sciendo

Management Systems
in
Production Engineering

2023, Volume 31, Issue 3, pp. 361-372

Date of submission of the article to the Editor: 03/2023
Date of acceptance of the article by the Editor: 07/2023

DOI 10.2478/mspe-2023-0040

OPTIMIZATION OF THE TIRE BUILDING DRUM FOR PASSENGER TIRES USING THE TRIZ METHODOLOGY

Peter Števko, Róbert Kohár, Damián Čechmánek,
Denisa Medvecká, František Nový
University of Zilina

Abstract:
This study deals with the research on the impact of the construction of a tire-building drum on the selected parameters of a passenger tire. The introductory part of the study deals with a comprehensive analysis of the production process and factors that affect the quality of the final tire product during production. The content of this analysis is also the naming of problematic parts and their subsequent influence on the resulting parameters of a passenger tire. The core of the study is an optimization design for improving the construction of the tire-building drum. The world-renowned TRIZ methodology was applied to achieve the desired improvement results. Using the TRIZ methodology, the technical system was analysed, identified problematic parts, and defined the technical and physical contradictions and proposed possibilities for their removal. The systematic approach to the solution of the task has generated options for the right solution and possible optimization by reducing the weight of individual parts of the tire-building drum. During analysis, simulations of the deformation and total stress will be available before and after optimization. The work's conclusion describes the results of the simulation and the development process for the experimental testing possibilities of the optimized equipment. The study output is also a systematic procedure for testing the technical system, which can help designers design and optimize some parts of similar technical systems.

Key words: *the building tire drum, passenger tires, TRIZ methodology, optimization of design, engineering simulation*

INTRODUCTION

There is constant pressure on tire manufacturers to increase the daily production of passenger tires. However, on the other hand, there is significant pressure on the overall optimization of production processes and a total shortening of times for individual production cycles. Currently (2022), the trend is introducing automation in all convection production areas. One such area is the rubber industry, which is very extensive in terms of the size of its portfolio [1]. The historical roots of tire production are linked to natural rubber discovered in the Amazon forests in the 18th century. Its intensive use in the industry was helped by the scientific discoveries of vulcanization with sulphur, which date back to 1839 [2].

In the 20th century, in connection with the rapid development of motoring, the production of tires also developed rapidly. Many manufacturers are operating in this market, offering tires of different sizes and drive characteristics. Under extensive competition, there are also several other tire production technologies [3, 4]. The entire tire production process consists of several stages before reaching the final product [5]. The initial phase of tire production is preparing the semi-finished products that make up the tire itself. The production of semi-finished products depends on the type of tire and its required drive properties. After processing and creating the semi-finished products, the next stage is called assembly. The individual semi-finished products are combined into the preliminary shape of the tire (Some publications refer to the term raw tire) [6]. Like every production device, the tire-building drum also brings unwanted production deviations along with the production; as they say, there is always room for improvement. It is precisely in the area of the improvement process that it is necessary always to define a clear goal at the beginning, determine a suitable method for achieving the resulting improvement effect, and work your way up to the desired results. Applying the TRIZ methodology to solve the task, problem parts are named, solution options are defined, and precise optimization proposals are established [7, 8, 9].

This study deals with investigating the problematic node of the assembly line. The assembly of the personal radial tires can be carried out with either one-stage or two-stage technology. The development of tire-building drums deals with many developers all world. Currently, several assembly line manufacturers are operating on the market and, with them, various tire assembly technologies, for example, the Chinese company Mesnac, the Dutch company VMI TIRE and the Slovak company Konštrukta Industry. Also, necessary to say that it exists at present that several patent documents describe the innovative design of this kind of mechanism. Examples are patent documents [10, 11, 12, 13, 14, 15]. The following example is the tire-building drum with a scalable drum shoulder, whose contracted configuration forms a three-layer nested cylinder, as the authors listed in the patent document [16]. The finishing tire-build line (Fig. 1) consists of one machine-technology device to produce raw tires.

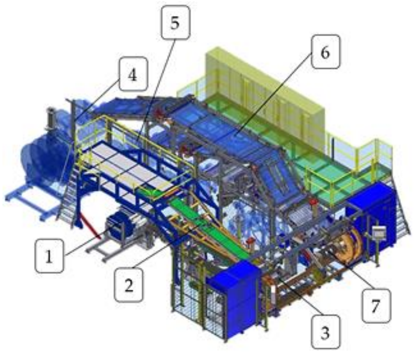

Fig. 1 The finishing tire-building line - single-stage technology
Source: [17].

In general, the conformation line consists of the following parts (Tab. 1).

Table 1
The part of the finishing tire-building line

Position	Title	Note
1	Skeleton stack	
2	Transferring	an exact division of the semi-finished product
3	Ready-made skeleton drum	the foot ropes are wound on the skeleton part
4	Steel bumper stack magazine	
5	Polyamide bumper magazine	
6	Transfer of bumpers	an exact division of the semi-finished product
7	Conformation of the bumper drum	connection of frame and bumper part

The solution of complex parts is identified using the recognised TRIZ methodology, which proves the expertise of the solution and defines the possible causes and their elimination options. A series of tests and the required optimisation are carried out for improvement. Based on the systematic procedure, a system approach to the possibility of testing such types of devices was proposed. The author of this world-renowned and very beneficial TRIZ method in the construction field is the patent officer and inventor Genrich Saulovič Altšuller. The author [18] worked in the post-war period at the patent office, where he came to the idea of the need to examine patents that were already known at that time. It was about analysing these patents to understand the principle of creation of these patents and how the product was approached. With this extensive study, he also identified some standard procedures and features in creating these patent solutions. Another important finding was that relatively few methodical solution procedures achieve innovative/inventive solutions. Thus, the TRIZ methodology is an empirically derived scientific method that contains many solving tools based on knowledge models for stimulating and generating creative thoughts (ideas) and accurate solutions [19, 20, 21, 22].

