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FEM modal analysis of a garlic harvester for varying geomorphologies[1]

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ABSTRACT - In family farming, mechanisation, when appropriate to the task and to the size of the property, can be one way of easing tiring and repetitive work, such as garlic harvesting. The present study is based on a model of harvester currently on the market, and proposes several improvements for mechanising the harvest on family farms, with an emphasis on sloping terrain, to reduce costs and increase productivity. Since the equipment currently on the market reduces the operational performance of these producers resulting in the high prices of commercial garlic, the aim of this study was to evaluate, using the Finite Element Method, the von Mises stresses and the displacement of a garlic harvester in different topographies. A structural analysis was carried out, and the vibration modules in the three main parts that make up the structure of the garlic harvester were checked: the structure supporting the scarifier point, the structure of the plant transport system, and the structure at the rear of the harvester. The structural modifications that were implemented corrected the initial high-stress conditions, showing improvements in stress concentration and areas of displacement. As such, the entire structure of the garlic harvester tends to withstand the proposed loads. From the results of the simulations, we conclude that the connecting support may undergo greater response from structural dynamics, and that frequencies greater than 45.7 Hz should be avoided since there are several natural frequencies above this range that might cause interference to the structure.

Key words: Displacement. Frequency and amplitude. Agricultural machinery. Family farming. Product development.

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INTRODUCTION

Garlic is grown and consumed worldwide. According to Cruz *et al*. (2019), Brazil is considered the second largest market, with 300,000 tons consumed annually. In Brazil, the states of Goiás, Minas Gerais, Santa Catarina and Rio Grande do Sul are the largest producers of garlic, with approximately 1.800 ha. However, industrial policies do not encourage the development of equipment aimed at the production units of family farmers, and despite there being great demand in Brazil, the industry prefers to focus its efforts on medium and large producers. Nevertheless, these smaller units also require equipment and labour for both cultivation and harvesting (ALBIERO *et al*., 2019; MAAS; MALVESTITI; GONTIJO, 2020).

To improve or design new agricultural machinery, a knowledge of plant morphology as well as the geomorphology of the area of cultivation is crucial (SOUZA *et al*., 2018). For instance, with reference to the morphology of garlic and the time of harvesting, the harvest must be carried out within three days, otherwise, the quality of the bulb may be compromised. According to Filgueira (2013), quality may be impaired, for example, by a reduction in the weight of the bulb, which loses its commercial status (market price). Also important for improving agricultural machinery used in harvesting garlic, is the geomorphological difference in the various Brazilian states where the garlic is grown. According to Höfg and Araújo-Júnior (2015), the slope of the land can be classified based on its potential for mechanisation, ranging from extremely suitable to not recommended. The slope of an area is a limiting factor to the use of agricultural machines, leading to difficulties in planting and harvesting. As a result, there is undue oversizing of the machinery and equipment used for harvesting on sloping terrain, which is why most of the equipment is designed to work on flat land.

With regard to the size of agricultural machinery, Niemczewski *et al*. (2014) found that most small machines on the Brazilian market are based on larger machines, their width being reduced to produce a model with fewer rows, maintaining the dimensions of the steel profiles used in the original designs. However, research on the mechanisation of garlic planting in these production units has shown no innovations for over a decade (BELTRAME; SCHMIDT, 2013).

According to Ruffoni and Reichert (2022), Brazilian manufacturers of agricultural machinery tend to innovate based on operation vs. management or operation vs. transaction, and seek to bring about improvements which focus on production. As such, the above research confirmed that the vast majority of agricultural machinery in Brazil is based on copying foreign agricultural machines, which are then adapted to the local climate and soils. However, there is a large gap in the literature regarding innovation and academic studies that can be directly applied to the market. On the other hand, Reis *et al*. (2020) state that Brazilian companies develop new products only when the market study shows them to be widely accepted; therefore, once an agricultural machine is in line with a strategic plan, a risk analysis is carried out that considers the scope of the machine to be produced. In China, where agricultural machinery is highly developed, researchers such as HOU *et al*. (2020) explain that studies related to agricultural machines, especially those aimed at harvesting garlic, have led to much important research; however, excavation and separating the plant from the soil are still in the process of development, and present great challenges that remain to be resolved. For Tian *et al*. (2018) and Xiaolian, Zhichao and Xiaorong (2017), this research is mainly focused on production units with a large area and flat topography, and there is a lack of development of agricultural machinery which can be adapted to smaller areas, as well as in analysing the efficiency, among other variables, of the machines on the market.

The geomorphology of agricultural land on the small properties of family farmers requires new technology. One trend towards the structural improvements that are needed for equipment already on the market that has been widely used with this methodology, and is already being applied to coffee, sugar cane and grapes on sloping terrain, is the use of computer software as a tool to help in developing the machinery, including the proposal of improvements that might contribute to the quality and reliability of the equipment being analysed, (FERREIRA *et al*., 2016; NIEMCZEWSKI *et al*., 2014; PEGORARO; GOMES; NOVAK, 2018; SILVA *et al*., 2018; VELLOSO *et al*., 2020).

Various methods have been proposed, one of them being the Finite Element Method (FEM). Simulations in projects applying FEM have shown important results for production units. Using FEM, Madenci and Guven (2015) proposed advanced analyses when modelling agricultural projects, using a parametric design language known as APDL; however, according to the authors, even with the possibility of optimisation afforded by integrating FEM with programming languages, it is still necessary to have a knowledge of the mechanical, geometric and dynamic contour properties to represent, as closely as possible, one model for the most varied situations in the field. Rozenfeld *et al*. (2006), also address the importance of three-dimensional drawings using Computer-Aided Design (CAD) systems, which make it possible to carry out several studies, including stress and displacement analysis, etc. Silva *et al*. (2018) demonstrate that the use of computerised design (CAD) enables a reduction in costs, in which unnecessary time and materials can be reduced through detailed assembly analysis of various imperfections in the gearing, synchrony and dynamics of the elements of the systems to be produced, including an increase in machine safety. As such, it becomes possible to predict operational and material failures, whether due to stress and/or to vibrations in the agricultural components. The study of force, displacement and vibration in projects involving FEM is therefore of great importance.

Given the above reasons, and as applied to other crops, the aim of this study was to analyse a garlic harvester currently on the market, propose improvements, define the ideal mesh to be applied in the simulation, evaluate the von Mises stresses and displacement of the structural parts of the harvester in different topographies. The Finite Element Method (FEM) was used to analyse three parts of the harvester: the structure supporting the scarifier point, the structure of the plant transport system, and the structure at the rear of the machine.

MATERIAL AND METHODS

The methodology was developed from computer simulations using FEM. Three-dimensional models of the structure of a machine currently on the market were generated via CAD (Figure 1) to represent the physical structure of the geometries under analysis.

The garlic harvester is L-shaped, and basically comprises three structures: (1) the structure of the plant transport system, with two guide wheels and guides that help to lift the leaves and stem of the garlic plant, which is then carried by a system of belts to the leaf and stem cutter; (2) the point support structure, the point or scarifier carrying out the function of breaking the soil and cutting the roots; (3) the structure at the rear of the garlic harvester that supports the conveyor guiding the bulbs for bagging to a hitch or tractor system.

Figure 1 - One-row commercial garlic harvester

The steps carried out during the methodology were: development of the 3D modelling of a machine, mesh convergence of the structural parts, FEM analysis, and, when the structure met the specifications, modal analysis and presentation of the results. If the structure did not meet the specifications, it was returned to be revised during the modelling phase.

3D Modelling and preparation

The Solidworks and Ansys 14.5 (ANSYS, 2014) software were used for modelling the systems. Using these tools, models of the structural parts were generated, i.e. the point, the base connecting the plant transport structure to the point support structure, and the main structure.

