A novel approach to the analytical modelling of an auger conveyor system for lunar regolith transportation

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Abstract
Auger-based transportation systems are a promising method to transport lunar regolith for in situ resource utilisation. An analytical model based on terrestrial auger conveyor industry guidelines is used to predict the behaviour and performance parameters of an auger conveyor system under a range of initial conditions. Key aspects of the model have been validated with published experimental data. The proposed model produces more accurate predictions than previous methods and calculates the inclination angle with the best conveying efficiency. The proposed model output flow predictions have on average 47\% less deviation from the experimental data mean than previous model predictions, while the predictions for power requirements without considering energy losses present 42.9\% and 59.2\% less deviation than previous predictions. When the losses are considered, the proposed model predictions are 70\% and 86.4\% more accurate than the previous models, which have been found to underestimate the power requirements of this type of conveyors.

Keywords Aerospace engineering • Auger conveyor • Excavation • ISRU • Lunar regolith • Moon

1 Introduction

There is an ever-growing interest in space exploration, with a multitude of satellite missions planned for the next few years and the Moon being one of the main objectives. Projects such as the Russian LUNA 27 lander [3], NASA's Artemis [31] and VIPER [12] programmes, ESA’s PROSPECT mission [38], JAXA’s SLIM [30], the Indian Chandrayaan 3 [16], and China’s Chang’e 6 [10] are expected to land on the Moon before the end of the decade. Furthermore, commercial missions by private companies like Astrobotic Technology [33], SpaceX [41], and Blue Origin [11] are also scheduled to land and perform experiments on the lunar surface in the near future. Several of these projects and experiments aim to test and develop in situ resource utilisation (ISRU) technologies, which could allow the utilisation of native lunar material.

Establishing a lunar base will provide an unmatched site for astronomical observation [8, 9, 21], testing of space technologies, and a drastic reduction in the energy costs of sending materials to space [37]. Around 22 times more energy is required to overcome Earth’s effective gravitational influence compared with the lunar case [7], which increases further if the atmospheric effects are considered. Due to the importance of reducing the amount of terrestrial materials, ISRU technologies that make use of lunar resources are of major interest [20]. These technologies are, for instance, expected to process the lunar regolith into construction material using 3D printing [5], selective laser melting [14], or microwaves [1]. In addition, the roughly 45\% of oxygen by weight in the lunar regolith [18] can be extracted for its use as propellant and in life support systems [19], with processes such as hydrogen reduction [39] or molten salt electrolysis [40], which recently achieved a 96\% of extraction efficiency [27]. To use these materials efficiently, ISRU technologies require methods of
collection and transportation of regolith to processing plants; the harsh lunar conditions, however, present significant challenges. Some of the principal ones regarding the transport of regolith are the lack of atmosphere, the reduced gravitational force, as well as the small size, electrostatic charge, and abrasiveness of the regolith particles [46].

The lunar surface is covered with a layer of unconsolidated rock particles [18] that lies over the lunar bedrock and can reach more than 10 m in depth. The terms soil and regolith are often used interchangeably, but the lunar soil refers to the portion of the lunar regolith with finer particles, smaller than 1 mm in grain size. The particle size of lunar soil varies between 40 and 800 µm with an average of around 70 µm, while the larger particles of regolith are often in the 2 – 3.7 mm range [26, 28].

The density of the lunar regolith is a vital variable to take into consideration for any excavation process. The relative density refers to the degree of particle packing compared with the maximum and minimum void ratio possible; therefore, it is given as a percentage of the maximum achievable density for the particular soil. Although the surface-level regolith is considerably loose in some regions as a result of the continuous meteorite bombardment, its relative density can increase rapidly after the first centimetres, ranging from 65% at 0–15 cm to 92% at 30–60 cm depth, as summarised by Carrier et al. [18].