The conformation tire process is one of the most challenging operations in the rubber industry. This critical process has the most significant influence on the quality of the final product. That is why high demands on skill and responsibility are placed on the worker. Of course, fully automated lines that a worker only fills are gradually introduced to supervisory functions. With the onset of the 4th industrial revolution, more and more emphasis is placed on this area of industrial production. The factors most influence the quality of conformation of the tire are production equipment (assembly line), assembly line operator (in some instances), quality of incoming semi-finished products (always) and environment and methodology of production (know-how).

METHOD, MATERIALS, AND MECHANICAL ELEMENTS

The subject of the experimental investigation is a tire-building drum to produce 15-inch tires for personal cars (Fig. 2). The primary goal of the tire-building drum is forming (shaping) the tire to the state before vulcanisation. Currently, the 4.0 industrial revolution is being implemented, focusing primarily on the efficiency of the production process through the automation of production processes with autonomous software control [23, 24]. Continuous research and development are also being carried out in new production lines for the rubber industry. The developers primarily focus on the tire-building drums for production tires.

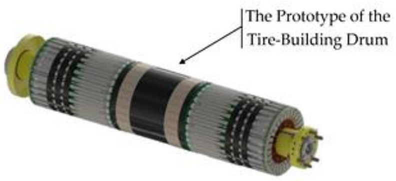

Fig. 2 The tire-building drum

This is mainly due to the need to speed up and make the process of making passenger car tires more efficient. A technical contradiction (Fig. 3) describes a situation where improving one part of the technical system using the usual methods leads to the deterioration of another mechanical function.

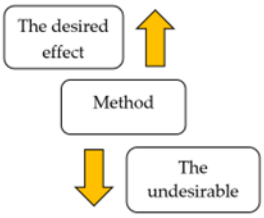

Fig. 3 A general model of technical contradiction

Two significant problems were revealed during the analysed of the tire-building drum. Problem no. 1, stated in the diagram below (Fig. 4), represents the higher weight of the tire-building drum itself, which ultimately generates a more significant load on the shaft of the tire-building drum.

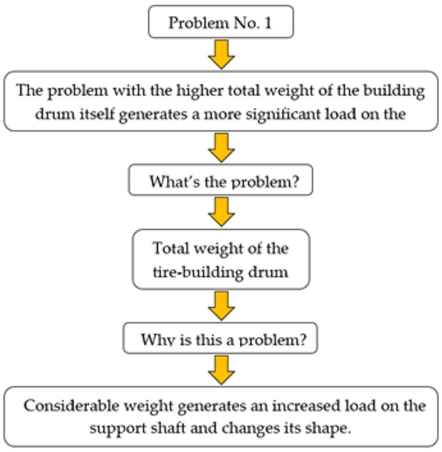

Fig. 4 Process diagram No. 1

During the search for the solution, two technical problems were identified that needed to remove using the synthetic phase of innovation, which deals with solving the innovation tasks. The synthetic phase provides answers to the fundamental question "How?" [25]. The ARIZ tool (algorithm for solving creative assignments) was used to solve this stage. This tool offers several possible procedures to find the right solution to the problem. However, the undesirable effect doesn't have to be manifested or be significantly limited.

With the help of the correct formulation of the technical contradiction, a system solution can be applied to achieve the desired mechanical properties. In this case, the main problem is the current total weight of the individual parts of the tire-building drum (Tab. 2).

Table 2
Formulation of technical contradiction point no. 1

Technical breakdown of the weight of the individual parts of the tire-building drum	
If	If we reduce the total weight of the construction of the individual parts of the building tire drum by optimizing from the point of view of changing the materials of certain mechanical elements.
After	We will achieve a reduction of the load acting from its own weight to change the shape of the support shaft.
But	Some mechanical properties of individual parts may deteriorate, and the service life of individual components may also be reduced.

The identification of typical improving and deteriorating parameters was realised according to the Altshuller table with 39 items of standard technical parameters. The first technical discrepancy is stated in the diagram below. The following graph describes the advance of the solution to the first problem (Fig. 5).

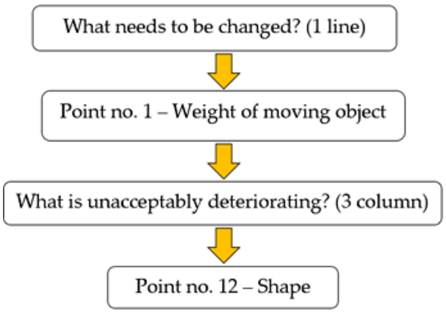

Fig. 5 Process diagram solution of problem no.1 (table 3)

Combining 2 points (no.1 and no.12) in the table (Tab. 3) brings the recommended solutions according to heuristic principles, specifically no.10, 14, 35 and 40. Inventive principle of no. 35 is most suitable for achieving improvement because it presents changes in the object's composition and parameters/properties.

Table 3
Representation of a selection from Altshuller's 39 parameters' classic technical properties

What needs to be changed?	What is unacceptably deteriorating?			
	10	11	12 Shape	13
1 Weight of moving object	⇒		10 14 **35** 40	1 35 1 9 39
2 Weight of non-moving object	8 10 1 9 35	13 29 10 18	13 10 29 14	26 39 1 40
3 Length of moving object	28 10	1 14 35	10 29 13 14	39 37 35
4 Length of non-moving object	28 10	1 14 35	13 14 15 7	39 37 35
5 Area of moving object	19 30 35 2	10 15 36 28	5 34 29 4	11 2 1 3 39

Problem No. 2, stated in the following diagram (Fig. 6), represents the deformation of the shaft of the tire-building drum, which is adversely manifested in the deteriorated symmetry during the making of tires.

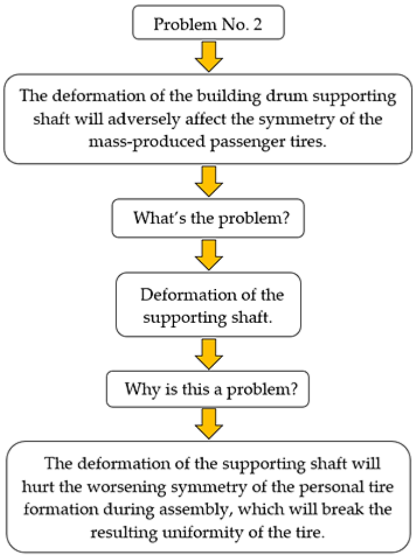

Fig. 6 Process diagram No. 2

The formulation of technical contradiction point no. 2 is stated in the table below (Tab. 4).