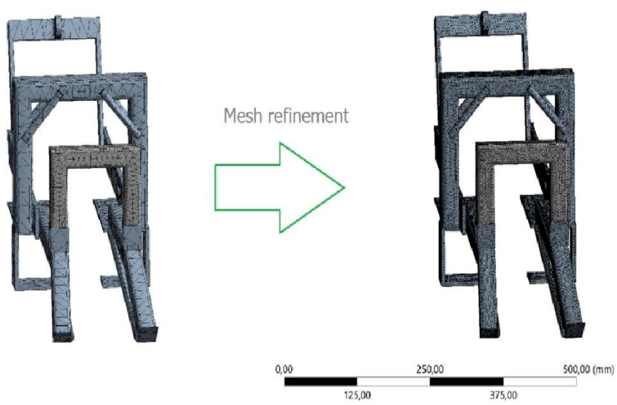
To generate the three-dimensional geometries of the parts involved, a computer with an Intel Core i7 Gen processor, 8 GB RAM memory and integrated UHD Graphics 620 video card (with 2 GB GDDR5 memory) was used.

Mesh Convergence

Using refinement, a mesh convergence study was applied in order ensure both the reliability of the mesh adopted for the geometric model and the stabilisation of costs (MADENCI; GUVEN, 2015; MION *et al.*, 2016). Figure 2 shows the geometric model of the point, considering the initial mesh and the mesh after convergence.

For this study, a second-order quadratic three-dimensional mesh element was assigned, hexahedral-dominant, and with three degrees of freedom per node (MADENCI; GUVEN, 2015). To carry out the convergence procedure, a maximum point was selected and monitored for the analysis; this served to check the variation and stabilisation of the values obtained. In this study, the number of elements was altered until the maximum point stabilised, when it was possible to verify

Figure 2 - Mesh convergence in the structure supporting the scarifier point



the graphical stability of the displacement and stress values in order to determine the ideal mesh to be used with the model in further studies.

Structural analysis using FEM

The Ansys 14.5 software was used for the numerical simulations. The material used for the structure was ASTM A36 steel, as it has good mechanical properties and weldability (AMERICAN WELDING SOCIETY, 2010; CELY *et al*., 2018; HIBBERLER, 2010), in addition to being commonly used by manufacturers of agricultural implements (CASTRO *et al*., 2016).

The parameters of the point contour were 0.46869 MPa, comprising the maximum value observed through experimentation, and applied to the front direct-contact surface of the implement (at a depth of 100 mm). The values obtained for the torsion and bending moments were 0.2197 and 0.0211 N mm^{-1}, respectively. The torsion and bending moments were calculated using the Ansys 14.5 software of the Computer Aided Engineering (CAE) system. The forces applied directly to the harvesting process were vertical (261.3 N), horizontal (-189.5 N) and transverse (442.0 N) (MACHADO *et al*., 1996; MACHADO; CHANG, 1996; MACHADO; REIS, 1997).

Figure 3 shows application of the forces used in the analysis to both the structure and attachment points.

The contour parameters for the base connecting the plant transport structure and the point support structure correspond to the transmission of forces from the base that holds the scarifier to the attachment points of the support (Figure 4).

The contour parameters of the structure at the rear of the garlic harvester were the same as those transmitted by the base connecting the plant transport structure and the point support structure. To these were added the weight of the operator (-980 N), weight of a bag of garlic (-392 N), weight of the belt and components (-294 N) and of their attachment points, i.e. the wheels and connection with the tractor (Figure 5). For this simulation, two modes of operation were used: i) 0% slope and ii) maximum operating slope, equal to 25%.

At this stage, each of the three components was checked to see whether it met the specified requirements. If the component failed, it was returned to the modelling phase to be revised.

Optimisation process of the point support structure

The first step in carrying out the process of improving the point was the insertion of a locking frame in the form of a U of 20 x 20 mm, using the Multiobjective Genetic Algorithm (MOGA) - NSGA II via FEM, an optimisation algorithm that is included in the software and that only requires the parameters to be defined by means of an XML file. The file was modified to create new parameters for the diameter of the locking bars. Python code was then used to edit the system control and set the parameters. The Python and XML files were linked in the commercial software file. In the next step, a structural analysis simulation file was created, related to the first result obtained when adding the forces. The final step was to run the MOGA – NSGA II

Figure 3 - Application of forces to the attachment points and the structure that supports the scarifier point

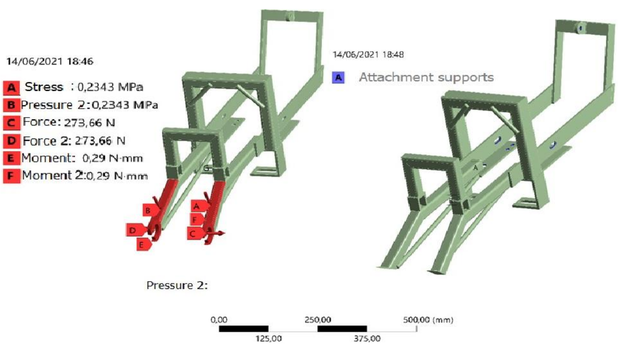


Figure 4 - Application of forces at the attachment points of the connecting base

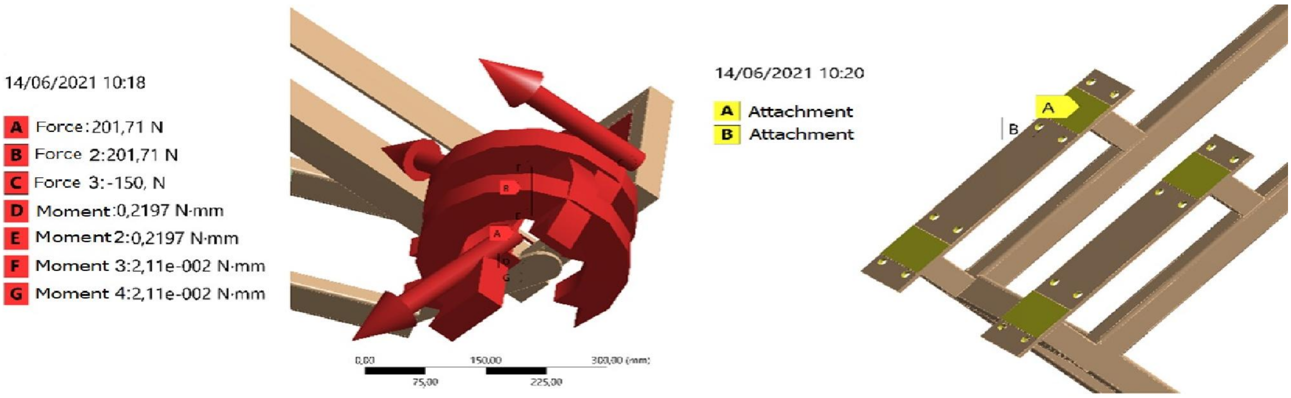


Figure 5 - Application of forces at the attachment points of the structure at the rear of the garlic harvester

