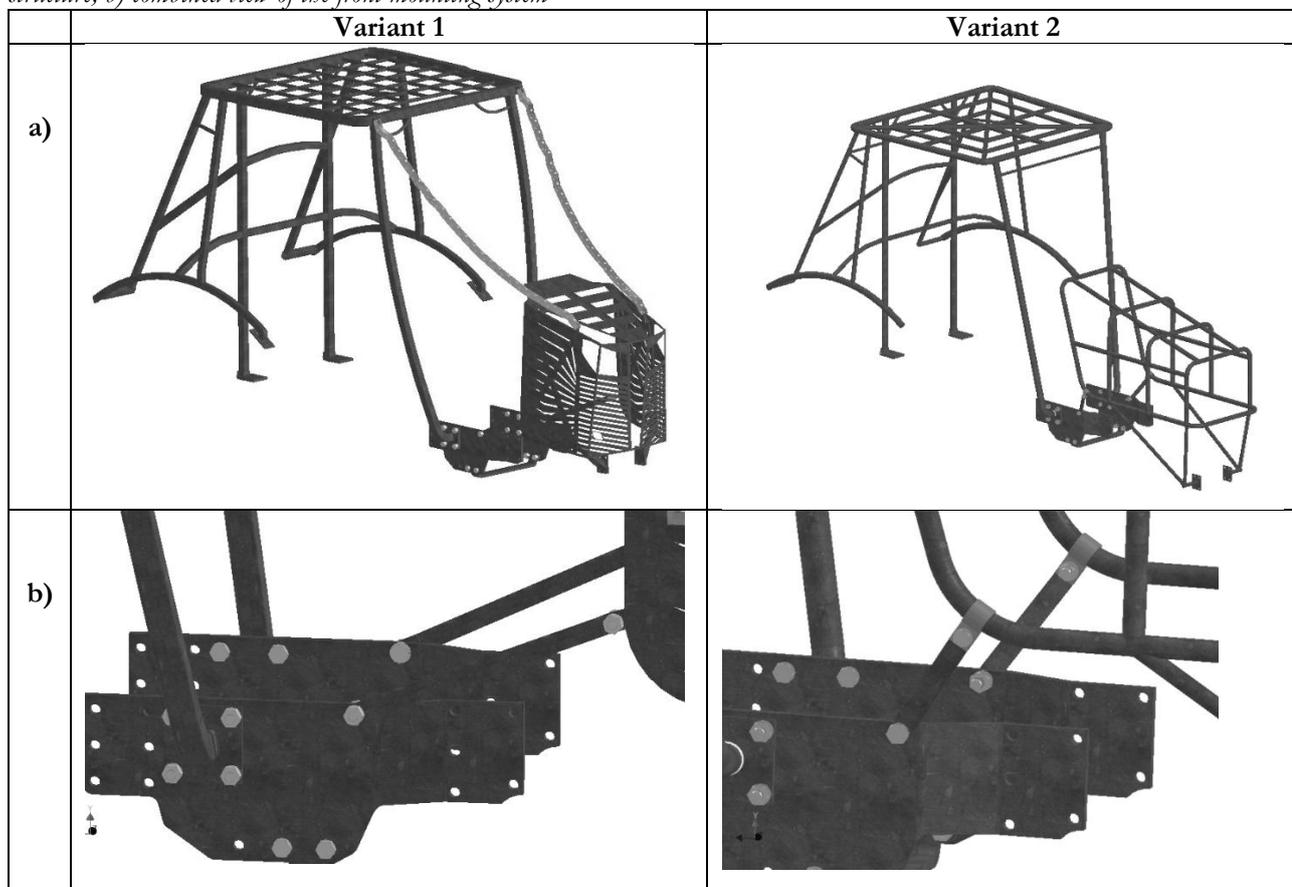
The two proposed tubular guard design variants were subjected to a point evaluation based on eight adopted criteria. The evaluated criteria included: meeting the main requirements, additional protection against damage, structural durability, limited tractor functionality, reduced maintenance, manufacturing costs, design innovation, and finally, aesthetics. On a three-point scale, with 3 being the highest, variant 1 received 19 points, while variant 2 received 15 points, partly because it did not adequately protect the engine compartment from falling tree limbs. Therefore, variant 1 was selected for further analysis. In this case, the upper section of the frame was designed with a truss made of 12 square profiles (25 x 25 mm) with a wall thickness of 3 mm.