Table 4

Formulation of technical contradiction point no. 2

Technical breakdown of the weight of the individual parts of the tire-building drum	
If	Increasing the strength of the shaft by using a reduction in the total load of the tire-building drum
After	An improvement in the symmetry during the tire building and, thus, the overall productivity of the tire-building drum will be achieved
But	At the expense of reducing the load on the shaft, the service life of individual parts can be reduced.

Combining 2 points (no.14 and no.39) in the table (Tab. 5) brings the recommended solutions according to heuristic principles, specifically no.29, 35, 10 and 14. The following graph describes the advance of the solution to the first problem (Fig. 7). In this case, the principle of fulfilling contradictory requirements is applied to solve the physical contradiction so that both conditions can be fulfilled simultaneously.

Table 5

Representation of a selection from Altshuller's 39 parameters' classic technical properties

What needs to be changed?	**What is deteriorating unacceptably?**			
	36	37	38	39 Productivity, performace
12. Shape	16 29 1 28	15 13 39	15 1 32	
13 Stability of object (resistance to change)	2 35 22 26	35 22 39 23	1 8 35	
14 Strength				29 35 10 14
15 Durability of moving object	10 4 29 15	19 29 39 35	6,10	35 17 14 19
16 Durability of non-moving object	N/a	25 34 6 35	1	20 10 16 3 38

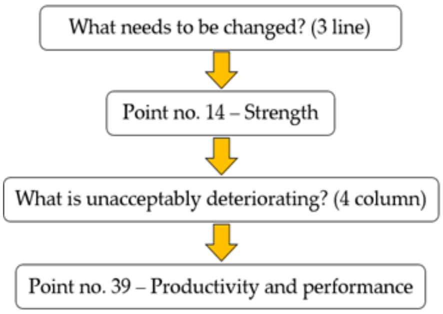

Fig. 7 Process diagram solution of problem no.1 (Table 5)

Physical contradiction

Technical and physical contradictions can be defined based on the technical system model conflict definition. A detailed description of the mentioned method can be found in the literature [16]. Generally, the physical contradiction represents two contradictory requirements placed on one physical parameter of the tire-building drum (Fig. 8). Acceptable results can reach using the following inventive principles, marked no. 10, 14, 29, 35, 40. As mentioned in the technical contradictions section, the most suitable method for solving the problem is marked no. 35, the so-called process of changing the parameters. The proposed solution can be viewed in different ways. One way to solve the problem is to change the material.

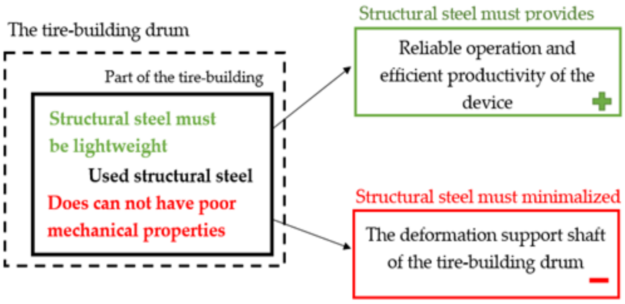

Fig. 8 Physical contradiction model of the tire-building drum

Verification stage – specific solution

The main problem, which significantly affects the correct functioning of the tire-building drum and the accuracy of the tire production, can be solved using an inventive method known as changing the parameters. Based on an extensive study using the TRIZ methodology, it was possible to identify the problem and subsequently determine the direction of the best solution. To achieve an innovative improvement of the technical system, it is necessary to re-evaluate the tire-building drum construction from the point of view of the materials used. The proposal aims to optimize the drum's structural design from the weight's point of view [11]. The weight of the individual mechanical elements of the drum subsystem is shown in the table below (Tab. 6).

In this case, it was found that it would be appropriate to focus on a possible change of material and evaluate the mass aspect of the constructions of the individual technical subsystems of the tire-building drum. A significant share in the increased weight of the technical system is the use of steel as the primary material of a large part of the structural elements.

Table 6
Analysis of the weight of individual TS subsystems of tire building drum

No.	Name of the subsystem TS	Weight
1	Shaft of drum	135.85 [kg]
2	Left pneumatic cylinder	100.99 [kg]
3	Left lever of the wrapping mechanism	51.8 [kg]
4	Right pneumatic cylinder	100.99 [kg]
5	Right lever of the wrapping mechanism	51.28 [kg]
6	Middle mechanism	14.89 [kg]
7	Total	455.29 [kg]

As is known, steel has excellent mechanical and dynamic properties, but at the expense of higher weight. Unfortunately, the higher weight causes the technical system to show certain operating deviations when fulfilling its primary function. The lever wrapping mechanism of the tire-building drum, which form the technical subsystem of the drum, is suitable for optimization either from the view of its current weight or function. The existing material composition of the structure of the wrapping mechanism consists of steel and copper in the present time (Fig. 9).

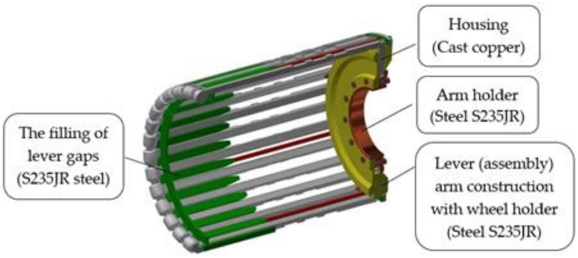

Fig. 9 Lever wrapping mechanism of the tire-building drum

Various factors, such as functional importance, strain range, and testing range, were considered when selecting materials (Tab. 7). The lever mechanism consists of 29 levers around the perimeter. The task of filling the lever gaps is to ensure the definition of the position of the lever in the idle state and to complete the peripheral surface for the winding of the semi-finished product in the initial phase of the assembly process. For this reason, the potential of replacing steel with plastic arises because this subassembly does not even serve as reinforcement and strengthening.

