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Research Article

Design of the shafts of a driven conveyor as part of a mobile working machine modification

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Abstract: The purchase of professional technical equipment for processing wooden logs does not always mean the trouble-free processing of a product. One such case is the mobile working machine solved in this research. There was found insufficient semi-automation of processes, technical documentation that did not correspond to the actual state, the need for tremendous effort from the operating personnel, the complete inoperability of some processes and the manufacturer's inability to solve the deficiencies of the machine. These are the reasons and motivations for the creation of the presented applied research, dealing mainly with the elimination of the aforementioned shortcomings. Commonly available and offered peripherals and accessories for the machine are not compatible, and therefore, the authors decided to implement their design to significantly improve the given state. At the same time, the results can be helpful in creating improvement designs for the technical equipment in question for a variety of manufacturers. The main of the given research is to design a driven conveyor of the machine. It is a specifically adapted chain conveyor as the input part of the machine.

Keywords: mobile working machine; finite element method; driven conveyor; wood processing

I. INTRODUCTION

Heating homes in rural areas and cottages with solid fuels, coal and especially wood, has always been one of the most popular methods of heating. With the development of technology and growing ecological thinking, humanity is looking for alternative ways to heat family homes [1]. The most frequently sought-after heating methods today are solar panels, heat pumps, gas boilers, pellet boilers and, of course, tiled stoves and fireplaces. However, in today's times of crisis and high gas and electricity prices, people are again interested in buying firewood, so they are returning to traditional methods of heating family homes and older homes. Therefore, heating by solid fuels, especially wood, is on the rise. Today's modern heating technologies offer many options for heating with wood, which are already built to comply with ever-tightening emission standards.

Preparing logs as the final product for a fireplace or stove is a demanding process. It requires considerable physical effort inherent in the manipulation of the wood mass to the previously mentioned final product [2]. In domestic conditions, people mostly use hand tools. However, they can also help themselves with electric machines, such as the wood splitter presented in this article (**Fig. 1**).

Figure 1. *A solved mobile working machine with additional input belt conveyor*

A conveyor is a part of a manipulation machine, which allows the transport of piece goods as well as bulk goods [3, 4]. It can be found in many kinds of enterprises, such as postal services, airport terminals [5], construction companies, the food industry [6, 7], the woodworking industry and others [8, 9]. Conveyors are even structural units of machines that serve for building roads and railway tracks for handling stones [10], asphalt and other materials during building and reconstruction of roads and railway tracks [11–15]. In addition, there are also smaller machines equipped with conveyors used in households. Depending on the goods transported, conveyors must meet the criteria from the strength point of view as well as from the dynamic point of view [16–18]. The main loaded components of conveyors are belts and shafts. Belts are usually made of rubber or plastic material [19–22], but other materials can also be found in their structure. The belts of a conveyor are stretched between two end shafts, which ensure their movement. Depending on the needs of the transported load, one or both shafts are driven. In the case solved in this research, only one is a drive shaft, and the other is a driven shaft. Such a technical solution has significantly lower demands for synchronization for the drive motor in comparison with two drive shafts [23, 24].

As already mentioned in the work [2], the operation of the machine consists of transporting the log to the working area, where the operator cuts it into specified lengths of blocks with a chain saw. Then, the splitting wedge, controlled by a hydraulic piston, splits the blocks. All working structural units are driven hydraulically from a pump driven by an electric motor with an output of 9.5 kW. The manufacturer of the machine in the accompanying technical documentation states that the maximum diameter of the input log d = 500 mm. However, the problem is that such a large log will not fit into the machine. It is possible to work with a maximum diameter of approximately 450 mm. However, even in this case, another problem arises, i.e., with the log being transported.

The splitting semi-automatic machine is sold together with an input roller conveyor 1 meter long without a drive [2]. Therefore, the log must be transported to the machine and the saw by hand. This represents approximately a meter of distance along the sheet metal part of the machine structure with significant friction. Therefore, manual transport of the log was eliminated by purchasing an additional belt conveyor (**Fig. 2**) driven by a hydraulic motor. This conveyor includes two shafts, which are designated for this research purposes as shaft No. 1 and shaft No. 2. Considering the drive force transmission, shaft No. 1 is the drive shaft and shaft No. 2 is the driven shaft. This step served as a replacement for the original roller conveyor. However, when testing the machine, it was found that the log is transported by the conveyor only until the moment it passes from the belt conveyor to the sheet metal part of the structure (**Fig. 2**). There, the log either hits the machine structure or, after passing to the sheet metal part, is stopped by passive resistance associated with the log slipping on the conveyor.