All machine cabs or tubular guards equipped with FOPS-certified structures provide operator safety from falling objects. This standard is standard for construction machinery, forklifts, and other vehicles operating in potentially hazardous environments (e.g., agricultural tractors with front loaders, forestry machinery). The strength level of a given structure depends on the vehicle's weight and intended use. The FOPS procedure strictly defines the conditions that a structure must meet to pass the test. In the case of the tubular guard for the Kubota MGX 135-IV tractor, Level I was applied, which means it can withstand a freely falling spherical body weighing 45 ± 2 kg from a suitable height, generating 1365 J of energy upon impact. The dropped object, made of ductile iron or solid steel, has a diameter of 200-250 mm. A 45 kg spherical body was dropped onto the developed Variant 1 tubular casing from a height of 3.092 m, after rounding, we assume 3.1 m, as in the work of Romanal et al. [24, 25]. For the developed conceptual design -variant 1-, the most commonly used strength rules were applied, based on the hypothesis of the highest shear strain energy,

known as the Huber-Misses-Hencky hypothesis [30]. It was assumed that the tubular casing would be made of S235 steel (formerly St3S) to reduce the prototype manufacturing costs. Then, the first strength condition (1) was adopted:

$$k_{allow} = \frac{R_e}{x} \ [MPa], \qquad (1)$$

Where:

R_e…The yield strength of the material [235 MPa],

x…The arbitrary safety factor.

Based on the analysis of the scientific literature and the experience of the research team carrying out the calculations, the following values of the safety factor were assumed:

- $x = 1.65$ – for the construction material,

Hence after rounding:

- $k_{allow} = 142$ MPa,

The 3D CAD model of the pipe casing, its discretization, and the finite element analysis (FEM) for the FOPS procedure were performed in Inventor Professional 2021 (Autodesk, Inc., California, U.S.A.) [31]. During construction of the computational model, tools were used to automatically fill the indicated volumes with finite elements while maintaining a high representation of the geometric form of the new pipe casing structure. The mesh defining the geometry of the pipe casing model was composed of 1,293,554 tetrahedral elements containing 687,840 nodes. This is a medium mesh. Then, for the purposes of strength analysis in accordance with the FOPS procedure of the new cover structure, the following boundary conditions were assumed: the cover frame was fixed at 3 points by means of a bolted connection, as shown in Fig. 2. This connection prevents rotation and displacement along the three directions of the Cartesian coordinate system.

Fig. 2 *Support points of the pipe cover - variant 1 (3 points marked with a red circle) for the purpose of FEM analysis in accordance with the FOPS procedure*

3 Results and discussion

The following analytical calculations 3.1; and verification calculations using the finite element method 3.2 were carried out in accordance with the codes specified by the Organisation for European Economic Co-operation (OECD) [10] in the field of FOPS (Falling Object Protective Structures) - a structure protecting the operator against falling objects.

3.1 Analytical calculations

According to the FOPS (Falling Object Protective Structures) procedure, a falling spherical body with a mass of 45 kg was dropped from a height of 3.1 m [24, 25]. During impact, energy W = 1365 J was generated. To calculate the pressure force necessary for correct simulation, the deformation depth of the structure had to be determined. In order not to violate the "operator's safe space" for the analyzed tubular casing structure, the maximum deformation s could be 100 mm. Then the average force acting on the structure would be:

$$W = F \cdot s \qquad (2)$$

$$F = \frac{W}{s} = \frac{1365J}{0.1m} = 13650 \ [N] \qquad (3)$$

Where:

W…Work (energy) [J];

s…Maximum deformation [m].