Table 7
Weights of selected parts before and after material optimization

	Weight before		Weight after		Total
Part/ assembly	Steel S235JR	Cooper	Aluminium	Plastic	Diff.
		3.26	0.985	-	2.275
The case	12.938	-	4.445	-	8.493
Arm holder	8.393	-	-	1.269	7.124
Lever	22.359	-	7.946	-	14.413
Total	43.69	3.26	13.376	1.269	-
Together total	46.95		14.64		32.305

From the data in the above table (Tab. 7), it can be concluded that when using aluminium alloy and plastic, it is possible to achieve a significant reduction in weight, which could have a positive effect on reducing the size of the load acting on the supporting shaft.

The made saving of the weight amounts to 32.305 kg. The central support element is also selected for optimisation (Fig. 10).

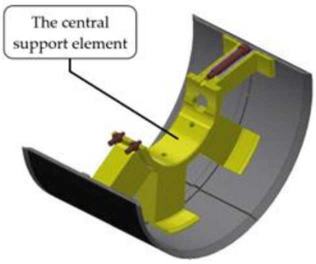

Fig. 10 The central support element of the tire-building drum

From the data in the above table (Tab. 7), it can be concluded that when using aluminium alloy and plastic, it is possible to achieve a significant reduction in weight, which could have a positive effect on reducing the size of the load acting on the supporting shaft. The made saving of the weight amounts to 32.305 kg. The central support element is also selected for optimisation (Fig. 10).

The middle part of the tire-building drum consists of the so-called central support element. This part is made of steel and will be replaced by aluminium (Tab. 8). Its task is to ensure the correct fit of the steel cords to the semi-finished product when the tire is formed by blowing compressed air. The made saving of the weight amounts to 5.778 kg.

Table 8
Weight of the holder shaft before and after material optimization

Title	Weight before	Weight after	Savinng weight
Part/assembly	Steel S235JR	Aluminium alloy	Diff.
The middle part	8.802	3.024	5.778

The pneumatic cylinder (Fig. 11) forms an integral part of the tire-building drum because it ensures sliding movement towards the centre. The pneumatic cylinder ensures the movement of the lever mechanism during the rolling process. This subsystem represents a complex system in terms of construction and functionality. Therefore, when

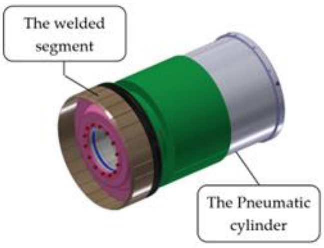

Fig. 11 Pneumatic cylinder of the wrapping mechanism

choosing a part suitable for optimization, only one element is considered, as an intervention in the structure of the cylindrical portion of the pneumatic cylinder would require much more complex structural modifications and subsequent testing after these modifications.
Weight of the welded segment before and after material optimization (Tab. 9).

Table 9
Weight of the welded segment before and after material optimization

Title	**Weight before**	**Weight after**	**Savinng weight**
Materials	Steel S235JR	Aluminium alloy	Diff.
The welded segment	13.609	4.675	8.934

The results in the following table (Tab. 10) express the weight savings of the individual parts of the tire-building drum. Savings were achieved by replacing some steel parts with aluminium alloy and plastic, which ultimately reduced the total weight tire-building drum by 88.256 kg.

Table 10
Summarized the results of optimizing the weight of individual parts of the tire-building drum

The technical subsystem	**Weight status before optimization [kg]**	**Weight status after optimization [kg]**	**Diff. [kg]**
The shaft	135.853	135.853	0
Right lever folding mechanism	51.283	18.978	32.305
Left lever folding mechanism	51.283	18.978	32.305
Intermediate mechanism	14.891	9.113	5.778
Right pneumatic cylinder	100.9	91.966	8.934
Left pneumatic cylinder	100.9	91.966	8.934
Total	455.29	366.854	88.256

This significant weight reduction should positively affect the overall load acting on the support shaft. It can be seen in the table that the significant saving was achieved precisely with the lever baling mechanism, up to 32.305 kg. The current state of the ready-made skeleton drum's total weight after optimizing the structure's weight reaches a value of 366.854 kg. It is, therefore, possible to state that the optimization goal of reducing the importance of the individual parts of the tire-building drum has been achieved.

EXPERIMENTAL

The problematic parts of the tire-building drum were identified in the previous chapter using the TRIZ methodology. In the next stage, they are analysed. The primary task of the tire-building drum shaft is carrying the tire-building drum's total weight and ensuring the entire Technical system rotation. From the point of view of construction, the tire-building drum represents a very complex specialized subsystem with many parts. In addition to its primary role, its construction includes a pneumatic distribution of a compressed air system, meaning the other technical system subsystems' driving force.
The structure (Fig. 12) has the character of a hollow shaft (1), while inside, there is a linear guide (2), the task of which is to ensure sliding movement (3), which has continuity with the other subsystems (left and right piston). This linear guidance provides both subsystems' displacement towards the shaft's centre. The linear guide is stored in bearings (4). The rest of the structure consists of common structural elements with the majority character of purchased parts. Due to the complexity of the construction of the hollow shaft, the functionality in implementing the compressed air distribution (5) directly into the building is not considered in this case with the optimization of this technical subsystem.

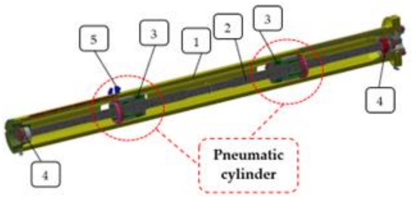

Fig. 12 The supporting shaft of the tire building drum

At the beginning of the stress and deformation analysis, it is necessary to define the size and position of the loading forces on the supporting shaft and to calculate the size of the reaction forces in these places. The loading "F" represents the value of the tire-building drum's weight, which act on the subsystem placed on the shaft (Fig. 13).