The lack of atmosphere and erosion agents make the regolith particles highly abrasive, while the accumulation of electrostatic charge caused by the constant radiation makes them adhere to any exposed equipment [23]. A significant number of the mechanisms sent to the lunar surface to date exhibit significant reliability issues, such as overheating caused by the covering of heat exchangers [23], excessive wear of joints or moving parts, clogged seals and sensors, or dust covering of optics and solar panels [46]. Regolith particles (Fig. 1) penetrate mechanisms and abrade the moving surfaces, presenting a challenge for medium- to long-term lunar missions. Due to the high abrasiveness of the lunar regolith, systems with few moving parts are more reliable [29].

The Moon’s gravitational acceleration is only 1/6th of that on Earth, which affects lunar systems in different ways, such as increasing dust settlement times [35] or limiting the available traction of vehicles [45, 46]. For excavator systems, reduced gravitational acceleration and a high gradient in the relative density of the regolith below the surface level, limit the maximum depth of cut as excavation forces increase rapidly. An increase in necessary excavation forces can be offset by adding mass to the system. However, this is expensive due to the high cost of sending material to the Moon [45]. Using lunar material as ballast would have a similar effect, but this is limited, as any lunar vehicle will sink in the regolith and eventually get stuck [44]. Therefore, adding extra mass directly reduces the payload capacity of the excavator. The efficient use of available traction forces on the lunar surface is a crucial design concern, particularly for excavation processes intended for surface-level regolith extraction [22].

Auger conveyors are widespread in terrestrial applications, being used for centuries to transport granular materials for the pharmaceutical, agricultural, or mining industries [32]. Some of the limitations of this type of conveyor are vibration and dust generation [32], as well as discontinuous feeding problems. Inclined conveyors at high rotating speeds can operate in a starve-feeding condition, where the material cannot enter the inlet due to the speed of the auger flights [43]. Most of these limitations can be mitigated with an appropriate design and use case for individual feedstock materials. For example, a forced-feeding conveyor design solves the starve-feeding condition. Further, screw conveyors present an opportunity to transport material reliably [22], without the need for auxiliary systems, and with only a fraction of the moving parts required for other solutions. They consist of simple parts that have proven capable of withstanding continuous operation in demanding environments [43].

There have been only a few analytical models that attempt to predict the performance of lunar regolith auger conveyor systems. However, existing models have a tendency to underestimate the power requirements necessary for operation. There is a need for a more accurate method to predict the performance of conveyor systems for ISRU operations, which allows for more precise estimations and comparisons between systems. Therefore, some of these previous models will be presently discussed and compared with a new model proposed by the authors to address the perceived accuracy from a power requirement perspective.

![Fig. 1 Scanning electron photomicrograph of a lunar regolith particle. This agglutinate presents a melted surface coated with small soil fragments. Part of soil sample 10084 from Apollo 11, NASA Photo S87-38812 [18]](image-url)
2 Model development

The present model aims to provide a more accurate prediction of the performance of an auger conveyor system than the existing models described subsequently. Auger performance depends on several parameters and conditions, which will be discussed in this section. To validate the present model, a comparison with previously reported experimental data has been conducted. Two previous attempts to model the behaviour of a conveyor system for lunar regolith transportation have been considered, Radulescu [34] and Ray et al. (2008) [36]. These models are presented in the following sections, and their predictions are compared with the predictions of the proposed model.

The fundamental design of auger conveyors has not changed significantly, with only a few new configurations such as shaftless conveyors or different flight shapes having been adopted for some applications. Although shaftless conveyors require less support, they are specially designed for sticky materials and withstand less torque than those with shafts, while different flight shapes and configurations generally are designed for mixing as well as transport. Therefore, a shafted screw conveyor with a standard flight shape was selected as the basic configuration for modelling. The system that the model aims to reproduce consists of a helical blade with a central shaft that rotates along its axis inside a stationary cylindrical casing, conveying powdered material from one end to the other.