For this reason, it is necessary to optimize the input conveyor and the article in question deals with the second part of this task, i.e., the design of the chain conveyor shafts. The authors presented in the article [2] their conceptual design of a chain conveyor, which will consist of two separate chain conveyors. The first of them will be foldable when transporting the machine. The location of the hydraulic motor (the motor from the purchased additional belt conveyor will be used) will be on the machine frame, and it would drive the shaft on the conveyor using a chain. A chain conveyor is more suitable for the transmission of larger forces, and there is no slippage between the chain and the sprocket. From the point of view of maintenance, the proposed variant is also suitable because a significantly smaller number of lubricated bearing houses is required in comparison with a belt conveyor. The authors also designed chains and sprockets in the work [2]. The current work aims to design conveyor shafts verified by analytical and numerical dimensioning and to build an accurate 3D CAD model of the proposed structure.

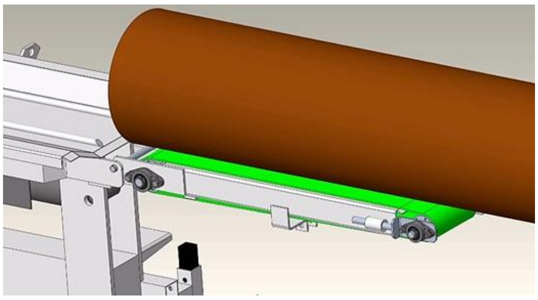

Figure 2. *A three-dimensional CAD model of the driven conveyor at the time of the log's transition from the conveyor to the sheet metal part of the machine*

II. MATERIALS AND METHODS

The calculations are based on the free body diagram method. The essential of this method consists in the fact, that coupling are replaced by forces and reactions. The first proposed chain conveyor has 2 shafts (**Fig. 3**). For each of them, the maximum torsional stress is calculated according to equation (1) or the bending stress according to equation (3). In the case of a shaft subjected to both torsion and bending, the reduced stress is calculated from the maximum stresses according to equation (5). The input values of the maximum bending and torsional moments will be obtained from the relevant analytical calculations. The suitability of each shaft will be verified in the FEM software Ansys. The maximum stresses found will be compared with the allowable stress σ_d, determined by equation (6). Both shafts will be designed with a diameter d = 20 mm in terms of the sprockets used [2]. Calculation of the torsional stress τ , see Eq.(1):

$$\tau = \frac{M_k}{W_k}, \tag{1}$$

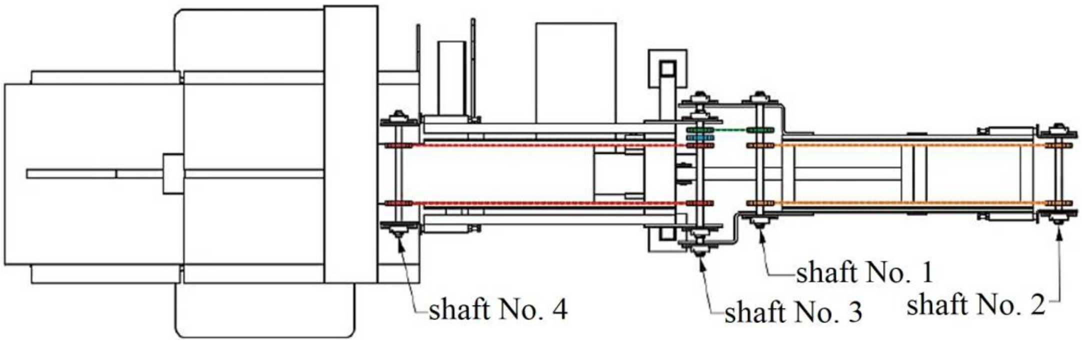

Figure 3. *A solved mobile working machine with additional input belt conveyor*

while for the circular cross-section of the shaft, see Eq.(2):

$$W_k = \frac{\pi \cdot d^3}{16}. \tag{2}$$

Calculation of bending stress is seen in Eq.(3):

$$\sigma = \frac{M_o}{W_o}, \tag{3}$$

whereas the circular cross-section of the shaft (Eq. (2)) applies Eq.(4):