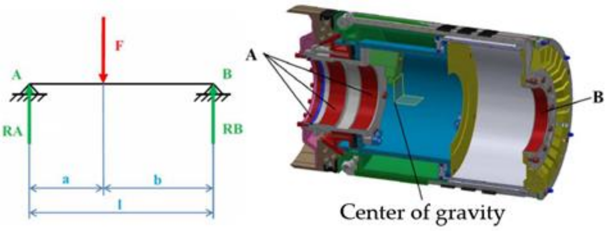

Fig. 13 Calculation Support reactions (left) and place of bearings on the shaft (Sign A, B), (right)

The parameters in the table below were used to calculate the supporting reactions (Tab. 11).

Table 11
The parameters of calculation before optimization

Designation	**Value**	**Units**
Weight of the right pneumatic cylinder	100.99	[Kg]
Weight of the left pneumatic cylinder	51.283	[Kg]
Weight of the both technical systems	152.273	[Kg]
Force	1493.8	[N]
Length - a	167.314	[mm]
Length - b	303.586	[mm]
Length - l	470.900	[mm]

Next is the static analysis of the supporting shaft of the existing technical system using the ANSYS Workbench software. Bearings support the rotating solid steel shaft at points A and B. Three equations are prepared, which present equations of the solid steel shaft for static balance in the "X" (Eq. 1) and "Y" (Eq. 2) axis, and also the equation for the bending moment M_A (Eq.3) [26].

$$\sum F_x = 0 \tag{1}$$

$$\sum F_y = 0 \ \rightarrow R_A - F + R_B = 0 \tag{2}$$

$$\sum M_A = (F \times a) - (R_B \times l) = 0 \tag{3}$$

Equation (2) is adjusted into the following relationship (4).

$$R_A = F - R_B, \ [N] \tag{4}$$

Also, equation (3) is adjusted into the relationship (5).

$$R_B = \frac{F \times a}{l}, \ [N] \tag{5}$$

The following task is to determine the size of the deformation of the supporting shaft in the form of the total deformation and the resulting stress curve. The bearing shaft is recalculated in two calculations for the Y and Z axes load. The simulation is prepared to show how the tension and deflection will develop since the supporting shaft has re-cessed both sides, which weakens the rigidity. Boundary conditions for the shaft of the tire-building drum loaded in axis Y are viewed graphically in the figure below (Fig. 14).

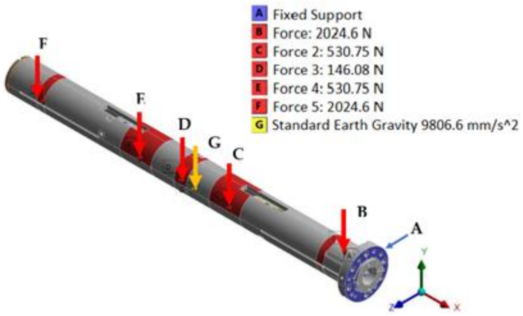

Fig. 14 The static analysis of the shaft of the tire-building drum – Y-axis

The boundary conditions implemented in the Z axis (Fig. 15) are thus defined in the same way as in the previous calculation of the Y axis. The element size of the finite element mesh was designed optimally to make the result as accurate as possible.

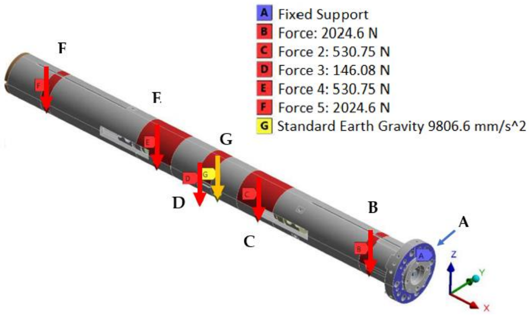

Fig. 15 The static analysis of the shaft of the tire-building drum – Z-axis

The shaft of the tire-building drum is loaded by the reaction forces of the individual parts of the tire-building drum, which arise in the place of storage as a reaction from the own weight of these parts. One side of the shafting has worked grooved for the tight tongue. The shaft of the tire-building drum is loaded by the reaction forces of the individual parts of the tire-building drum, which arise in the place of storage as a reaction from the own weight of these parts. Next, boundary conditions are set for the lever-wrapping mechanism (Fig. 16), which is also subjected to calculating the Equivalent Stress and total deformation.

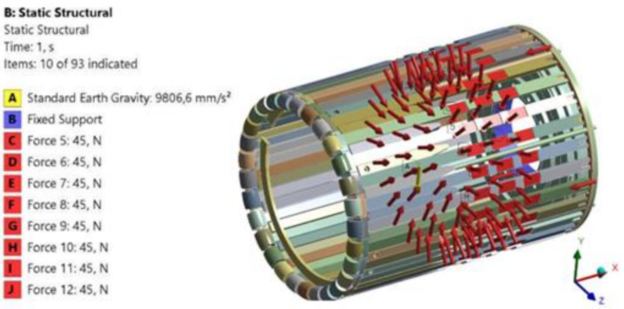

Fig. 16 Boundary conditions for the calculation of the lever wrapping mechanism

The controller of the wrapping lever is the last element subjected to the calculation. The setting of the boundary conditions is stated in the figure below (Fig. 17).

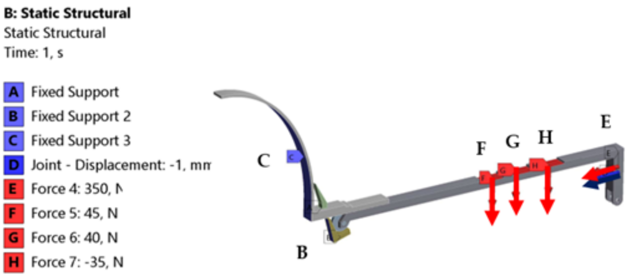

Fig. 17 Boundary conditions of the calculation of the wrapping lever

RESULTS OF THE SIMULATIONS

The verification progress run using a simulation in the ANSYS Workbench environment software. The experiment's first phase is realized calculation of the Equivalent Stress of the shaft of the tire-building drum, made with structural steel (S235JR) and loaded is a total weight of 455.29 kg in the Y and Z-axis. The result of the Equivalent stress in the Y-axis (Fig. 18) and the Z-axis (Fig. 19) are stated below.