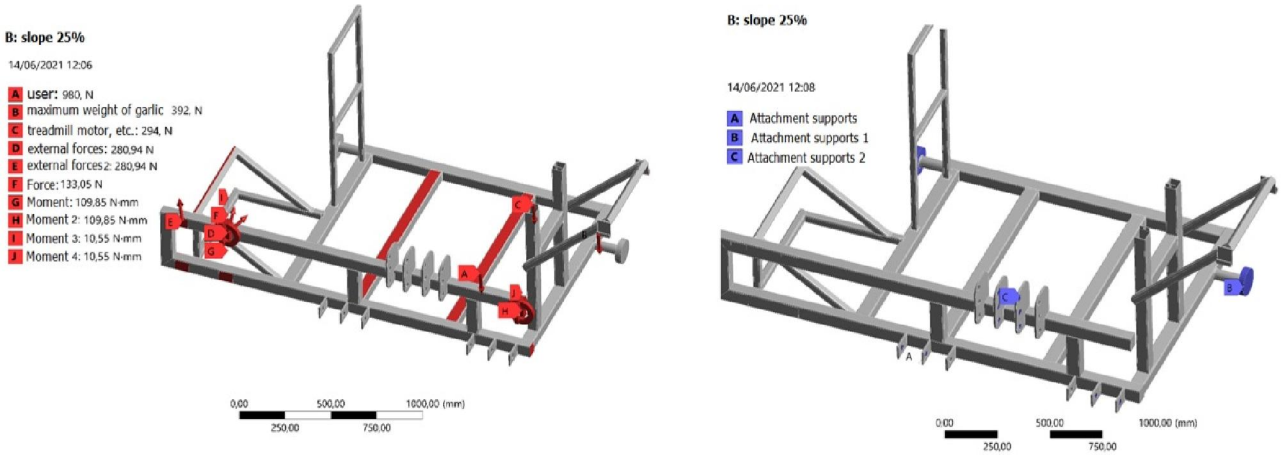
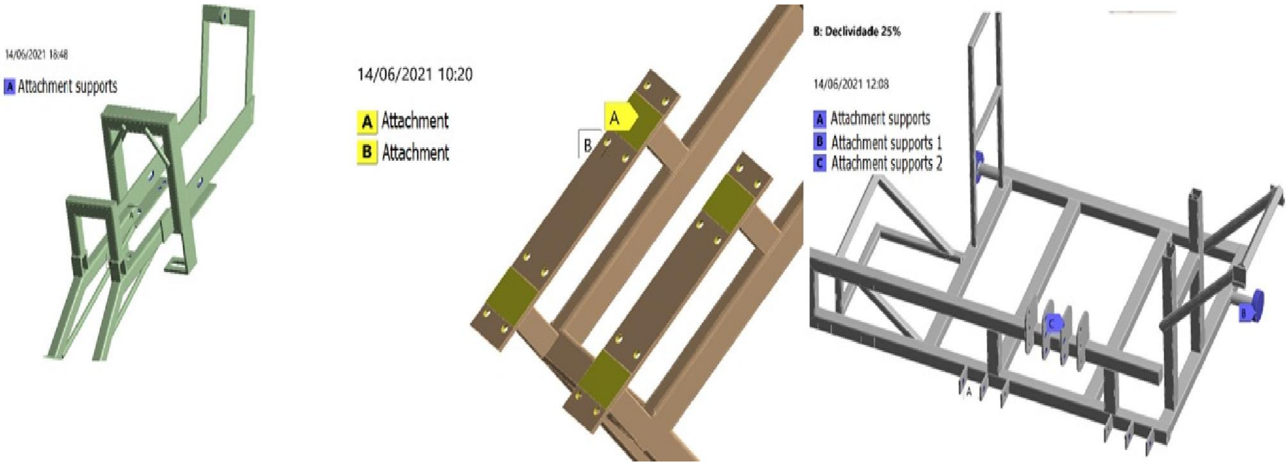


Figure 6 - Application of forces at the attachment points of the structures



optimisation process, whose objective was to minimise the maximum displacement during the harvesting process by reducing it to values < 1.8 mm; the maximum stress, which was reduced to values < 52 MPa; and to minimise the weight. The limits established when altering the diameter of the bars were whole units between 0 mm and 15 mm (zero being considered as removing the bar), which varied as two-by-two locking pairs, i.e. activating the one on the left would activate the one on the right.

Modal analysis

Similar to the structural analysis, the modal analysis was developed using the same three parts of the harvester. The purpose of the analysis was to find the vibration frequency of the first six vibration modes of each structural part, in addition to evaluating the effect of each natural frequency on the displacement of the components.

The support structure of the point and the connecting base were attached, and the main structure was locked at the wheel support points and connected to the tractor as recommended (Figure 6). For the second analysis, a free body was simulated, with no restrictions on movement. The modal analysis was carried out using the Ansys 14.5 software.

RESULTS AND DISCUSSION

Mesh convergence analysis, used in each of the three components of the simulation, is related to stabilising costs and the von Mises stress. The results of the statistical simulations are related to the use of the equipment.

Mesh convergence analysis

The results of the mesh convergence are shown in Figures 7, 8 and 9. Note that in Figure 7, upon reaching 452075 nodes (which corresponds to 255047 elements for the point); in Figure 8, upon reaching 491884 nodes (which corresponds to 238176 elements for the connecting base) and in Figure 9, upon reaching 491884 nodes (which corresponds to 238176 elements for the structure) the stress curves tend to stabilise, showing that for this number of elements, the simulation is reliable at the scarifier point, the connecting base and the structure, with the least computational cost.

Based on the results of the mesh convergence, a maximum element size of 2, 5 and 6 mm was established for the point, connecting base and structure, respectively. In each case, the quality parameter used was ‘medium’, both for the contours and for the quality of the element conversion.

Load simulations

It can be seen from the simulations that the point support structure exceeded the yield strength which, according to the American Welding Society (2010), is 250 MPa. As a result, improvements were proposed so that the point obtained a minimum safety factor equal to or greater than 3.8, from which it was possible to identify the ideal point geometry for the study. The evolution of the proposal process for improvement and optimisation can be seen in Figure 10.

The improvements proposed in the geometry of the point support structure (Figure 10) were, from (a) to (b), adding reinforcement at the site of the wheels, forming a U of 20 x 20 mm, and from (b) to (c), inserting activation points for the bars used for locking the structure. The optimisation process was run by varying the diameter of the attachment bars to achieve 12 mm and the activation of six of the 10 activation points of the bars.

Figures 11 and 12 show the maximum displacements and von Mises equivalent stress distributions for the final version of the geometry of the point support structure. Niemczewski *et al*. (2014) showed that calculations of displacement in a structure made by FEM are reliable, by submitting a full-scale prototype to loadings of vertical forces, in order to compare the displacements with those obtained with the software.

Figure 7 - Mesh convergence process shown as a function of (a) the von Mises stress and (b) time step for the scarifier point

