DESIGN AND FEASBILITY ANALYSIS OF VERTICAL STATIC FLIGHT SCREW CONVEYOR USAGE IN GRANULATED FERTILIZER TRANSPORTATION

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Abstract. This study investigates the feasibility of using a vertical static flight screw conveyor for transporting granulated fertilizers in an autonomous agricultural robot service station. The research employs the Discrete Element Method to simulate particle movement and collisions, allowing for the evaluation of various screw conveyor designs. Experiments were conducted to determine the granulometric and mechanical properties of the fertilizer, measurements taken to calculate the bulk density and subsequent tests performed to assess particle behaviour under compression and shear forces. The results indicated that the static screw conveyor can achieve comparable or superior productivity compared to traditional screw conveyors, with the optimal number of in-feed scoops identified as two. Additionally, the geometry of the in-feed scoops significantly impacts productivity, with a closed-top design providing enhanced performance. The findings highlight the potential of the Olds Elevator LLC's innovative approach to overcome common issues associated with conventional screw conveyors, such as pulsating flow and high energy consumption. Simulation results showed that the productivity of the static screw conveyor can reach up to 41.23 g·s-1 representing an approximate 28% improvement over traditional designs. The study concludes that the proposed screw conveyor design is suitable for efficient granulated fertilizer transport, offering a reliable solution for improving the efficiency of autonomous agricultural operations.

Keywords: agricultural robots, fertilization, precision farming, discrete element method (DEM).

Introduction

Precision agriculture is a key direction in modern agricultural development, focusing on optimizing resource utilization and increasing yield through technological solutions [1]. This concept relies on data-driven decision-making, utilizing General Positioning System (GPS) technology, sensors, drones, and automated equipment to adapt agricultural processes according to agrotechnical requirements [2]. Precision agriculture helps reduce environmental impact, optimize labor usage, and improve production efficiency [3]. One of the essential aspects of precision agriculture and smart farming in general is precision fertilization, which minimizes fertilizer overuse and reduces nutrient leaching into the environment [2]. Precision fertilization employs measurement devices and automated control systems to dose fertilizer according to the soil nutrient content and plant requirements. In recent years, the use of robots in agricultural scene, which are capable of navigating fields, collecting data, and performing precise fertilization operations, has increased [4-6]. For robots to operate efficiently, they require a continuous supply of both energy and necessary fertilizer resources [7-8]. To address this issue, fertilizing robot service station has been developed, performing multiple functions such as charging robots and refilling fertilizers [3]. Such service stations reduce the need for human labor and minimize work interruptions, thereby increasing the efficiency and sustainability of agricultural operations [3]. In such autonomous service stations, it is crucial to generate energy locally while ensuring minimal energy consumption of the station itself. For this reason, the robot, the station, and its integrated modules must operate with maximum energy efficiency. If energy consumption is minimized, solar panels covering the station may be sufficient to power the entire system, enabling operations to be carried out entirely using renewable energy. The Agrobotics workgroup at the Institute of Forestry and Engineering of the Estonian University of Life Sciences is developing an agrorobot designed to maintain cultivated plants. For the robot to function effectively, it requires a service station, which includes a fertilizer refilling system. A screw conveyor is considered as part of this system [9].

Olds Elevator tested both traditional and their own screw conveyors using the Discrete Element Method (DEM). Simulations and experiments showed that Olds Elevator ensures more uniform material flow without pulsation, reducing particle damage, easing maintenance, and improving energy efficiency. It outperforms traditional screw conveyors in efficiency and durability, but conventional designs may still be preferable for horizontal transport, higher capacity, or lower costs. However, no tests have been conducted specifically with granulated fertilizers [10].

The aim of this article is to analyze the feasibility of a vertical static flight screw conveyor for efficient transportation of granulated fertilizers in an autonomous agricultural robot service station. The

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efficiency of this transport method is critical as it helps reduce energy consumption. Additionally, it enhances the reliability of autonomous agricultural robots and minimizes the need for human intervention in the fertilizer loading process.