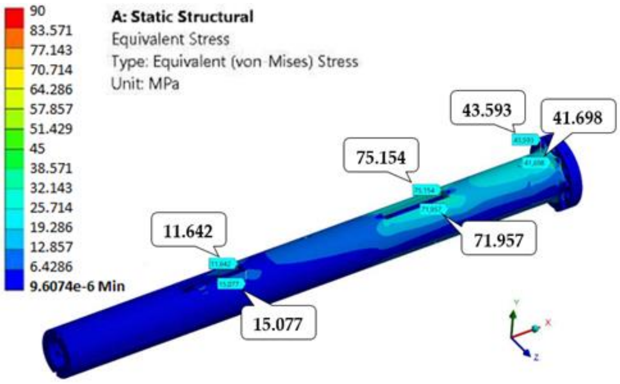

Fig. 18 Equivalent (von Mises) Stress for Y-axis

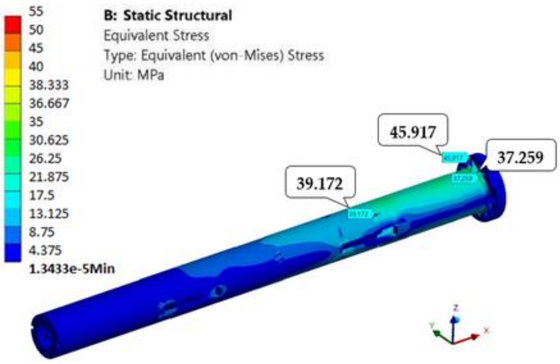

Fig. 19 Equivalent (von-Mises) Stress for Z-axis

The following phase calculates the Total deformation for the tire-building shaft loaded same weight of 455.29 kg. The calculation is realized in Y (Fig. 20) and Z-axis (Fig. 21).

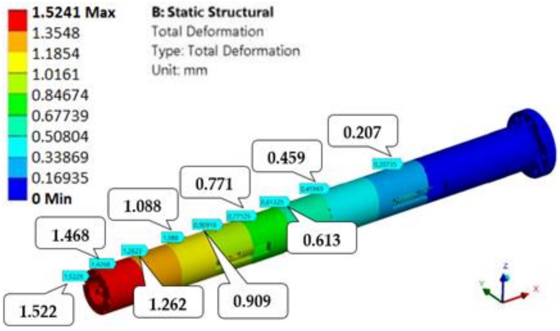

Fig. 20 Deformation in the Y-axis

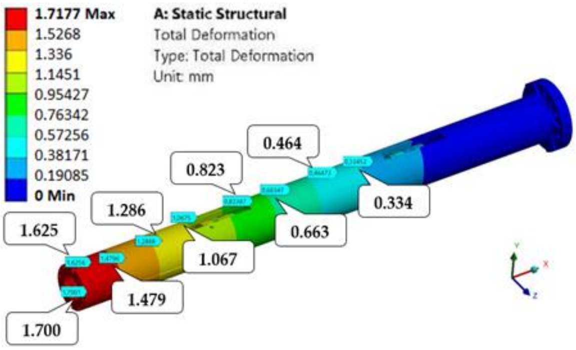

Fig. 21 Deformation in the Z-axis

The results are viewed in the following figures.
The table listed the results of the Stress von-mises and total deformation (Tab. 12) for the Y and Z-axis setting.

Table 12
Results of the static analysis of the supporting shaft in the direction of the Y-axis and Z-axis

Axis	Stress von-mises	Total deformation
Y axis	90 [MPa]	1.717 [mm]
Z axis	55 [MPa]	1.524 [mm]

The following calculation is the same as in the previous Equivalent Stress and Total deformation of shaft analysis. The results are for Y-axis (Fig. 22), and Z-axis (Fig. 23) stated in the figures below.

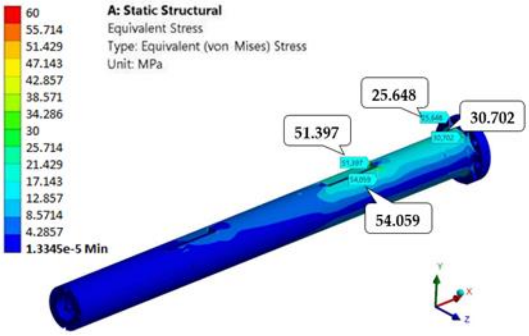

Fig. 22 Equivalent (von-Mises) Stress for Y-axis

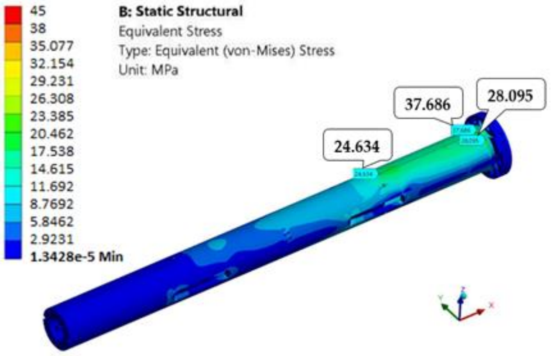

Fig. 23 Equivalent (von Mises) Stress for Z-axis

The change material of the subsystem brings a smaller weight for the tire-building drum. Therefore, the simulation is set with less weight of 366.854 kg. The last phase calculates the Total deformation of the tire-building drum shaft after material modification of the subsystem. The total weight is, in this case, also 366.854 kg. The calculation is realized in Y (Fig. 24) and Z-axis (Fig. 25). The results are viewed in the following figures.