$$W_o = \frac{\pi \cdot d^3}{32}. \tag{4}$$

Calculation of the reduced stress is based on Eq.(5):

$$\sigma_{red} = \sqrt{\sigma^2 + 3 \cdot \tau^2}. \tag{5}$$

Calculation of the allowable stress of shafts (Eq.(6)), which are designed from material S355J0 steel, the yield strength is R_e = 355 MPa, the considered safety factor k = 2 and the dynamic load factor δ = 1.6:

$$\sigma_{dov} = \tau_{dov} = \frac{R_e}{k \cdot \delta}. \tag{6}$$

The drive shaft No. 1 will be subjected to the torsional and bending stresses by the sprockets during operation, while the stress on the driven shaft No. 2 is assumed to be only bending.

The torsional stress on shaft No. 1 can be determined using the equilibrium condition (Eq.(7)) according to the diagram in **Fig. 4**:

$$\sum M_i = M_k - M_{k1} - M_{k1} = 0. \tag{7}$$

A scheme of the considered load of shaft No. 2 is depicted in **Fig. 5**. As reported in [2], the value of the transmitted torque M_k is 18.91 Nm. The torque curves were determined by the classical elasticity and strength of materials. The bending effects on the shaft No. 1 can be quantified using Eq.(8):

$$\sum M_{iA1} = F_{N1} \cdot 0.05875 + F_{N1} \cdot (0.05875 + 0{,}1791) + R_{B1} \cdot 0.3866 = 0, \tag{8}$$

from which, after insertion, the reaction R_{B1} is obtained in the right bearing. The same procedure applies to the sum of the moments into the bearing B_1, from which, after insertion, the reaction R_{A1} is obtained in the left bearing.

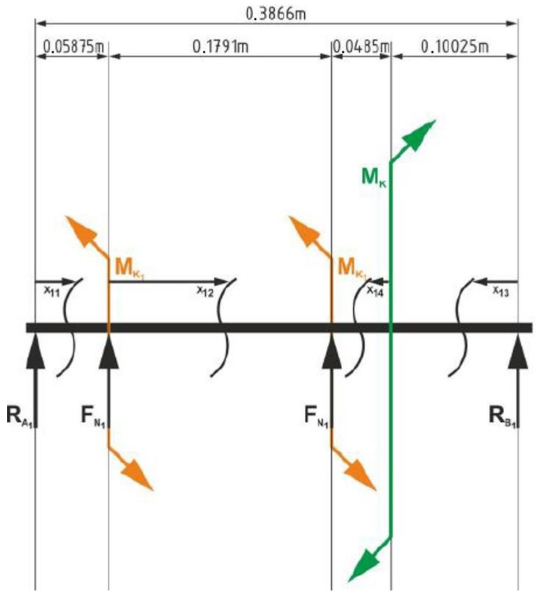

Figure 4. *Considered geometry and load of shaft No. 1*

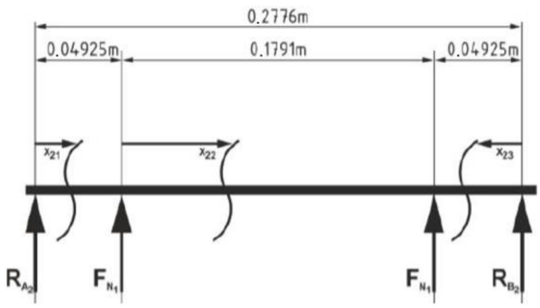

Figure 5. *Considered geometry and load of shaft No. 2*

The bending effects on the shaft No. 2 can be quantified using Eq.(9):

$$\sum M_{iA2} = F_{N1} \cdot 0.04925 + F_{N1} \cdot (0.04925 + 0{,}1791) + R_{B2} \cdot 0.2776 = 0\,, \tag{9}$$

from where, after insertion, the reaction R_{B2} is received in the right bearing. The same procedure applies to the sum of moments in bearing B_2, from where, after insertion, the reaction R_{A2} is obtained in the left bearing of shaft No. 2. The modification consisted of creating surfaces loaded by bearings or gears.

III. Results and discussion

This section clearly, in tabular form (**Table 1**), provides the results of the compiled analytical model (equations 1 to 9) and associated partial intermediate calculations. Using this model, the shafts of the first conveyor were designed, which will be used in the design of a real prototype of the conveyor implemented in the process of semi-automation of the working machine. The analytically determined torque curves of both shafts are shown in **Fig. 6** and **Fig. 7**. The largest values were used to calculate the applied stresses since the shafts are prismatic.