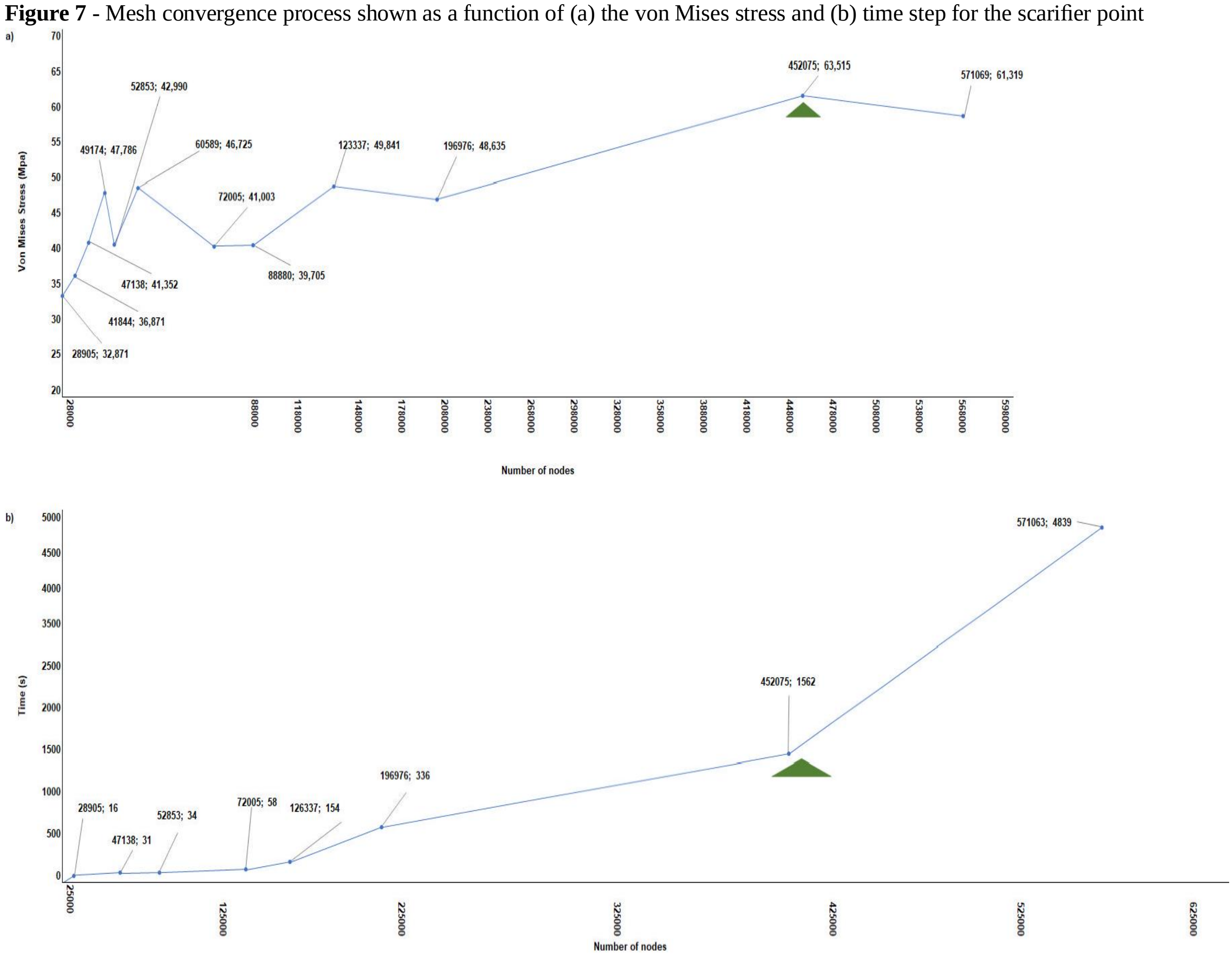


Figure 8 - Mesh refinement process shown as a function of (a) the von Mises stress and (b) time step for the connecting base of the plant transport system

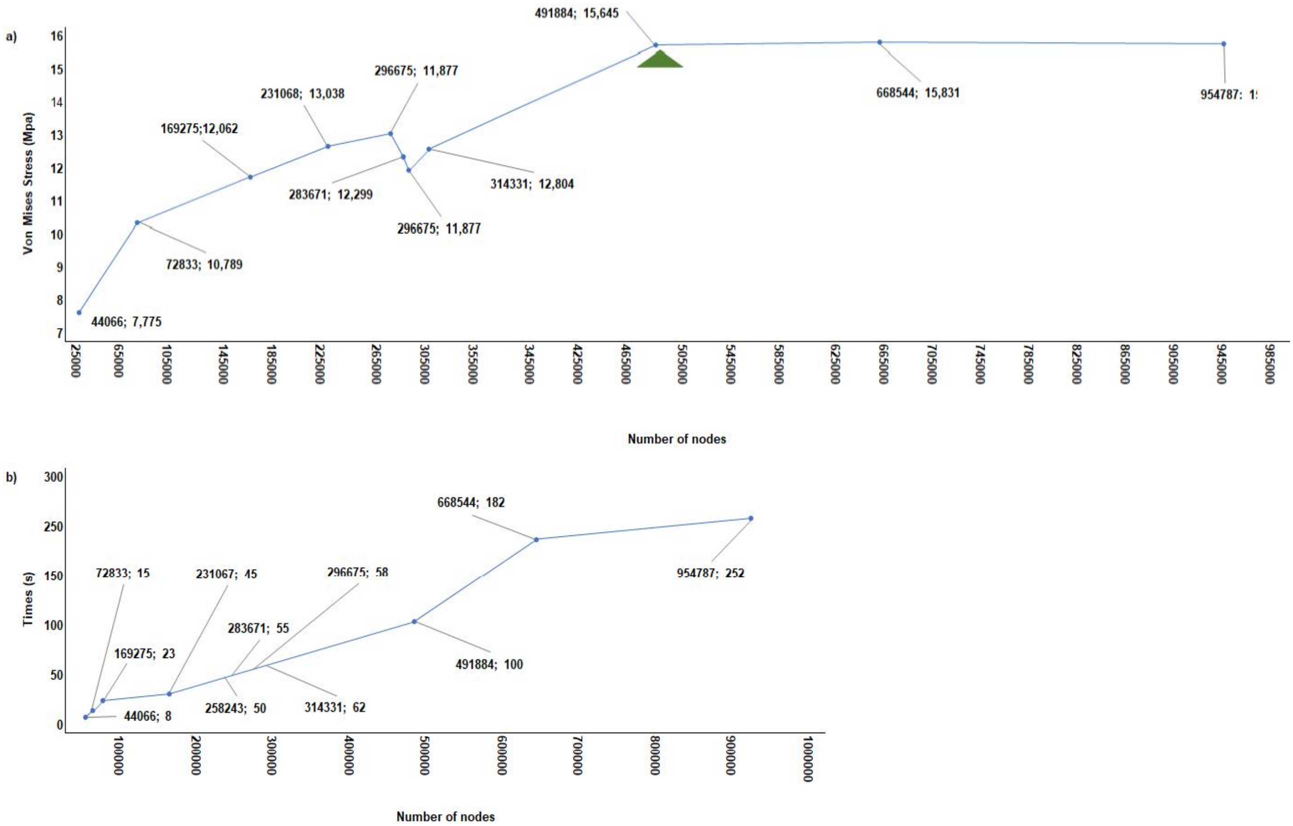
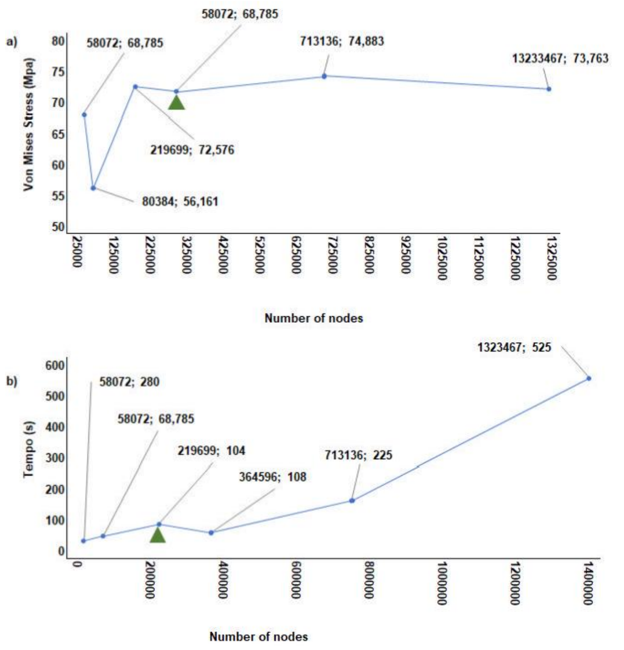


Figure 9 - Mesh convergence process shown as a function of (a) the von Mises stress and (b) time step for the structure



Figures 13 and 14 show that the life of the point support is greater than 10^6, i.e. according to the literature, the working life can be considered infinite; furthermore, the analysed load can be increased by up to 1.21 times and, as per the literature, the working life will still be considered infinite (AVITABILE; PETER, 2017; BUDYNAS; NISBETT, 2016; MEDEIROS, 2016).

It can be seen from Figures 12 and 13 that maximum deformation of the point support structure was limited to 0.11191 mm and that the maximum stress was 51.996 MPa. This value is below the limit of ASTM A36 steel (250 MPa), with a safety factor (SF) of 4.81 at the stress concentration points. As such, the point support structure will withstand the proposed loads once the adjustments are carried out.

The maximum displacements and the von Mises equivalent stress distributions for the structure of the plant transport system are shown in Figures 15 and 16, respectively.