A general diagram of the layout can be seen in Fig. 2, where $m_{in}$ and $m_{out}$ refer to the mass flow in the input and output measured in $kg/s$, respectively. The filling ratio $F_R$ refers to the average percentage of volume filled by the material transported in relation to the inner volume of the cylinder casing, the inclination angle $\beta$ is the angle between the auger shaft and the ground plane, and the length $L$ indicates the distance from the inlet to the auger shaft and the ground plane, measured from the input to the output opening in $m$. $H$ is the height perpendicular to the ground plane, measured from the input to the output opening in $m$, $\omega$ is the rotational speed of the auger inside the casing measured in $rps$, and $p$ is the pitch of the auger threads in $m$.

There is a lack of characterised setup results for ISRU auger conveyor systems reflecting lunar conditions, with considerable differences between experimental setups [34, 43]. Lunar regolith simulants, although they are fundamentally different from the actual regolith, provide the best approximation to the material that a conveyor would need to withstand [42, 43]. Despite this, a considerable number of studies [17, 34] generally use uncharacterised sand as a lunar regolith analogue for proof-of-concept studies. Although there are significant differences between sand and regolith simulants, the high cost of the simulants can make it prohibitively expensive to conduct large-scale experimentation. Therefore, if sand or similar materials are used, which is reasonable, it is vital to include the key geotechnical properties to allow the performance comparison with other setups [22].

2.1 Radulescu model

The model presented by Radulescu et al. [34] obtained the output mass flow $m_{out}$ in $kg/s$ of an auger conveyor using Eq. 1. Here, $\rho$ represents the material density in $kg/m^3$, $w_g$ the width of the output gap in $m$, and $r_c$ and $r_s$ the radius of the casing and the shaft in $m$, respectively.

Fig. 2 Overview of the model’s layout, side view, and A-B section. The material is introduced as $m_{in}$ and expelled as $m_{out}$ with the rotation of the auger shaft. It is conveyed along the length $L$, inclined at an angle $\beta$, filling a fraction $F_R$ of the cylinder casing inner volume.
The axial velocity of the auger blades $v_a$ can be calculated with Eq. 2, where the pitch in $m$ is given by $p$.

$$v_a = p \omega$$ (2)

The Radulescu model employs Eq. 3 for predicting power requirements. The required power $P$ assumes a constant friction coefficient with a value of $\mu = 0.5$ and that the particle is ejected at the edge of the auger’s blade. This method is simple, but underestimates the power requirements of the system; it does not include a component that considers the power necessary to lift the material if the inclination angle is nonzero (i.e. $\beta > 0^\circ$).

$$P = m_{OUT} \left( \frac{L g \mu}{4} + \frac{r_c \omega}{2} \right) \left( \left[ W \right] \right)$$ (3)

The Radulescu model [34] further simplifies the performance predictions of an auger conveyor by not considering the filling ratio of the casing volume or the auger inclination angle. It also uses a single-component approach to calculate the system power requirements. The impact of these three major simplifications will be explained in more detail in the following sections.

Fadyeibi et al. [13] have made recommendations in line with industry for handling granular materials with screw conveyors [4, 25]. The filling ratio $F_R$ can be introduced in the equations using a coefficient with values between 0 and 1, which correlates to the percentage of inner volume filled with material. This is the preferred method that the Conveyor Equipment Manufacturers Association (CEMA) recommends in their Screw Conveyors for Bulk Materials (Standard No.350, ANSI/CEMA) [2]. In terrestrial applications without forced feeding, this filling ratio is usually around 15–45%, depending on the material properties [2]. For sand, silica (SiO$_2$), and alumina (Al$_2$O$_3$), the filling ratio $F_R$ or conveyor filling percentage in the tables found in [25] and [2] is 0.15. These low $F_R$ values mean that without a system to force the feed of material into the conveyor, a major part of the inner volume of the auger will be empty. Not considering this parameter in the model leads to significant discrepancies between the theoretical and experimental performances. Low gravity conditions affect the conveying efficiency and cohesion effects, scaling by the square root of the gravity ratio (a reduction with a factor of 2.45 for the terrestrial to lunar comparison), and appreciably reduce auger power requirements [43]. Under this condition, a lower torque requirement allows for the transport of material at a higher $F_R$, and its control becomes crucial because the conveying performance is more sensitive to the inter-particle cohesion due to the lower inertial forces [43].