To achieve the objectives of this article, the following tasks were set.

1. Determine the granulometric parameters of the fertilizer used.
2. Determine the mechanical parameters of the fertilizer used.
3. Design various screw conveyor solutions.
4. Compare different design solutions by conducting DEM simulations and evaluate their applicability.

The information presented in this article provides a foundation for further development of a full scale conveyor system.

Materials and methods

To determine the bulk density of the granulated fertilizer YaraMila Cropcare NPK(s) 8-11-23 (29), measurements were conducted, where 100 ml of the fertilizer were weighed, and the bulk density was calculated as the average of all measurement results. According to the manufacturer's data, 88% of the fertilizer consists of granules sized between 2-4 mm [11].

For designing an efficient and high-performance screw conveyor, it is essential to understand the mechanical properties of the granulated fertilizer particles [12]. Extensive tests were conducted, including particle sieving, compression, and shear tests. For the simulation, 5 times 100 g of fertilizer were sieved using sieves with aperture diameters ranging from 5.4 mm to 0.5 mm. The mass of each fraction was determined by weighing, allowing the identification of the most prevalent particle size distribution. To determine mechanical properties, 200 granules were randomly selected, 100 for compression tests and 100 for shear tests. Each granule dimensions, including the width, length, and height, were measured using a caliper, and their mass was precisely weighed with a Kern ABJ 220-4NM scale. The tests were carried out using an Instron 5969 universal testing machine, which is widely used for determining the mechanical properties of materials [13]. In compression tests, a screw head was used to apply pressure to the granule until it fractured. In shear tests, a blade was used to apply shear force until the granule broke. In both cases, the maximum force required to break the granule was recorded. Before starting the tests, each granule dimensions and mass were entered into Instron software. This allowed for correlating the physical properties of the granules, such as the size and mass, with their mechanical strength, thereby optimizing the screw conveyor design according to the material properties.

The design of the screw conveyor was based on two different technologies: the traditional conveyor, where the screw rotates around its axis [14], and an innovative solution developed by Olds Elevator LLC's [15-17], where the screw remains stationary while the surrounding casing rotates. In a traditional screw conveyor, the rotation of the screw ensures uniform material movement [14], whereas in the rotating-casing system, material is transported efficiently through gravity and friction [17]. The concept is to combine the advantages of both systems, enabling smooth and efficient lifting of granulated material up to a maximum height of 1.8 meters while using minimal power consumption.

DEM is a computational technique for modelling particle dynamics, widely used in engineering and material science. It simulates individual particle movement, interactions, and material behaviour, aiding in equipment optimization. In agriculture, DEM is applied to fertilizer and seed distribution modelling, as well as analysing grain flow. This study utilizes open-source DEM software to simulate a screw conveyor transporting the granulated fertilizer, comparing two configurations: a rotating screw with a fixed casing and a stationary screw with a rotating casing [18-20].

A prerequisite for the simulation was to configure the software according to the selected parameters, using a typical screw conveyor geometry in the model, with the diameter and pitch corresponding to a scaled-down version of a real conveyor. Using a scaled-down model reduces the simulation duration, as performing DEM simulations is a computationally intensive process. The shapes and sizes of the granulated fertilizer particles are based on laboratory measurement data, and the interactions between the screw and casing are realistically modeled to account for friction and particle dynamics. Material properties were also defined for the simulation: the average bulk density of the fertilizer granules is $\rho_{avg} = 1200$ kg·m^{-3}, the average particle size is $D_{avg} = 3.68$ mm, and the friction coefficient between particles is μ = 0.25 [21]. The conveyor's case and screw are made of stainless steel, AISI 304 with the elastic modulus of E_{ss} = 200 GPa [22] and Poisson's ratio of ν_{ss} = 0.30 [23]. For the fertilizer particles, the elastic modulus is E_{gr} = 208 MPa [24], and Poisson's ratio of ν_{gr} = 0.25 [24-25]. The simulation conditions were kept consistent across all cases: the duration was t = 10 s and the rotation speed was n = 200 min^{-1}, in both cases: a) static screw with a rotating casing and b) dynamic screw with a stationary casing. Olds Elevator engineers used n = 320 min^{-1} to test their conveyor [17], but based on the calculations, n = 200 min^{-1} was chosen for the simulation, following the principles of a traditional screw conveyor. The screw conveyor invented by Olds Elevator LLC's features two in-feed scoops at the bottom, allowing granules to enter the system and start moving upward. In order to understand better the influence of scoop geometry and their quantity, the authors created five design variations (Fig. 1-5).