As a part of the research, the shafts were analyzed using the finite element method. Ansys software was applied to these numerical analyses. The geometry of the shafts designed by analytical calculation was created in the Catia and VR5 programs, modified and inserted into the FEM software Ansys. Volume elements were set up to create finite element models for the shafts. As shaft No. 1 is subjected to both torsion and bending, surfaces loaded by forces and torques were created according to the scheme in **Fig. 4**. The size of the elements when creating the mesh was chosen to be 2 mm and an automatic method was used to generate the mesh. The number of mesh nodes of shaft no. was 154,866, and of mesh elements was 35,934. The same procedure will also be used to obtain numerical results for shaft No. 2 (**Fig. 5**), whose model contained 146,403 nodes and 34,860 elements with a size of 2 mm. **Figs. 8** and **9** show the results of the shaft stresses determined using numerical simulation.

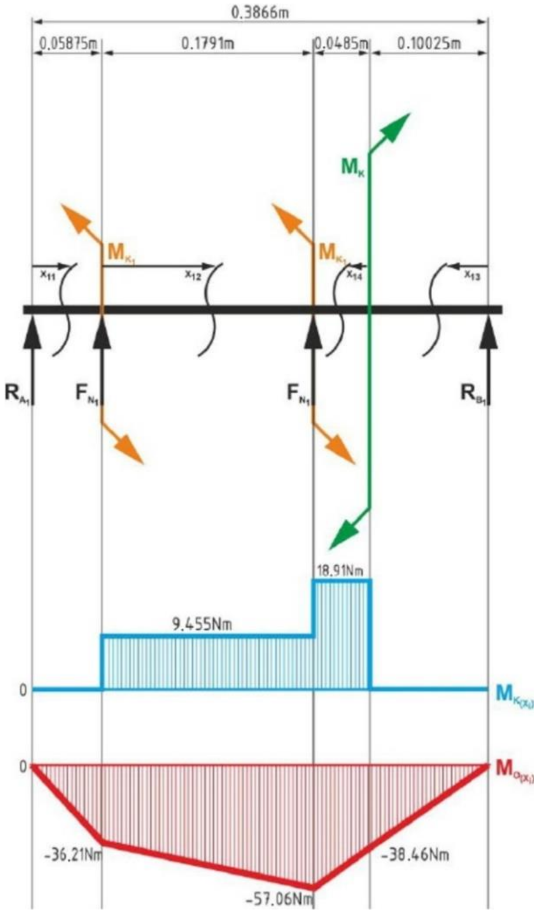

Figure 6. *Analyzed torque curves of the shaft No. 1*

Table 1. *Results of solving the created mathematical model*

Equation	*Quantity and designation*	*Result*	*Unit*
(1)	Torsional stress of shaft No. 1, τ_{k1}	12.04	MPa
(2)	Section modulus in torsion of the proposed shafts, W_k	$1.5708 \cdot 10^{-6}$	m^3
(3)	Bending stress of shaft No. 1, σ_{o1}	72.65	MPa
(3)	Bending stress of shaft No. 2, σ_{o2}	30.62	MPa
(4)	Bending cross-sectional modulus of the proposed shafts, $W_{o1.2}$	$7.854 \cdot 10^{-7}$	m^3
(5)	Reduced stress of shaft No. 1, σ_{red1}	75.58	MPa
(6)	Permissible shaft load, σ_{dov}	111	MPa
(7)	Torque of the driven sprockets of the conveyor, M_{k1}	9.455	Nm
-	Torque of the driving sprocket of the conveyor, M_k	18.91	Nm
(8)	Reaction of the right bearing of shaft No. 1, R_{B1}	–383.6	N
-	Reaction of the left bearing of shaft No. 1, R_{A1}	–614.4	N
(9)	Reaction of the right bearing of shaft No. 2, R_{B2}	–500	N
-	Reaction of the left bearing of shaft No. 2, R_{A2}	–500	N
-	Analytically determined required diameter of shaft No. 1, d_1	0.017	m
-	Analytically determined required diameter of shaft No. 1, d_2	0.013	m