Figures 15 and 16 show that maximum deformation in the plant transport system and the point support structure

Figure 10 - Evolution of the process for simulating the structure supporting the scarifier point

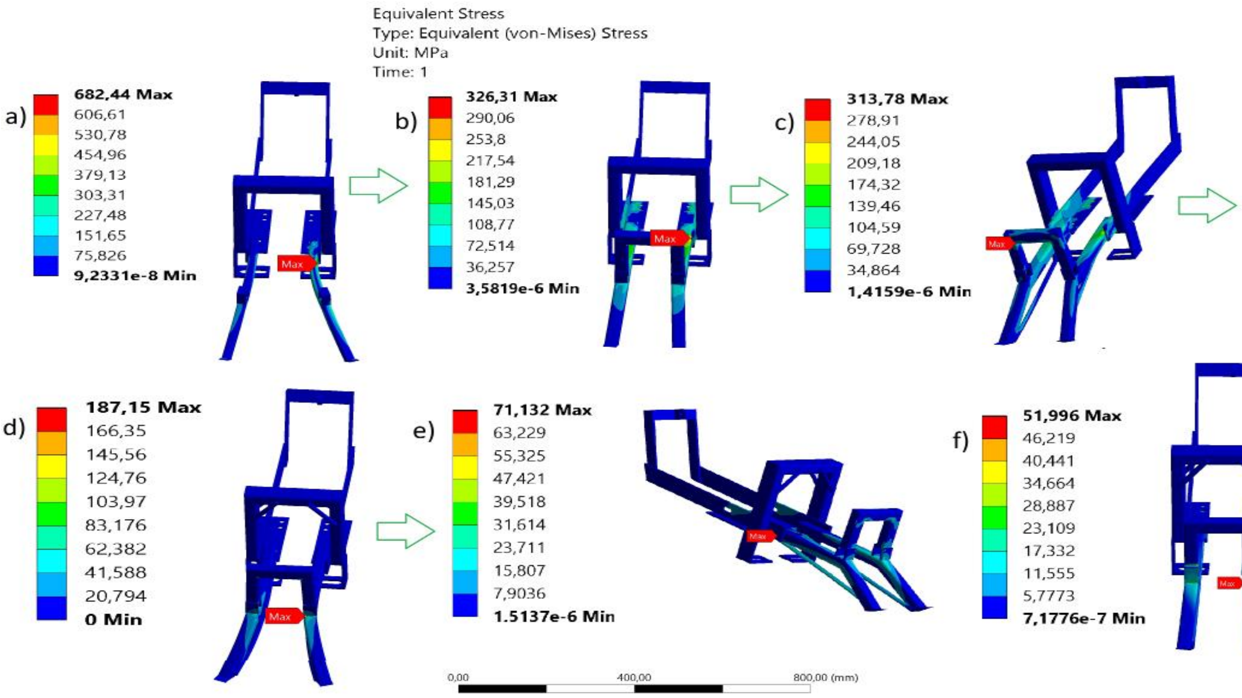


Figure 11 - Von Mises stress in the structure supporting the scarifier point

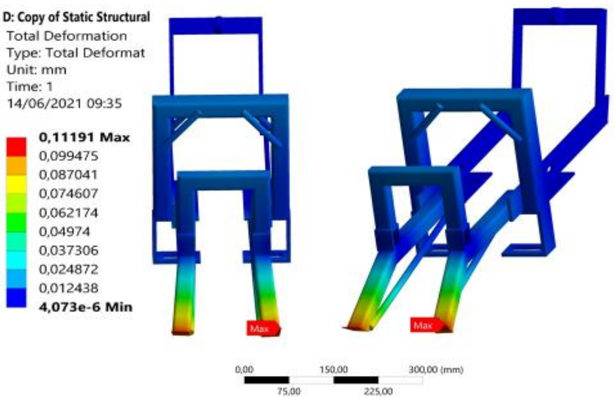


Figure 12 - Von Mises stress in the structure supporting the scarifier point

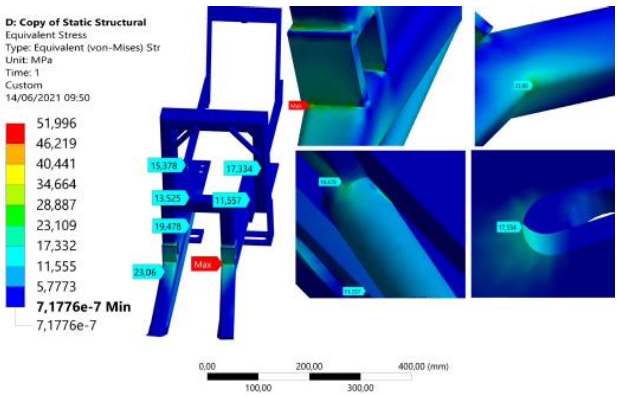


Figure 13 - Fatigue safety factor in the structure supporting the scarifier point

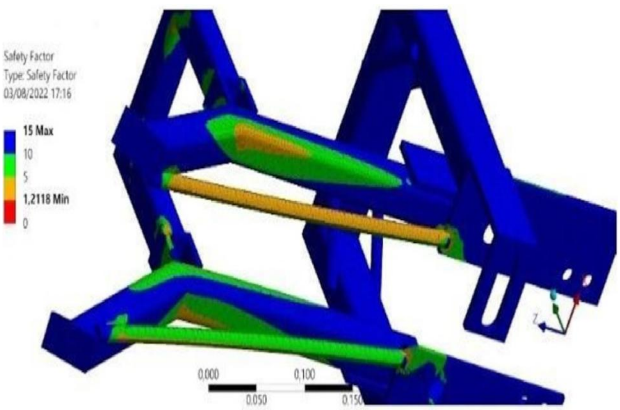
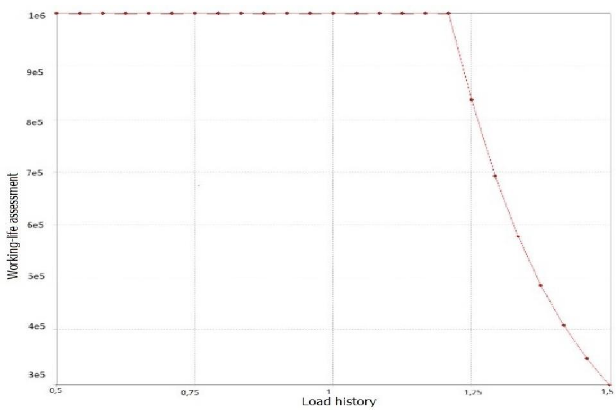


Figure 14 - History of the working life of the structure supporting the scarifier point given the proposed increase in load



was limited to 0.45172 mm, and that the maximum stress was 15.645 MPa. This value is well below the limit of ASTM A36 steel (250 MPa), with an SF of 15.98 at the stress concentration points. As such, the structure of the plant transport system and the point support structure will also withstand the proposed loads.

When analysing fatigue in Figures 17 and 18, it can be seen that the life of the structure of the plant transport system is greater than 10^6, i.e. according to the literature, the working life can be considered infinite; furthermore, the analysed load can be increased by up to 1.16 times and, as per the literature, the working life will still be considered infinite (AVITABILE; PETER, 2017; BUDYNAS; NISBETT, 2016; MEDEIROS, 2016).

The respective maximum displacements for a slope of 25% and 0% are shown in Figures 19 and 20. Distribution of the von Mises equivalent stress at 25% and 0% shown are shown in Figures 21 and 22, respectively.

It can be seen in Figures 19, 20, 21 and 22 that the maximum deformation in the structure at the rear of the garlic harvester was limited to 1.26 mm for a slope of 25%, and that the maximum stress was also found for a slope of 25%, with a value of 73.89 MPa. This value is below the limit of ASTM A36 steel (250 MPa), with an SF of 3.38 at the stress concentration points. Therefore, based on the numerical simulations that were carried out, it can be affirmed that the structure will support the proposed loads.