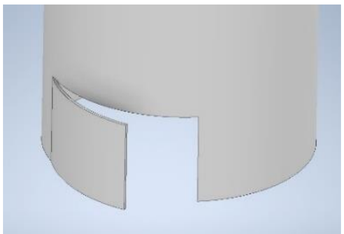

Fig. 1. **In-feed scoop**

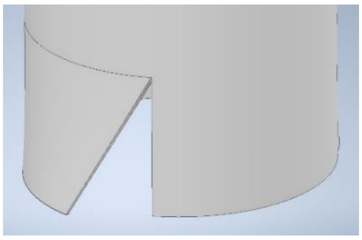

Fig. 2. **Angled in-feed scoop**

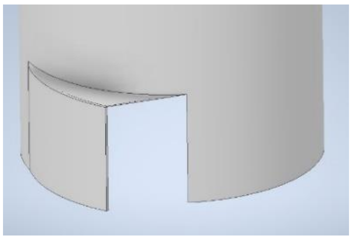

Fig. 3. **Top closed in-feed scoop version 1**

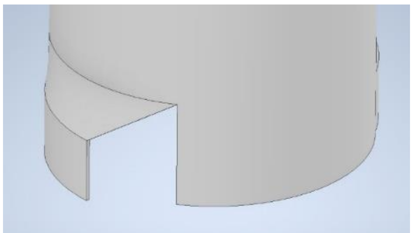

Fig. 4. **Top closed in-feed scoop version 2**

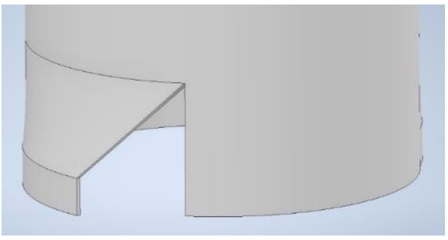

Fig. 5. **Top closed in-feed scoop version 3**

The different designs of the in-feed pick up scoops were created to identify the optimal scoop shape that ensures the highest productivity in grams per second after the simulations. To determine the productivity of the conveyors, their flow rates were calculated. This involved measuring the mass of the granules at the discharge pipe at two time points: when the first granules began to flow out and at the end of the simulation. The difference in mass was divided by the time interval, resulting in the flow rate in grams per second. The flow rate was determined using formula 1:

$$Q = \frac{m}{t}, \tag{1}$$

where m – outflow mass, g;
t – outflow time, s.

After the simulation, various parameters are collected and analyzed. The most important parameter is productivity, as the amount of transported material over time determines which screw conveyor is better. Since the service station is located in an area without electricity and the station generates its own required power, the necessary mechanical energy to create particle movement must be as low as possible [3]. The simulation results are compared to determine which design can transport the fertilizer more efficiently while minimizing energy loss. The DEM simulation helps determine the trajectory and the flow of the particles [20]. Based on the results it could be decided whether it is more advantageous to rotate the screw or the casing in terms of the screw conveyor efficiency.

Results and discussion

Traditional screw conveyors are based on a rotating screw that pushes material upward [14]. This can lead to problems such as material backflow, where particles move back down, thereby reducing efficiency. The continuous contact between metal and material wears down the equipment, resulting in high friction and significant energy consumption [14; 23]. Olds Elevator overcomes these issues, as the material forms a dynamic seal that reduces backflow and friction. Olds Elevator tests have shown that the conveyor has twice the flow rate and lower energy consumption compared to a conventional vertical screw conveyor [15; 17], but after several simulations it can be argued that regarding transportation of the mineral fertilizer it was not significantly better than the conventional solution.