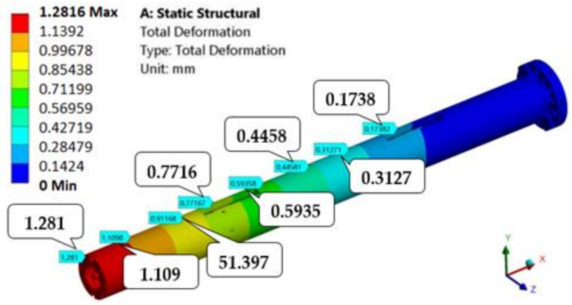

Fig. 24 Deformation in the Y-axis

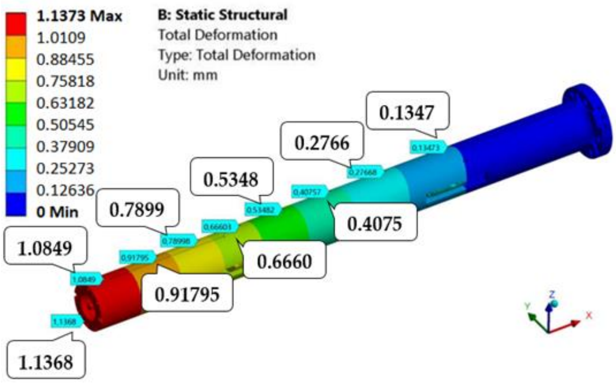

Fig. 25 Deformation in the Z-axis

Comparison of the shaft of the tire-building drum simulation results before and after optimization in the Y and Z axis are stated in the table below (Tab. 13). The effects of the Equivalent stress and Total deformation after the change material are significantly lower and acceptable.

Table 13
The comparison of the results of stress and deformation in the Y and Z axes

	Before optimisation		After optimisation	Improvement achieved
Axis –Y–	Stress von-mises	90 [MPa]	55 [MPa]	35 [MPa]
	Total deformation	1.717 [mm]	1.281 [mm]	0.436 [mm]
Axis –Z–	Stress von-mises	60 [MPa]	45 [MPa]	15 [MPa]
	Total deformation	1.524 [mm]	1.137 [mm]	0.386 [mm]

The Equivalent Stress and Total deformation simulation are also realized for the lever wrapping mechanism. The simulation results are stated only for calculating the lever wrapping mechanism with optimized weight. The first result is the stated for Equivalent Stress (Fig. 26).

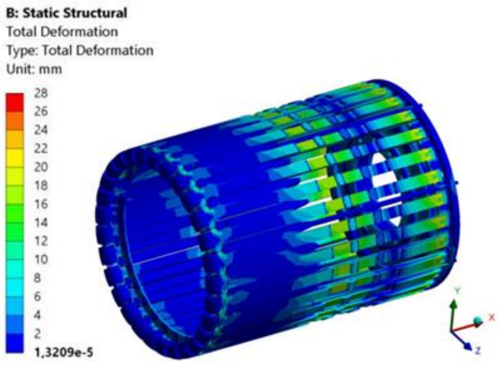

Fig. 26 Equivalent Stress of the lever wrapping mechanism

The maximum value (peak) of the equivalent stress was 28 MPa. The stress distribution is most concentrated in the area of the lever arms. The greatest stress concentration is focused at the point of the bend of the lever and the last storage groove for the rubber belts. It can be concluded that the results of the equivalent stress do not have a very negative effect on the construction of the mechanism. Similarly, as in the first case, the result of the total deformation is only stated for the optimised lever wrapping mechanism (Fig. 27).

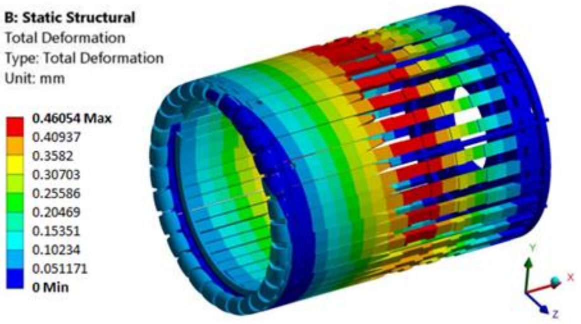

Fig. 27 Deformations of the lever wrapping mechanism

The resulting deformation of the wrapping lever mechanism is 0.192 mm. Also, it meets the required structure conditions of the device. In these technical settings, no damage device will occur in the future. The results for the Wrapping lever mechanism are summarised in the table below (Tab. 14).

Table 14
The summarized results before/after the material optimisation of the Wrapping lever mechanism

	Before optimisation	After optimisation	Results
Equivalent Stress	28 [MPa]	28 [MPa]	0 [MPa]
Total deformation	0.1922 [mm]	0.4605 [mm]	0.2683 [mm]

The last stage of the experiment is to prepare a simulation of the Equivalent stress and Total deformation. Results are only stated for the optimised Wrapping lever. The resulting course of the total equivalent stress with a maximum value of ~ 80 MPa can be seen below (Fig. 28). The tension is most concentrated in the places of the milled grooves for placing the rubber belts.

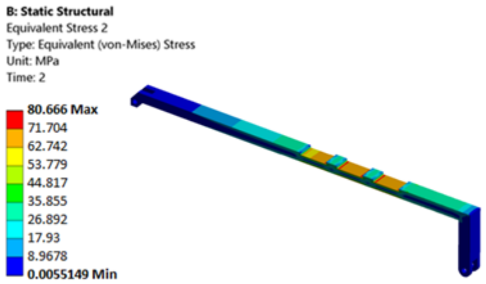

Fig. 28 Equivalent (von Mises) Stress of the wrapping lever

The resulting course of the Total deformation with a maximum value of ~ 4.8 mm can be seen in Fig. 29. However, this value represents the deformation in the tire area wrapping around the beads. In the end part of the lever near the pulley, those values are an order of magnitude lower, which does not represent a possible risk. The result of the Total deformation is viewed below.