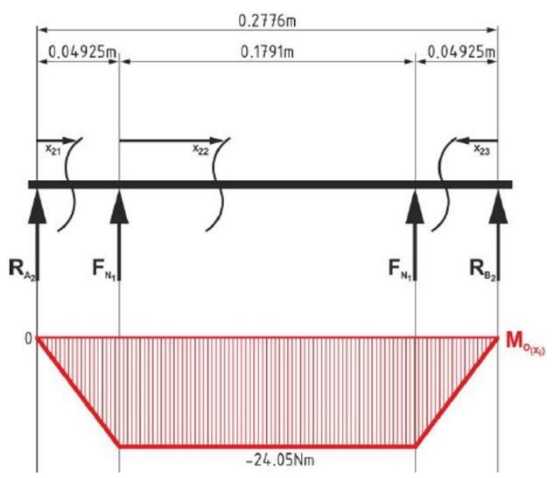

__Figure 7.__ Analyzed torque curves of shaft No. 2

By comparing the results of analytical and numerical calculations, it is possible to conclude that these results are very similar. The reduced maximum stress of shaft No. 1, according to the analytical method, was 75.58 MPa and, according to the numerical method, 74.82 MPa. The equivalent stress of shaft No. 2, according to the analytical method, has a value of 30.62 MPa in comparison with the numerical method, which provided a result of 30.5 MPa. For this reason, the shafts are suitable for implementation in the form of a practical conveyor design.

Fig. 10 shows a three-dimensional model of the solved conveyor, and **Fig. 11** depicts a real implementation of the design. It can be seen how it looks in the reality.

In addition to the shafts themselves, the conveyor structure (**Figs. 10** and **11**) will also consist of a main frame made of two U50 cross-section bars, to which three rectangular TR OBD 40×20×3 – 246 profiles are welded from the inside. The remaining supporting parts are made of differently bent flat bars.

The conveyor shafts are mounted in UCFL 204 bearing housings, which are attached to the conveyor frame with M10 bolts. The first supporting part of conveyor No. 1 is a square profile TR 4HR 40×3 – 915 connected by pins to the conveyor and the main frame of the machine.