A total of eight simulations were conducted: one with screw rotation and seven with casing rotation. In the case of casing rotation, a cut had to be made at the bottom end of the casing to ensure the upward movement of the fertilizer granules. Initially, with a single cut, the granules did not start moving upward; however, with two scoops, the system functioned properly, allowing the granules to move up along the screw. With three scoops, everything worked very well, but the productivity remained lower than that with two scoops. Additionally, simulations were performed with in-feed pick up scoops of different geometries, as shown in Fig. 2-5. The productivity improved with various geometries compared to the original in-feed pick up scoop. In Fig. 6, there is a traditional screw conveyor, and in Fig. 7, there is the conveyor with the most productive in-feed scoop design. The images show simulations of both conveyors at specific time moments to compare their productivity.

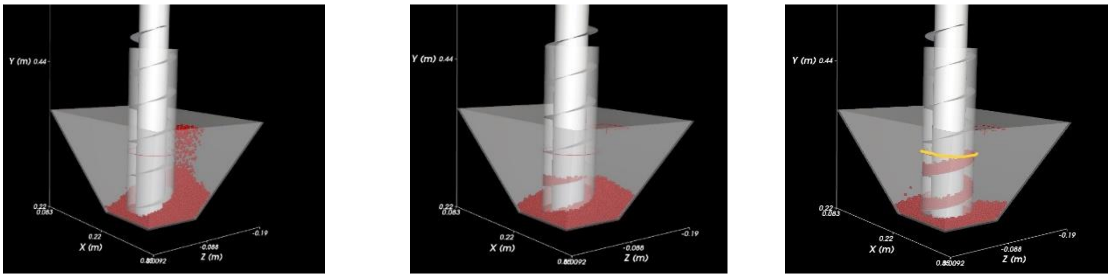

Fig 6. **Three simulation steps of a rotating screw conveyor at time 3 s, 3.7 s and 7.5 s, where yellow line marks outlet**

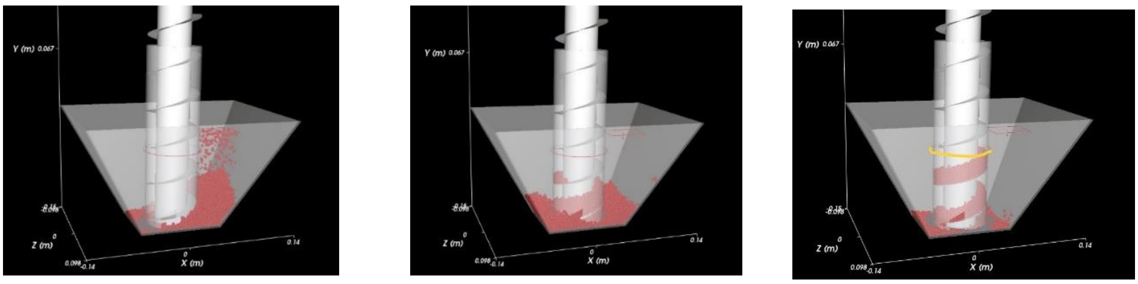

Fig 7. **Three simulation steps of a rotating casing conveyor with top-closed in-feed pick up scoop version 2 at time 3 s, 3.7 s and 7.5 s, where yellow line marks outlet**

To visualize the productivity of different conveyor designs, all the data is presented in Fig. 8, where quotient of the discharge mass M_{dsc} and discharge time T_{dsc} results in the discharge flow and thereby illustrates productivity. In the legend of Fig. 8, the line number corresponds to the design variation number.