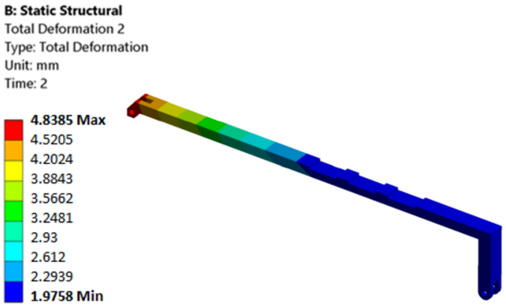

Fig. 29 Total deformation of the wrapping lever

The results for the Wrapping lever are summarised in the table below (Tab. 15).

In conclusion, it can be stated that the achieved results represent an improvement and point to the correctness of optimizing with the help of material change, which arose from the TRIZ methodology when the technical and physical contradiction was correctly identified.

Table 15
The summarized results before/after the material optimisation of the Wrapping lever

	Before optimisation	**After optimisation**	**Results**
Stress von mises	83.232 [MPa]	80.666 [MPa]	2.566 [MPa]
Total deformation	4.8379 [mm]	4.8385 [mm]	0.0006 [mm]

Modal analysis

Modal analysis (Fig. 30) is solved by the Finite Element Method (FEM) using ANSYS software.

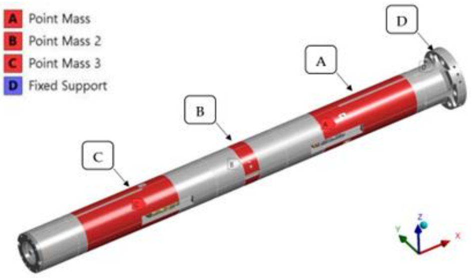

Fig. 30 Modal analysis setting

Due to a large number of output numeric data of the modal analysis simulation, only the results table is presented. It analyses natural frequency, where the finite element network consists of linear elements. The oscillation tendency changes with the gradual increase of natural frequencies. The table (Tab. 16) shows the results of the first six mode shapes of the system with the corresponding natural frequency.

Table 16
The table of the results of the modal analysis

Mode shape	1	2	3	4	5	6
Natural frequencies Quadratic elements	20.0 [Hz]	21.1 [Hz]	42.7 [Hz]	42.7 [Hz]	79.6 [Hz]	107.9 [Hz]
Natural frequencies Linear elements	23.6 [Hz]	24.4 [Hz]	80.9 [Hz]	81.9 [Hz]	105.3 [Hz]	114.4 [Hz]

In the first two own mode shapes, the whole system vibrates. In the following two mode shapes (3 and 4), oscillation tends to manifest mainly on the linear line. Change in mode shape No. 5 is primarily viewed on the hollow shaft. In the final mode shape, No. 6, the mechanical system oscillates again at a much higher natural frequency than with mode shapes No. 1 and No. 2.

CONCLUSION AND DISCUSSION

After a comprehensive analysis of the issue of tire production, weak structural points of the assembly line were identified, which could be improved through appropriately chosen optimization. Among the most problematic parts is the centring system of individual components during the entire assembly process, from the winding of the details to the ready-made shape of the tire. The shortcomings of the centring system cause a dynamic imbalance of the tire, which would be significantly manifested by rolling during operation. It is necessary to eliminate this problem by adding weights around the tire's circumference so that the roll is reduced to the limit of possible permissible deviations prescribed by the manufacturer. Another shortcoming that can arise during tire production is the uniform distribution of joints during the assembly of individual tire components. Improper allocation of joints leads to the creation of weak points of the tire prone to deformation during the assembly process or permanent breach of integrity. Using the optimization of problem nodes, a significant reduction in the possible occurrence of adverse effects on the resulting parameters of the tire was achieved.

The problem was solved using the world-renowned scientific method TRIZ. The material optimization of the ready-made drum brought positive results in the area of weight and also in the resulting course of stresses and deformations, which were verified using control simulations. The chosen method of solving the mentioned problem is in line with the trend of current development because more and more emphasis is placed on the virtual testing of systems using software before accurate prototype testing. Ultimately, computer support saves costs spent on development.

In conclusion, it can be concluded that the simulation of stress and deformation couplings yields results that point to a positive contribution to achieving the improvement of the primary function of the technical system, which is the formation of the basic shape of the tire to the state before vulcanization. The results also showed that optimizing some parts of the assembly drum system makes it possible to increase the productivity of the assembly line and thus reduce the number of non-conforming products. The study output is also a systematic procedure for testing the technical system, which can help designers design and optimize some parts of similar technical systems.

ACKNOWLEDGEMENTS

This article was funded by the University of Žilina project 313011ASY4 – "Strategic implementation of additive technologies to strengthen the intervention capacities of emergencies caused by the COVID – 19 pandemics".

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Peter Števko
ORCID ID: 0000-0001-5639-9442
University of Zilina
Faculty of Mechanical Engineering
Department of Design and Mechanical Elements
Univerzitna 8215/1, 010 26 Zilina, Slovakia
e-mail: peter.stevko@fstroj.uniza.sk

Róbert Kohár
ORCID ID: 0000-0001-7872-2829
University of Zilina
Faculty of Mechanical Engineering
Department of Design and Mechanical Elements
Univerzitna 8215/1, 010 26 Zilina, Slovakia
e-mail: robert.kohar@fstroj.uniza.sk

Damián Čechmánek
ORCID ID: 0000-0003-2143-6009
University of Zilina
Faculty of Mechanical Engineering
Department of Design and Mechanical Elements
Univerzitna 8215/1, 010 26 Zilina, Slovakia
e-mail: damian.cechmanek@fstroj.uniza.sk

Denisa Medvecká
ORCID ID: 0000-0002-0553-885X
University of Zilina
Faculty of Mechanical Engineering
Research and Service Centre
Univerzitna 8215/1, 010 26 Zilina, Slovakia
e-mail: denisa.medvecka@fstroj.uniza.sk

František Nový
ORCID ID: 0000-0002-7527-5020
University of Zilina
Faculty of Mechanical Engineering
Department of Materials Engineering
Univerzitna 8215/1, 010 26 Zilina, Slovakia
e-mail: frantisek.novy@fstroj.uniza.sk