Figure 15 - Displacement of the plant transport system

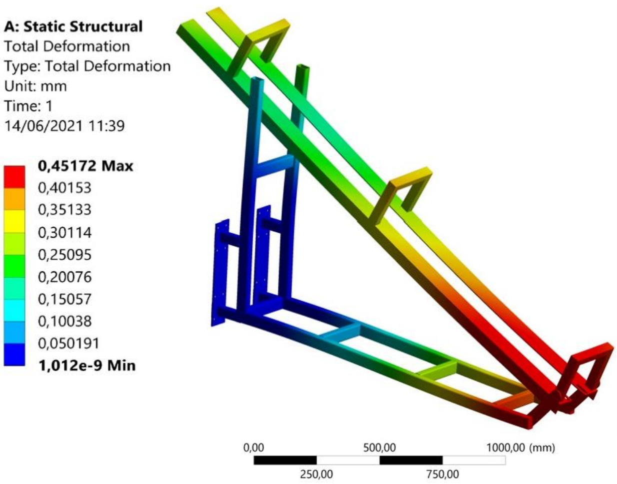


Figure 17 - Fatigue safety factor in the plant transport system

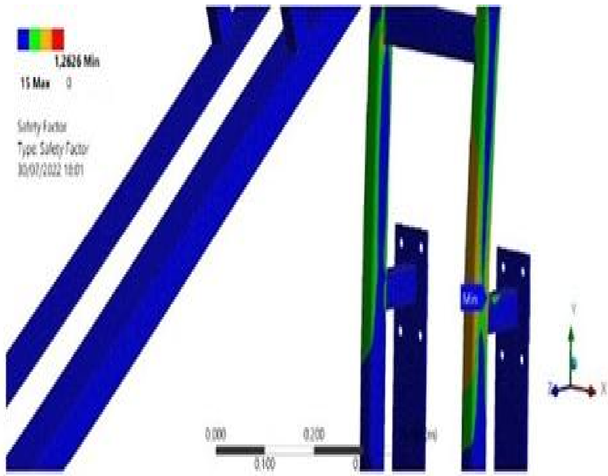


Figure 16 - Von Mises stress in the structure of the plant transport system

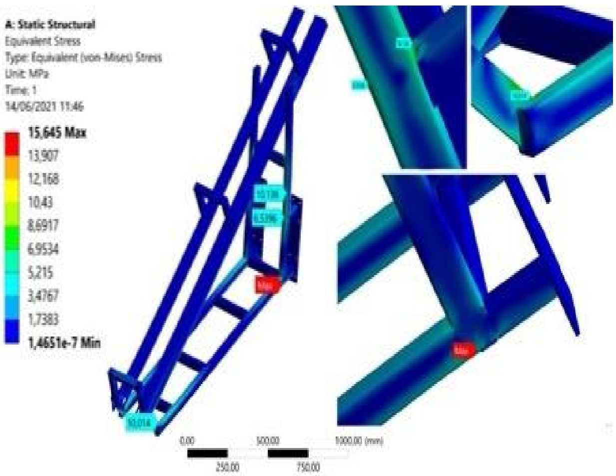


Figure 18 - History of the working life of the plant transport system given the proposed increase in load

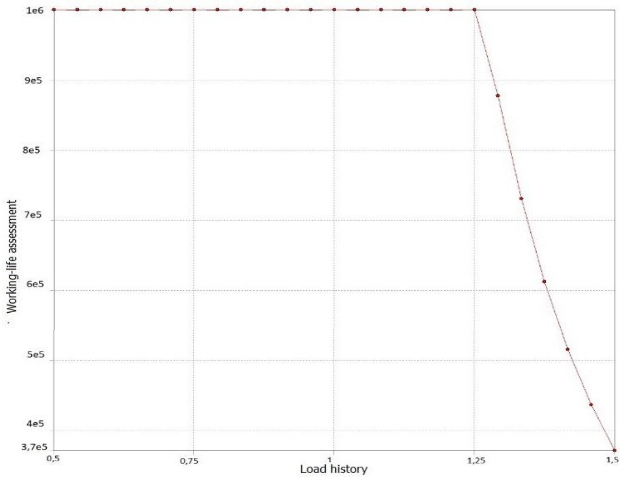


Figure 19 - Deformation in the rear structure of the garlic harvester for a slope of 25%

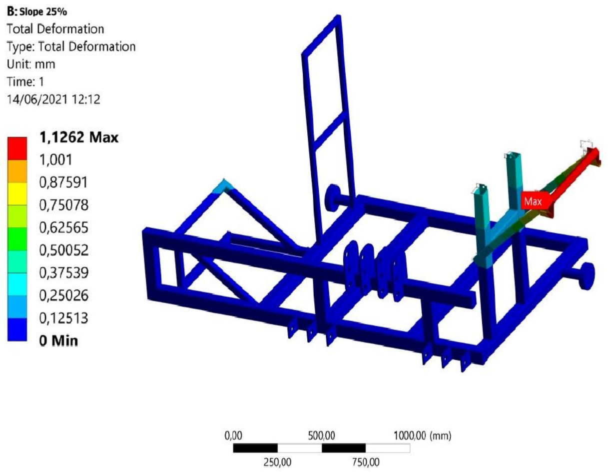


Figure 22 - Von Mises stress in the rear structure of the garlic harvester for a slope of 0%

Figure 20 - Deformation in the rear structure of the garlic harvester for a slope of 0%

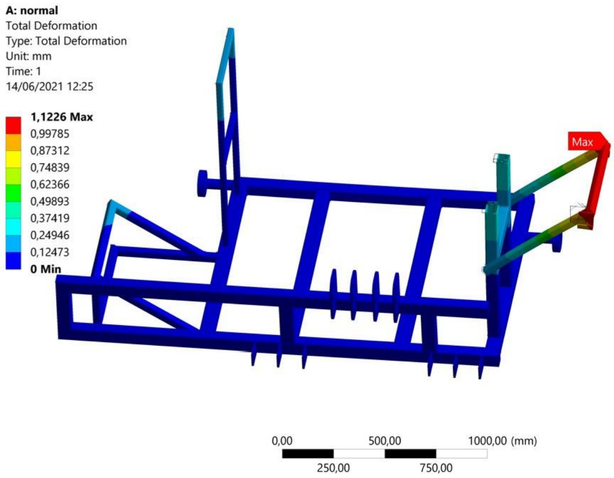


Figure 23 - Fatigue safety factor for the worst case found between slopes (25%)

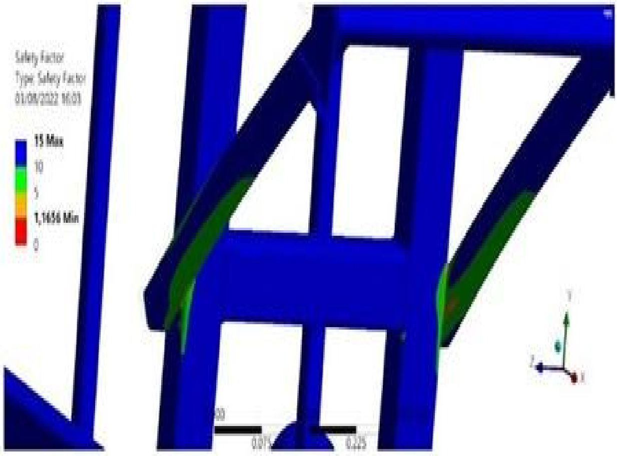


Figure 21 – Von Mises stress in the rear structure of the garlic harvester for a slope of 25%