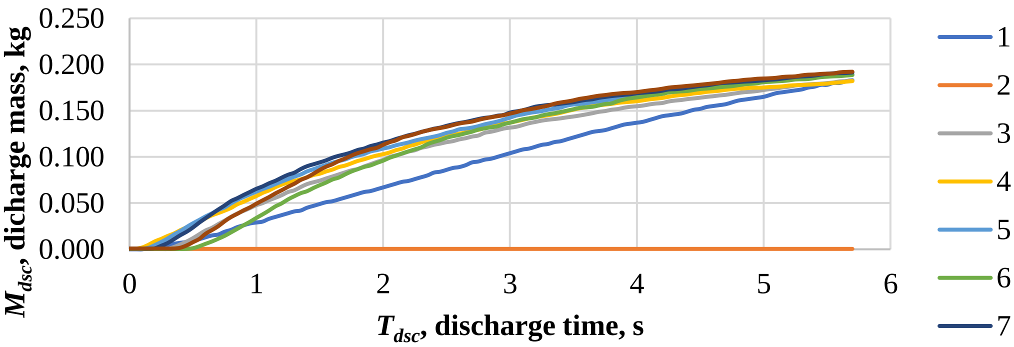

Fig 8. **Material flow of 8 different simulated screw conveyor designs**

Based on the data shown in Fig. 8, it is possible to determine the best in-feed scoop design by calculating the discharge flow for each of the design iterations:

1. Rotating screw conveyor → 32.28 $g \cdot s^{-1}$
2. One in-feed pick up scoop with rotating casing conveyor → 0 $g \cdot s^{-1}$
3. Two in-feed pick up scoops with rotating casing conveyor → 33.74 $g \cdot s^{-1}$
4. Three in-feed pick up scoops with rotating casing conveyor → 31.88 $g \cdot s^{-1}$
5. Angled in-feed pick up scoops with rotating casing conveyor → 39.60 $g \cdot s^{-1}$
6. Top closed in-feed pick up scoops version 1 with rotating casing conveyor → 33.65 $g \cdot s^{-1}$
7. Top closed in-feed pick up scoops version 2 with rotating casing conveyor → 41.23 $g \cdot s^{-1}$
8. Top closed in-feed pick up scoops version 3 with rotating casing conveyor → 35.95 $g \cdot s^{-1}$

Based on the simulations the productivity of the traditional screw conveyor was 32.28 $g \cdot s^{-1}$, the Olds Elevator conveyor achieved 33.74 $g \cdot s^{-1}$ and the authors proposed scoop design iteration yielded in 41.23 $g \cdot s^{-1}$. Compared to the traditional screw, the proposed scoop design offers 28% greater productivity.

The size distribution and moisture content of fertilizer granules affect the conveyor's throughput and application uniformity. Uniform and dry particles ensure predictable flow, while varying sizes or moist granules tend to cause non-uniformity [26]. Different fertilizers vary in particle distribution, granulometric and mechanical parameters, for example, organic fertilizers may clump [21; 24; 25]. This study focused on a dry mineral fertilizer, confirming the conveyor's suitability for its transport.

Creating a prototype utilizing the proposed in-feed scoop design and testing its measured fertilizer discharge flow against the simulation results is planned. Further research also includes determining the fertilizer discharge flow dependency from moisture and the conveyor compatibility with organic fertilizers.

Conclusions

1. Based on calculations and simulations, it can be concluded that a vertical static screw conveyor design is suitable for transporting granulated fertilizers.
2. The static screw conveyor provides better productivity up to 28% in the transportation of granulated fertilizers compared to a conventional screw conveyor.
3. In the case of a static screw conveyor, the number of in-feed scoops affects productivity. Based on the simulations, the optimal number appears to be 2.
4. The geometry of the in-feed scoops also influences the productivity of the static screw conveyor. A closed-top design with a slight angle has better results.

Author contributions

Conceptualization, T.L.; methodology, K.M. and T.L.; software, K.M.; validation, K.M. and T.L; formal analysis, K.M.; investigation, K.M. and T.L; writing – original draft preparation, K.M. and T.L.; writing – review and editing, T.L; visualization, K.M.; project administration, T.L.; funding acquisition, T.L. All authors have read and agreed to the published version of the manuscript.

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