The auger inclination angle also has a significant effect on the specific power, increasing at higher inclination angles [25]. Therefore, including $\beta$ allows a model to predict the behaviour of inclined conveyors and expands its capabilities significantly. Previous research and some engineering guides use an inclination coefficient often named $C$, which increases the specific power at higher $\beta$ angles as shown in Fig. 3 [6, 25]. This coefficient, which depends on the geometry and type of auger, is obtained by experimental values and is widely used to dimension auger conveyors. The effect that $C$ has on the system performance illustrates why auger conveyors should be horizontal if possible.

Despite this, multiple applications engender a necessity to lift the material, and although low inclination conveyors are more efficient, the length of the auger has a major impact on the conveying friction. Therefore, understanding the variation in system performance due to inclination and length changes is vital for the design of an inclined conveyor.

The third limitation of the Radulescu model is the power consumption calculation, which uses a single-component approach that does not include an inclination factor.

### 2.2 Ray model

The second model, proposed by Ray et al. [36], includes a filling ratio, $F_R$ factor and also accounts for the increase in specific power at inclinations angles $\beta > 0^\circ$ when calculating the mass output $m_{OUT}$. Despite this, Ray et al. [36] do not consider the shaft volume and only include four different values for $F_R$ and $C$ in their tabulated results, limiting the precision of the model predictions.

To calculate the power required to convey the material, Chakarborthy et al. [6] and Ray [36] use a more complex three-component method. In Eq. 4, these components are: the power required to convey the material horizontally ($P_H$ in Eq. 5), the power required to rotate the screw in an unloaded condition ($P_N$ in Eq. 6), and the power necessary to lift the material to the required height $H$ if the inclination angle is $\beta > 0^\circ$ ($P_{st}$ in Eq. 7). All of the equations are set to give the result in Watts ($[W]$), and the sum of the three power components from Eqs. 5–7 in 4 gives the total power required $P$.

$$P = P_H + P_N + P_{st} \left( [W] \right)$$ (4)

$$P_H = m_{OUT} L g \times \left( [W] \right)$$ (5)

$$P_N = \frac{2 r_c L}{0.02} \left( [W] \right)$$ (6)

$$P_{st} = m_{OUT} \rho g H \left( [W] \right)$$ (7)
The frictional coefficient \( k \) in Eq. 5, also termed a “progress resistance coefficient” [6], is a material parameter with a value usually between 2 and 4 [36]. The frictional coefficient is used instead of the friction coefficient between the transported material and the casing that contains this because it also accounts for the additional internal frictions that take place between the material particles [36]. Therefore, the frictional coefficient \( k \) already includes the normal coefficient of friction \( \mu \) and is expected to have a greater value than \( \mu \) for the same materials. For sand, Tables in [36] give \( k \) a value of 4. The power required to transport the material horizontally \( P_H \) is the major power requirement component in most operating conditions. In Eq. 6, the denominator has a value of 0.02 and is an experimental weighting factor for the \( P_N \) component [6]. In summary, this model includes more parameters than the previous one, while also adding the possibility to calculate the power requirements for inclined auger conveyors.