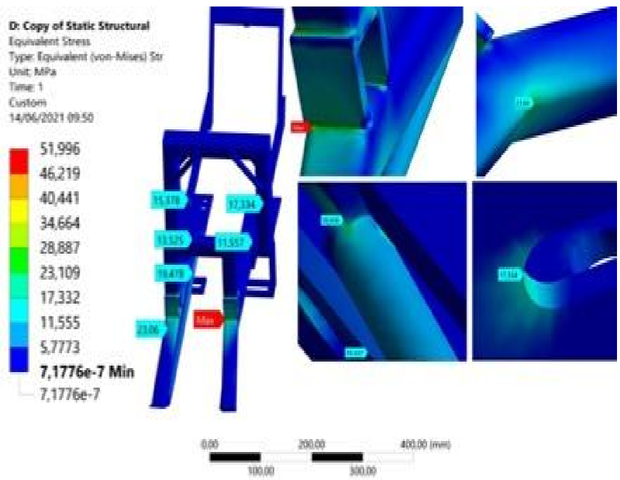
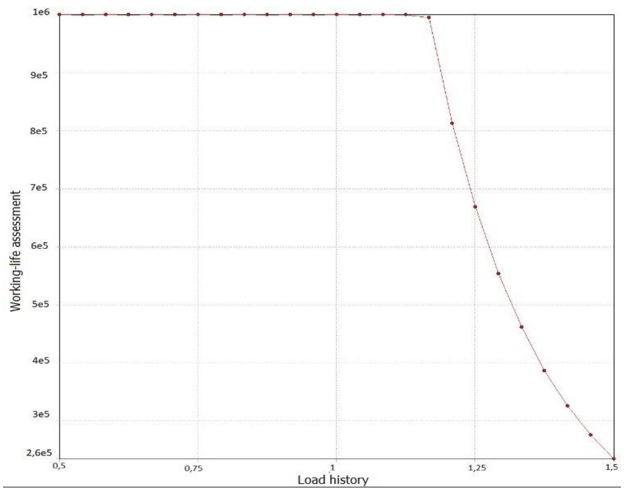


Figure 24 - History of the working life of the rear part of the garlic harvester given the proposed increase in load



Figures 23 and 24, it can be seen that the life of the structure is greater than 10^6, i.e. according to the literature, the working life can be considered infinite; furthermore, the analysed load can be increased by up to 1.16 times and, as per the literature, the working life will still be considered infinite (AVITABILE; PETER, 2017; BUDYNAS; NISBETT, 2016; MEDEIROS, 2016).

Modal analysis

Ways of approaching the dynamics, support and mechanical properties of a structural part of a machine was studied by Pegoraro, Gomes and Novak (2018), expanding the effectiveness of operations involving agricultural machinery. Using the CAE system, Silva *et al*. (2018) similarly found that the results of numerical modelling obtained with the Ansys software were effective. Figures 25, 26 and 27 show the first six modules for each of the structural elements.

Figure 25 - Results of displacement (mm) for rigid-body modal simulations in the structure supporting the scarifier point

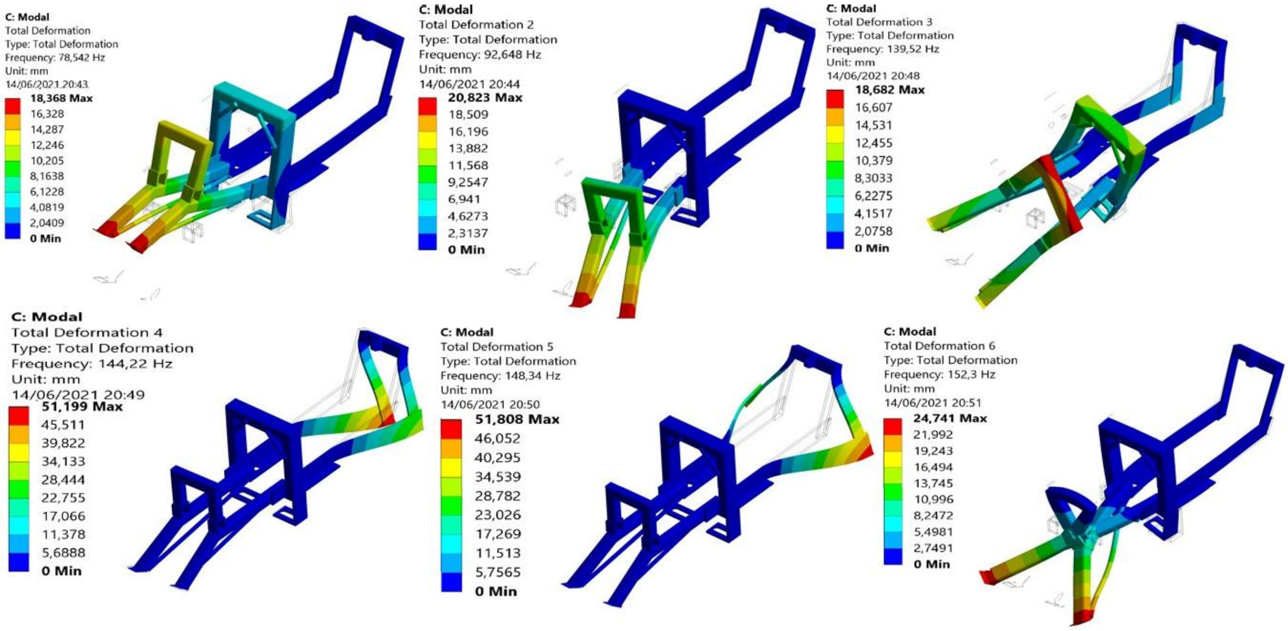


Figure 26 - Results of displacement (mm) for modal simulations in the plant transport system

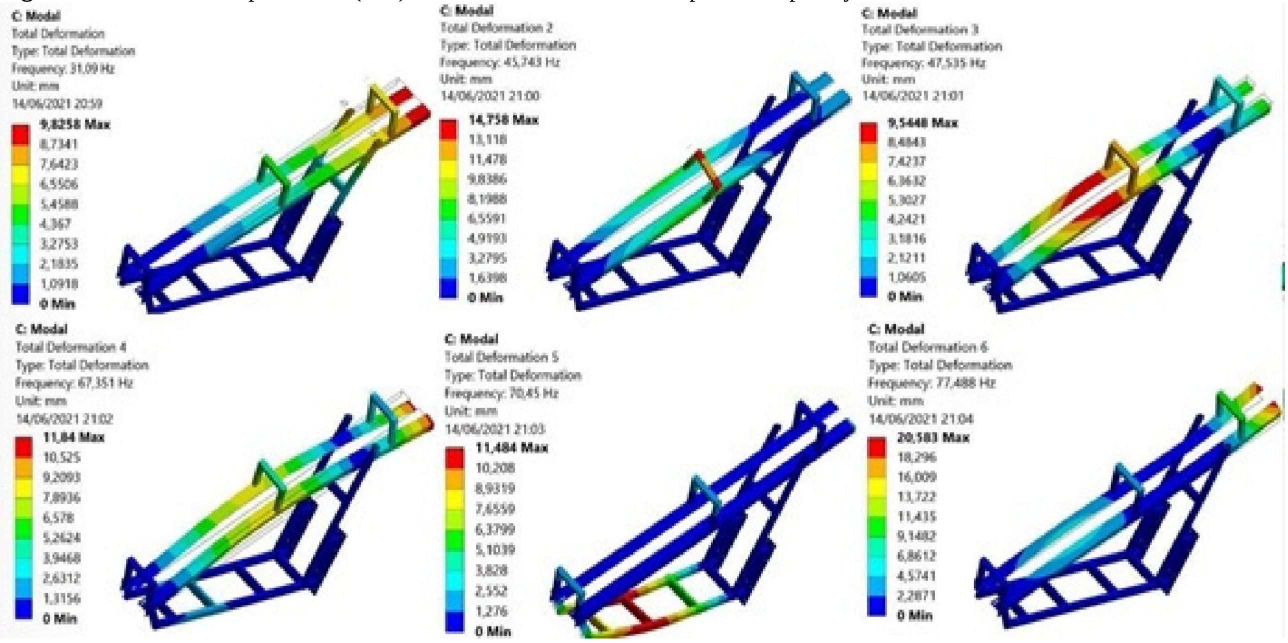


Figure 27 - Results of displacement (mm) for modal simulations in the rear structure of the garlic harvester