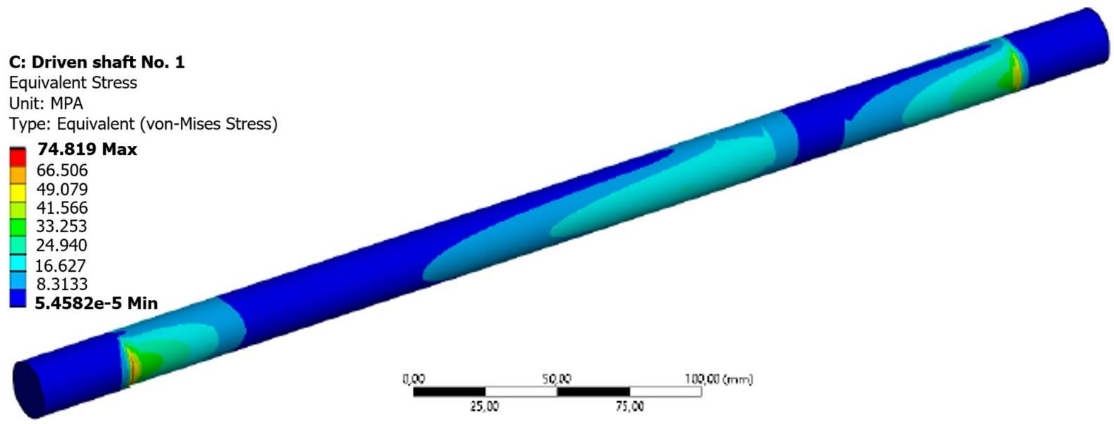

__Figure 8.__ Reduced stress distribution in shaft No. 1

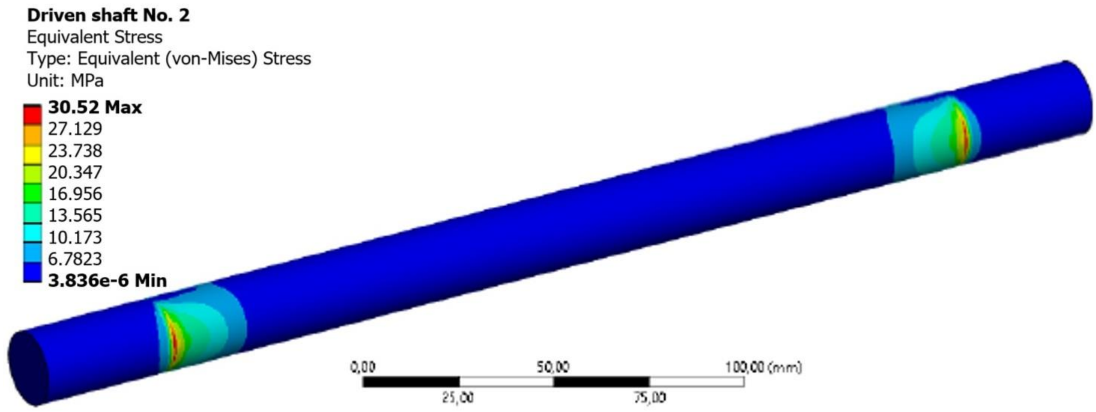

__Figure 9.__ Reduced stress distribution in shaft No. 2

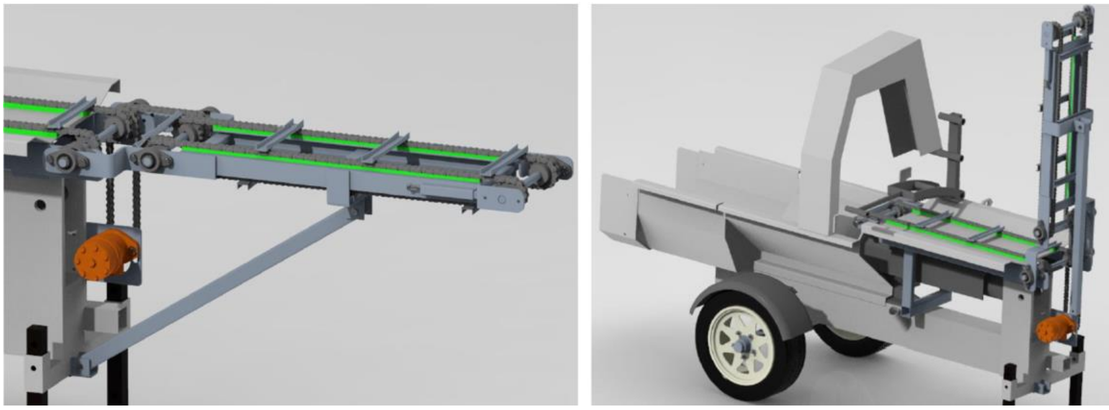

Figure 10. *A three-dimensional CAD model of the designed chain driven conveyor in a working position (left) and in a transport position (right)*

Figure 11. *A real implementation of the designed chain driven conveyor in a working position (left) and in a transport position (right)*

The second supporting part will be presented in further research as shaft No. 3, on which the conveyor frame is mounted using two UCFL 204 bearing housings. The conveyor is mounted on shaft No. 3 due to the need to fold conveyor No. 1 by more than 90° during transport. This is a mobile working machine, and when folding it, it will not be necessary to disassemble the chain. The sprocket on shaft No. 1 will be driven by the drive sprocket on shaft No. 3. The folding of conveyor No. 1 in the transport position can be seen in Figs. 10 and 11 on the right side. Further, future research in this field will also focus on the dynamic analysis of the designed conveyor. The main objective will be to perform eigenanalysis in order to find safe operational ranges for rotational movement [25]. The purpose will be to identify a possible operational rotation and to avoid the operation of the machine in harmful frequency ranges [26, 27].

IV. Conclusions

The aim of the paper was an engineering design of the shafts of a driven chain conveyor designed for a specific purpose. Both shafts were designed and analyzed using analytical and numerical calculations. Based on the results, it was found that it is possible to manufacture individual parts and safely install them on the working machine. It can be said that all expected goals were met. In further research, the authors will focus on the creation of a second chain conveyor, which will also include a drive since this conveyor will be a driving one.

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AUTHOR CONTRIBUTIONS

M. Blatnický: Conceptualization, Methodology, Formal analysis, investigation, Writing - original draft preparation.

J. Dižo: Methodology, Validation, Investigation, Data curation, Writing - review and editing, Project Administration.

A. Lovska: Software, Formal Analysis, Investigation, Data curation, Visualisation, Project Administration.

O. Kravchenko: Validation, Investigation, Supervision, Writing - review and editing, Visualisation, Project administration.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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