### 2.3 Proposed model

The proposed model aims to be a useful tool in the preliminary study and design phase of lunar regolith auger conveyor systems and to improve the results of previous methods. The purpose is not to describe a specific system completely, but rather to give an insight into the performance characteristics of an auger system and its requirements during initial development. It does not consider certain lunar conditions such as the electrostatic charge and adhesion of the regolith particles, or the effects of temperature and vacuum. The addition of such parameters would result in an extremely complex model out of the scope of this work and not necessarily useful for the early design stages of a prototype. This approach is not uncommon; for example, Walton et al. [43] did not include the electrostatic charge of the particles or the temperature in their calculations, and neither did Wilkinson et al. [44], along with the effects of vacuum. Such limitations do not make these models ineffective or less useful, as they are still able to predict the behaviour of the systems they model reasonably well; it is, however, vital to know the limitations of each model. There is not yet a model that includes every variable able to affect a lunar system, and existing models like the ones previously introduced often lack many important parameters. To calculate the \( \dot{m}_{OUT} \) of material, the proposed model uses the Radulescu approach but includes the \( FR \) and \( C \) components. With the first two changes applied to Eq. 1, Eq. 8 can be used to calculate \( \dot{m}_{OUT} \) in \( kg/s \). As previously discussed, \( FR \) is assumed as 0.15 for this case, and \( C \) is a coefficient that depends on the inclination angle \( \beta \).

\[
\dot{m}_{OUT} = FR C \frac{1}{2} \omega \rho \omega \left( r_i^2 - r_s^2 \right)
\]  

For the power requirement calculation, the method recommended by CEMA [2] and other conveyor companies, such as KWS Manufacturing Company [25], has been applied. Several sources suggest this method as it is the result of historical empirical observations from many conveyor manufacturers [15, 24]. This method also uses a three-component approach to calculate the power requirement \( P \) of the conveyor system: the power required to overcome friction \( (P_F \) in Eq. 10), the power required to move the material at the required rate \( (P_M \) in Eq. 11), and the power required to lift the material to the required height.
The equations and the tables employed from CEMA, along with some examples and further explanations, can be found in [2].

\[
P = (P_F + P_M + P_{st}) \cdot 745.7 \text{ (W)} \tag{9}
\]

\[
P_F = \frac{L \cdot \cos \theta \cdot F_d \cdot F_b \cdot 745.7}{1 \times 10^6} \text{ (W)} \tag{10}
\]

\[
P_M = \frac{(m_{\text{OUT}} \cdot 35.315) \cdot L \cdot W \cdot f \cdot F_m \cdot F_p \cdot 745.7}{\rho \cdot 3.6 \times 10^3} \text{ (W)} \tag{11}
\]

where \(F_b\) is the bearing factor, \(F_m\) the material factor, \(F_d\) the auger diameter factor, \(F_p\) the paddle factor, and \(F_f\) the flight factor. These factors increase the power requirement predictions if higher friction bearings, materials more difficult to transport, wider diameter augers or different flight shapes are used.

In Eq. 10, \(F_b = 1\) if ball bearings are used and \(F_d\) can be obtained from Table 1. In Eq. 11, \(F_f = 1\) for standard flights, \(F_m = 2\) for sand, and \(F_p = 1\) if there are no intermediate paddles at reverse pitch. The constant 35.315 included in Eq. 11 is set to convert \(ft^3/h\) to \(m^3/h\); 3.6 \(\times\) \(10^3\) is used to convert from \(kg/s\) to \(tons/h\).

With the three different models described, a comparison of the power requirement predictions has been undertaken. The Radulescu experimental values and setup conditions [34] are considered to compare and provide validation of

### Table 1 Auger diameter factor \(F_d\) for different auger diameters in inches and mm, adapted and approximated from [25] (originally in inches)

| Auger \(\varnothing\) (inch) | \(F_d\) | 4   | 6   | 9   | 12  | 14  | 16  | 18  | 20  |
|-----------------------------|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| 12                          |         | 12  | 18  | 31  | 55  | 78  | 106 | 135 | 165 |
| 18                          |         | 305 | 457 | 787 | 1397| 1981| 2692| 3429| 4191|