A value of 13650 N was adopted as the boundary parameter for the strength analysis. According to the analytical calculation procedure, the bending stress σ_g will be calculated first, followed by the shear stress τ_t, and finally the reduced stresses according to the Huber-Misses-Hencky hypothesis. To calculate the indicated stresses, also assuming the worst-case scenario, when a spherical body hits four truss profiles, one must calculate the impact force Fu, the bending strength modulus Wx, and the cross-sectional area of the square profile A. Therefore, the impact force is ¼ of the force F, i.e., Fu = 6825 N for the used profile with dimensions of 25 mm × 25 mm × 3 mm, forming the truss, the bending strength modulus of one profile is Wx = 1735 mm3, while the cross-sectional area of the square profile is A = 264 mm2.

Bending stresses:

$$\sigma_g = \frac{M}{W_x} = \frac{F_u \cdot r}{W_x} = \frac{6825 \ N \cdot 33{,}4mm}{1735 \ mm^3}$$
$$= \frac{227500 Nmm}{1735 \ mm^3} \qquad (4)$$
$$= 131{,}39 \ [MPa]$$

Shear stresses:

$$\tau_t = \frac{F_u}{A} = \frac{6825 \ N}{264 \ mm^2} = 25{,}85 \ [MPa] \qquad (5)$$

Stresses reduced according to the Huber-Mises Hencky hypothesis:

$$\sigma_{H-M} = \sqrt{\sigma_g{}^2 + 3 \times \tau_t{}^2}$$
$$= \sqrt{131{,}39^2 + 3 \times 25{,}85^2} \quad (6)$$
$$= 138{,}80 \, [MPa]$$
$$\sigma_{H-M} < k_{accept}$$

Where:

σ_{H-M}…Stresses reduced according to the Huber-Mises Hencky hypothesis [MPa];

σ_g…Bending stresses [MPa];

τ_t…Shear stresses [MPa].

To sum up the analytical calculations, it should be stated that the strength condition has been met, because the reduced stresses according to the Huber-Misses-Hencky hypothesis amounting to 138.80 MPa are lower than the permissible stresses, kallow= 142 MPa.

3.2 Finite Element Method (FEM) verification calculations

The strength tests conducted focused on the analysis of reduced Von Misses stresses for the developed new concept of a tubular guard (variant 1) dedicated to the Kubota MGX 135-IV tractor. The assumptions adopted for this analysis were identical to those for the analytical method presented in section 3.1. Figure 3, right-hand view, and Figure 4, left-hand view, show the results of the reduced stress analysis according to the Huber-Mises-Hencky hypothesis, where the maximum stress was 122.8 MPa. Similar results were obtained by Zhang at all using FEM to analyze the falling object protective structure (FOPS) of a CL958 loader [32].

Figure 5 shows the locations of the most heavily loaded nodes, with Figure 5a showing the new guard from the front, and Figure 4b showing the tractor's front frame mounts. Figure 5a shows orange circles showing the areas of concentrated stresses ranging from 35 to 50 MPa, while Figure 4b shows red circles showing the areas of the highest stresses, i.e., the bent flat bar connecting the two panels of the front frame, and the bend of the square profile supporting the upper frame with the truss.
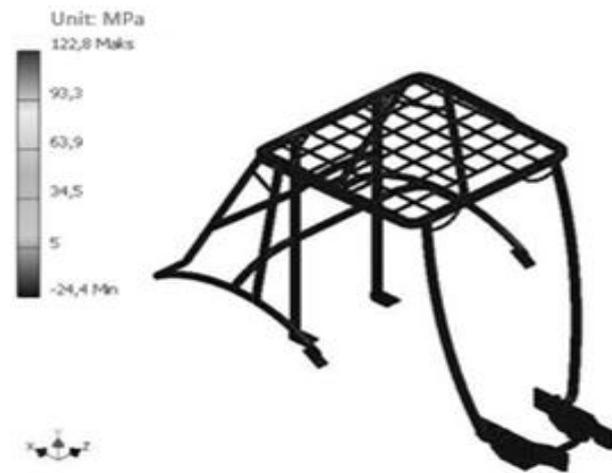

Fig. 3 *Results of the reduced stress analysis according to the Huber-Mises-Hencky hypothesis – variant no. 1 - FOPS test: right-side view*