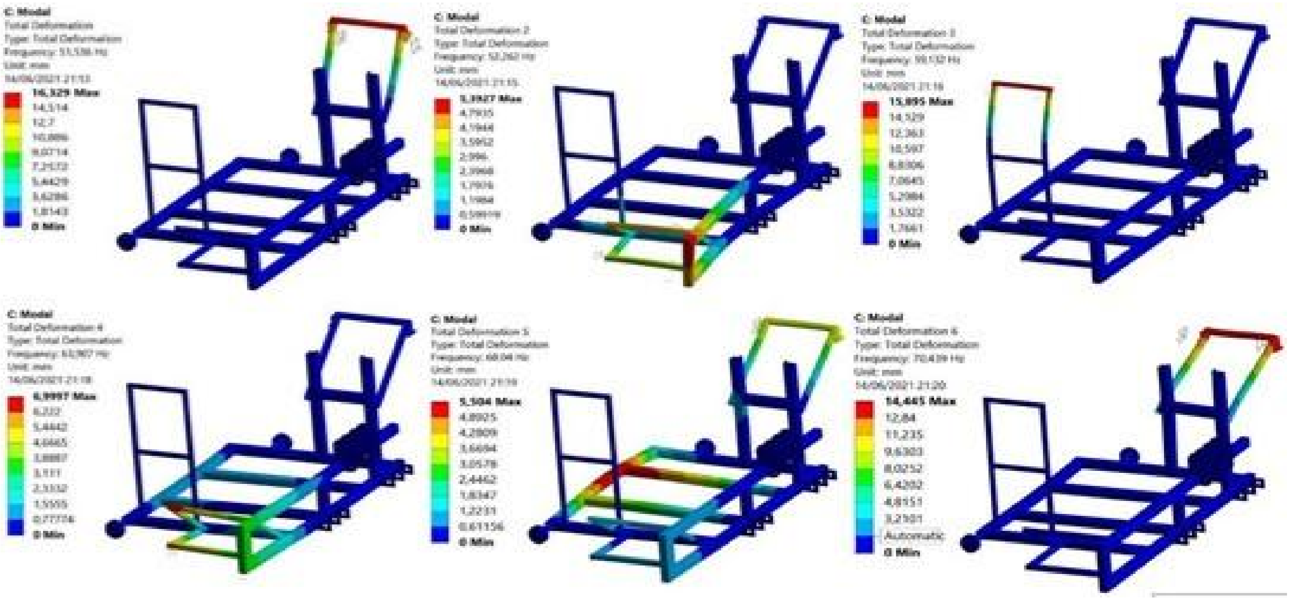


Figure 28 – Result for free-body modal frequency in the structure supporting the scarifier point

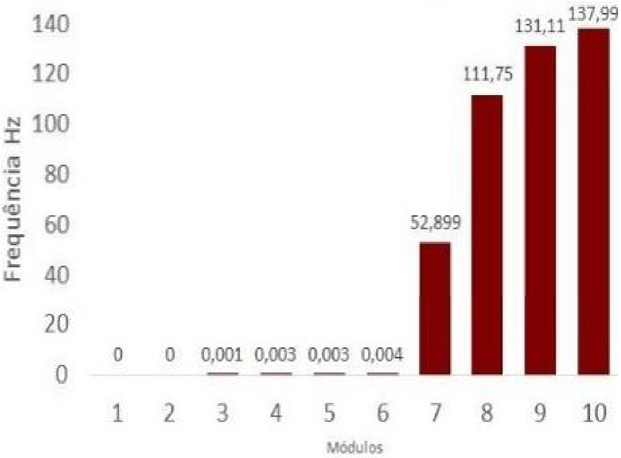


Figure 29 - Result for free-body modal frequency in the transport system

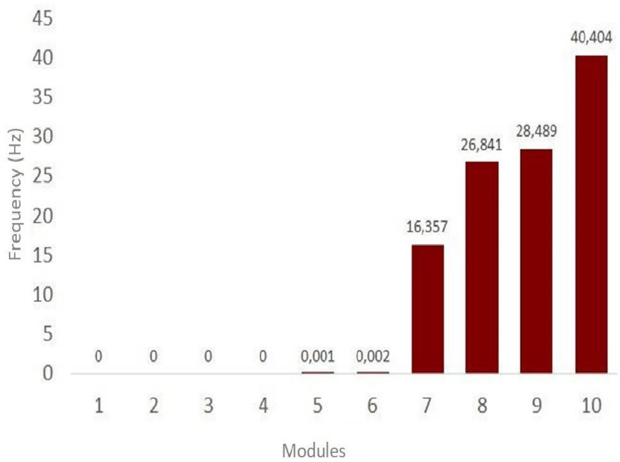
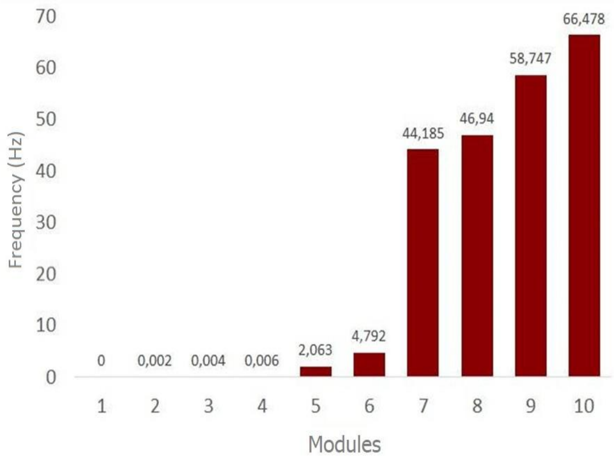


Figure 30 - Result for free-body modal frequency in the rear structure of the garlic harvester



Figures 28, 29 and 30 show the results of the free-body simulations for the first ten modules. In free-body analysis, the initial modules are treated as null.

Cunha, Duarte and Rodrigues (2009) carried out studies on an agricultural tractor with a four-cylinder diesel engine. According to the authors, the displacements tend to show values at idle of 30 Hz and, at a rotation of 2200 rpm, of 36.7 Hz. Comparing the studies carried out in the modal analysis, it could be seen that the displacements included in the operating range of the tractor engine appear only in the support structure connecting the main structure and the point. The structure in question presented a natural frequency of 31.09 Hz with a maximum deformation of 9.8258 mm, and was the main vibratory frequency needing to be controlled. The other frequencies are all above 45.74 Hz, and it is unlikely that they suffer any type of interference from the tractor engine. Velloso *et al*. (2020), studied the dynamic behaviour of coffee plants, and concluded that a study of the frequencies extracted in simulations was validated in laboratory tests.

The free-body analysis shows that the transport system presents frequencies below 10 Hz, which may be influenced by the displacement of the tractor stimulating the spring-mass system of the tyres. However, the structure at the rear of the machine presented a frequency of 16.35 Hz, which is close to that when the soil is broken by the lugs of the tyres and by the scarifier, and which varies between 11 and 13 Hz.

CONCLUSIONS

1. Through a process of improvements implemented in the geometries under analysis, it was possible to reinforce, by simulation, the structure that supports the scarifier point, which can be the basis for developing a new product, eliminating unnecessary expense and failure of the part;
2. Following analysis and the implementation of improvements, the present project had an overall safety factor of 3.38, expressed by the harvester structure, the garlic support structure, and the structure that supports the plant transport system;
3. From the simulations, it can be seen that the variation in stress in the structure is practically the same for a slope of 0% and 25%. It can also be shown that the variation in slope had almost no influence on the results of the FEM;
4. The connecting support of the transport system in the fixed-modal simulation is the only one to be affected by the engine. It is therefore necessary to avoid frequencies above 45.74 Hz, to prevent interference in the structure;
5. In the free-body modal simulation, the connecting support of the transport system presented frequency modules of 2.06 and 4.79 Hz. The rear structure of the machine presented a frequency module of 16.35 Hz, which should be controlled when operating the equipment;
6. The research is highly relevant to the area, as it is based on a harvester designed for varying geomorphologies. It is well-known that in many practical cases the scarifier point undergoes deformation and breakage, and is the main component to fail during the harvest. The suggestions for improvements presented using implementation and enhancement help in adapting a garlic harvester for different geomorphologies;
7. The structures of the garlic harvester under analysis, together with the suggestions for improvements, showed no fatigue failure for the number of project life cycles.

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