### Table 2 Initial conditions and parameters of the Radulescu experiment, used for model performance comparison [34]

| Feature                              | Symbol | Value  | Unit |
|--------------------------------------|--------|--------|------|
| Pitch of auger threads               | \(\rho\) | 0.078  | m    |
| Ejection nozzle width                | \(w_g\) | 0.064  | m    |
| Effective auger length               | \(L\)  | 0.52   | m    |
| Inner casing radius                  | \(r_c\) | 0.076  | m    |
| Shaft radius                         | \(r_s\) | 0.039  | m    |
| Gravitational force                  | \(g\)  | 9.81   | m/s² |
| Density (sand)                       | \(\rho\) | 1500   | kg/m³|
| Height                               | \(H\)  | 0      | m    |
| Inclination angle                    | \(\beta\) | 0      | °    |

Fig. 4 Comparison between the Radulescu [34], Ray [36], and proposed model power requirement predictions under the conditions and parameters presented in Table 2.
Fig. 5 Rotational speeds $\omega$ and experiment duration $t$ for the 29 different Radulescu runs [34] on the left and right axis, respectively.

Fig. 6 Comparison of total material conveyed $m_{out}$ between Radulescu’s predictions, the proposed model predictions, and the experimental results. The experimental data are included with error bars [34].
the models. The key parameters and initial conditions are presented in Table 2.

The results of the power requirement calculations using the three different methods are shown in Fig. 4, where the difference in the model’s predictions can be identified. The Radulescu model predicted the lowest power requirement, of approximately 7% of the proposed model average values. The Ray model predicts a higher power demand, around a third of the proposed model’s mean and about four times more than Radulescu’s model. In the following section, these predictions will be compared to the Radulescu experimental results.

3 Results and validation

3.1 Validation with experimental results

In this section, the presented model’s predictions will be compared with predictions and experimental results reported by Radulescu et al. [34]. In those experiments, the length of the auger was set to $L = 0.52\, m$, the inclination angle to $\beta = 0^\circ$; the remaining parameters are included in Table 2. Therefore, the inclination and length part of the model cannot be validated using these experimental results. The only parts that can be validated are the predictions about the output mass flow $m_{out}$ and the power consumption $P$ of the system.

Radulescu et al. [34] make an initial theoretical prediction about the performance of the system in their article. One of the problems that the authors point out is the variability of the input mass caused by a lack of control of

| Model                        | Variable | Mean | Unit | Deviation (%) |
|------------------------------|----------|------|------|---------------|
| Experimental results         | $m_{out}$| 7.4  | kg   |               |
| Radulescu model [34]         | $m_{out}$| 3.6  | kg   | 51.4          |
| Proposed model               | $m_{out}$| 5.4  | kg   | 27.0          |
| Experimental results         | $P$      | 42.7 | W    |               |
| Radulescu model [34]         | $P$      | 1.8  | W    | 95.8          |
| Ray model [36]               | $P$      | 8.8  | W    | 79.4          |
| Proposed model without losses| $P$      | 27.1 | W    | 36.5          |
| Proposed model with losses   | $P$      | 38.7 | W    | 9.4           |

The deviation is calculated using Eq. 12.

Fig. 7 Comparison of the power requirements predictions between Radulescu, Ray, and the proposed model with and without losses. The experimental data are included with error bars [34]
the depth of material being fed to the conveyor, stating that the variations in depth could easily cause a 10 – 20% difference in the results [34]. These were the case even with controlled conditions and a rotational speed of \( \omega = 418.3 \pm 7.4 \text{ rpm} \) through the 29 runs of experiments. The rotational speed \( \omega \) and time \( t \) distributions can be seen in Fig. 5, where \( t \) refers to the length of the experiment in seconds. The total output mass across the 29 runs was \( m_{\text{out}} = 7.4 \pm 2.1 \text{ kg} \) and the power used by the auger \( P = 42.7 \pm 10 \text{ W} \), with the results presenting significant scatter.