Fig. 4 *Results of reduced stress analysis according to the Huber-Mises hypothesis – variant no. 1 - FOPS test: left side view*
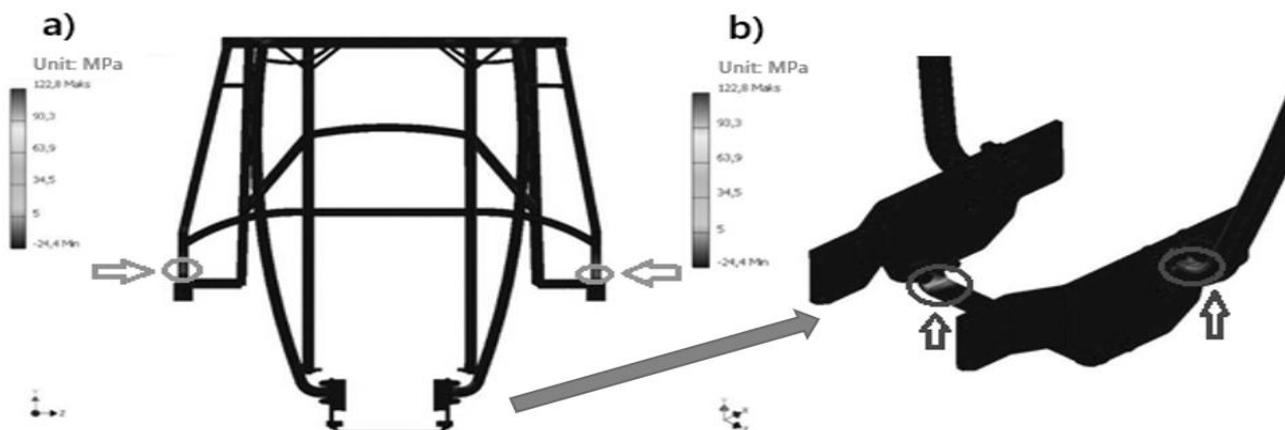

Fig. 5 *Results of reduced stresses according to the Huber-Mises-Hencky hypothesis – variant no. 1 – FOPS test: a) front view of the entire tubular frame, b) view of the front frame brackets (red circles mark the places of the highest stresses, while orange circles mark the places of stress accumulation)*

The presented tubular guard design for the Kubota MGX 135-IV tractor is capable of withstanding forces occurring during falls of heavy objects or tree branches, maintaining the safety zone around the operator, which was also analyzed earlier [17, 33, 34]. The finite element method (FEM) used is widely used in mechanical engineering [35, 36] and can also be used in many industrial fields, e.g. for optimizing truss structures [37] or optimizing the frame system of a forming carriage [38].

4 Conclusions

A strength analysis indicated by the FOPS procedure, conducted analytically and verified using the finite element method (FEM) for the tubular guard structure dedicated to the Kubota MGX 135-IV tractor, demonstrated that it meets all assumed strength criteria. The prepared and analyzed 3D CAD model of the new tubular guard, enabling forestry work with the Kubota MGX 135-IV tractor, contained no nodes where stresses exceeded the maximum allowable stresses (Klow). The difference in reduced stresses, according to the Huber-Mises hypothesis, between the analytical calculations and the FEM method is 16 MPa, which is less than 12%. The designed tubular guard structure also has acceptable stiffness and is capable of protecting the operator by absorbing and dissipating the energy of a falling tree limb. We planned the next step to be a ROPS strength analysis for the newly developed tubular guard, which should absorb energy through plastic deformation. Therefore, in subsequent stages, nonlinear strength analyses with plasticity and large displacements will be performed. In summary, the new tubular guard designed for the Kubota MGX 135-IV tractor meets the established assumptions defined by FOPS standards. The analytical and simulation methods used allowed us to conclude that the new guard design has a significant potential for commercial use, especially since no similar guard is currently available on the Polish or European market. It should also be noted that the designed guard is based on the design of the Kubota MGX 135-IV tractor, in accordance with the manufacturer's recommendations, while not restricting the tractor's functionality or the operator's visibility. It emphasizes the aggressive nature of the Kubota brand, appreciated by loyal customers.

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