The variables compared are the total output mass conveyed \( m_{\text{out}} = \dot{m}_{\text{out}} \cdot t \) and the power consumption of the conveyor \( P \). Figure 6 compares the predictions of the Radulescu model, the proposed model, and the experimental data [34]. The Radulescu model predictions have a mean of \( \dot{m}_{\text{out}} = 3.6 \text{ kg} \) and a standard deviation of 0.2 kg; the proposed model mean is \( \dot{m}_{\text{out}} = 5.4 \text{ kg} \) with an standard deviation of 0.4 kg and the experimental data present a mean \( \dot{m}_{\text{out}} = 7.4 \text{ kg} \) with an standard deviation of 2.1 kg [34]. These results are included in Table 3 and show a 24.3% reduction in the deviation from the experimental results when both models are compared. This deviation \( D \) is calculated with Eq. 12, where \( \mu_E \) represents the experimental mean value and \( \mu_M \) the model mean. This deviation represents the percentage of approximation of a model to the experimental results.

\[
D = \frac{\mu_E - \mu_M}{\mu_E} \times 100
\]  

(12)

For the conveyor’s power consumption \( P \), Fig. 7 shows the comparison between the proposed model predictions with and without losses, Ray’s model and Radulescu’s model predictions, as well as the experimental values. Although significantly more accurate than the other model’s predictions, the proposed model still slightly underestimates the conveyor power requirements. Radulescu et al. [34] state that the major difference between the power requirements and their predictions can be caused by considerable losses in the input and output of material, losses
in the transmission mechanism and a lack of control in the depth of cut. The material losses are a factor that can explain the underestimation of power requirements of the models, but nevertheless, the prediction error is quite large and shows the need for a model that better predicts the behaviour of the system. With torque measurements from the original setup, a more precise assumption could have been made. In Fig. 7, the Radulescu prediction is the furthest from the experimental values, followed by Ray’s. Both with and without losses considered, the proposed model’s predictions fit the experimental values significantly better than the previous methods. The results are included in Table 3 and show a 42.9 and 59.2% reduction in the deviation from the experimental result mean when the proposed model is compared with the models of Radulescu and Ray, respectively. When the losses are considered, the deviation from the experimental mean is 70 and 86.4% lower than the two previous methods. The validation of the model with experimental results that use a regolith simulant is an imperative step for future work.

3.2 Model predictions

The proposed analytical model aims to predict the behaviour of the system’s performance, given a set of parameters from the Radulescu setup [34] as presented in Table 2. The model was implemented in MATLAB 2019. The effects of four key parameters are explored, and plots to show the changes that these cause in the performance of the conveyor are included at the end of the section. The key parameters examined are: the auger rotational speed $\omega$, filling ratio $F_R$ of the conveyor, inclination angle $\beta$, and length $L$.
3.2.1 Filling ratio

As discussed previously, the filling ratio $FR$ has a major effect on the conveyor behaviour. The internal cohesion, friction, grain size among other material properties will affect the $FR$ of the conveyor, which can be increased with a forced feeding system or with an appropriate inlet design. The results of the model for five different $FR$ values are plotted in Fig. 8, which shows the important effect that the filling ratio of the conveyor has on the material flow rate $\dot{m}_{OUT}$. Higher $FR$ causes the increase of $\dot{m}_{OUT}$ as more material is being conveyed at the same time, with the penalty of higher torque requirements. It is easy to see why considering a $FR$ of 1 instead of the 0.15 recommended by [2] could lead to significant discrepancies in the model predictions. The power requirement shows a similar trend, with a direct relationship between the energy needs and both the $FR$ and $\omega$. The specific power ($W/kg$) is also affected by $FR$, requiring less power to convey the same mass of material at higher filling ratios.

3.2.2 Length

The length of the conveyor has a significant effect on the model results, being one of the most important variables in the friction component $P_F$. $P_F$ is the component with the greatest effect in the total power requirement, as the screw conveyors use the friction between the auger and the casing to convey the material. This effect shows the importance of keeping $L$ as short as possible, making it a vital part of the design constraints for an auger conveyor. The length does not affect the $\dot{m}_{OUT}$ of the material, as it affects the time it takes to transport the material but not its flow rate. Therefore, lengthening the auger causes a linear increase in specific power due to the added friction. The sensitivity analysis with six values of $L$ is plotted and presented in Fig. 9.

3.2.3 Inclination

The effect of high $\beta$ angles is not easy to predict, as some material slips off the auger and interferes with the material below. As a result of this behaviour, vertical screw conveyors tend to exhibit considerably lower efficiencies than...
horizontal ones and are usually designed with smaller diameters. However, this effect is reduced in low gravity conditions \[43\], making them a more viable option for lunar conditions. The inclination of the conveyor has an impact on both the \(m_{\text{OUT}}\) and \(P\). The output flow rate \(m_{\text{OUT}}\) is affected by the inclination of the auger, but its effect is not as important as the \(F_R\) for small \(\beta\). There is also a slight reduction in the power requirements, but the power to lift the material \(P_{st}\) is the smallest of the three power components. Therefore, the effects of \(P_{st}\) are not as substantial as

\[\begin{align*}
\text{Fig. 11} & \quad \text{Sensitivity analysis of the inclination angle } \beta \text{ and length } L \text{ combinations for an inclined auger conveyor with height } H = 0.25 \, m. \text{ The mass flow } m_{\text{OUT}}, \text{ absolute and specific power of six different combinations are compared across the } \omega \text{ range.}
\end{align*}\]

\[\begin{align*}
\text{Fig. 12} & \quad \text{Specific power at different auger angles normalised by the length of the auger}
\end{align*}\]
the previous cases. The plots that result from the inclination sensitivity analysis with inclination angles $\beta = [0, 5, 10, 15, 20]^\circ$ are shown in Fig. 10.

### 3.2.4 Length and inclination

Analysing the length and inclination provides a good insight into the influence of both parameters on the auger performance. However, it is also interesting to observe how the combination of both affects the performance of the system. At a set height, the inclination angle $\beta$ and length $L$ are mutually dependent. This assumption is often useful as lifting the material over the minimum necessary height wastes energy, and for the case of extraction, the transmission height is usually set by other conditions such as local topography or minimisation of material and mass of the overall conveyor system. The plots for six different combinations of $\beta$ and $L$ for a set height of 25 cm are shown in Fig. 11. The results show a constant decrease of $m_{\text{out}}$ at higher $\beta$ angles. This is because $L$ does not affect the $m_{\text{out}}$. Due to the stronger effect of the friction component compared with the material lifting portion of $P$, the power requirement greatly increases for shallower combinations, as $L$ increases following a rational function with the reduction of $\beta$. When the specific power is normalised by the length of the conveyor, it rapidly increases at higher inclination angles, as can be seen in Fig. 12.

### 4 Conclusions

Auger conveyor systems are a promising method for lunar regolith transportation, as well as many other applications, which should be further investigated. They have a low number of moving parts, are one of the simplest conveying methods, do not require auxiliary systems to work, and have been extensively studied and used terrestrially. A new analytical model has been developed and compared to two existing predictive models. The proposed model can be used to predict the behaviour of an auger conveyor and test the effect of the different parameters involved, which could be used to design more efficient regolith transport systems. The proposed model’s predictions show that the main power requirements are due to friction, with the filling ratio $F_R$ and length $L$ being the most critical parameters. The model also predicts the angle with the lowest specific power required for an inclined conveyor of known conveying height $H$. Existing models that are used to predict the performance of an auger conveyor system greatly underestimate the power requirements. The proposed model presented in this paper uses industrial guidelines for this type of conveyors and predicts a power consumption that more closely matches the experimental results of previously developed setups. The proposed model output flow $m_{\text{out}}$ predictions are on average 24.3% closer to the experimental data mean than existing models, while the predictions for the power requirements without considering energy losses are 42.9% and 59.2% closer than previous models. When the losses are considered, the proposed model predictions are 70% and 86.4% more accurate than existing models.

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### Declarations

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

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