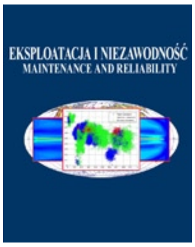

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Optimization of a screw conveyor's exploitation parameters

Indexed by: Web of Science Group

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Highlights

- Verification of theoretical design methods with experiments and simulations results.
- Computer DEM simulations as an advanced tool for designing screw conveyors.
- Optimization of construction and exploitation parameters of a screw conveyor.

Abstract

The paper describes the problem of designing screw conveyors in terms of determining their exploitation characteristics. Based on the actual values of mass efficiency and power demand obtained in a laboratory experiment, the theoretical design methods and the numerical discrete element method model results were verified. The obtained results have shown that the currently used theoretical methods underestimate the mass efficiency and power demand compared to experiments when typical values of filling rate coefficient and progress resistance coefficient are used. It was also shown that the results of DEM simulations are in good agreement with the experiments in terms of mass efficiency and power demand. Based on the exploitation characteristics determined in DEM simulations for different constructions of the screw and different rotational speeds, multi-objective optimization of the exploitation parameters of the screw was performed in order to minimize the power demand of a screw conveyor and simultaneously maximize its mass efficiency. The optimization results showed that it is possible to find such construction and the rotational speed that will maximize the mass efficiency of the conveyor and keep the power demand low, reducing the exploitation costs of the device.

Keywords

screw conveyor, discrete element method, bulk material, exploitation characteristics.

1. Introduction

Screw conveyors are intended for the short-distance transportation of bulk materials in food, agricultural, energy, or lime industry plants. They are also used when other processes, such as mixing, heating, cooling, drying, moistening, or precise proportioning, are required. A screw conveyor can be used for transportation in three planes: vertical, horizontal, or at a certain inclination angle. Simple construction and working principle, together with an easy adjustment of their efficiency through the change of the shaft's rotational speed, are the key advantages of the screw conveyors. Currently, screw conveyors can be equipped with screw flights of diverse shapes. Depending on the application, the screws may have varying pitches, conical internal and external diameters through the whole length, and the flights may be irregular in shape. In so-called reversible conveyors, used for bi-directional transportation of material, we can even find flights of opposite twist directions mounted on one shaft. Such untypical constructions of screws are possible with advanced flight production technologies, such as forming in hydraulic presses without preheating the prefabricated parts.

Producing any shapes and sizes of the screw flights is not a technological problem. What is challenging for the engineers is the designing process of the screw conveyors. Their construction and exploitation parameters must meet the defined requirements concerning the mass efficiency, filling rate of the trough, or providing the necessary power to the drive. The behavior of bulk materials during transportation by a screw conveyor is very complicated. It depends on many factors, such as the type and shape of the screw flights, the rotational speed of the shaft, the way of proportioning of the material, or the physical properties of the material. Theoretical methods for designing the screw conveyors do not consider all the factors mentioned above or oversimplify them. In the case of typical bulk materials of uniform granulation and standard constructions of the screws (constant pitch, constant internal and external diameters) and fed by one source, e.g., a hopper, theoretical methods allow reasonable estimation of the exploitation parameters of the screw conveyors. In the case of materials of specific properties (cohesive or strongly aerated materials) or for unusual shapes of screws or multiple feeding points, these methods do not provide reliable results of efficiency and power [16]. For this reason, the external diameters of the screws and power demands are very often chosen to be safely larger. Such an approach is unfavorable because of the excessive use of materials, ineffective use of the drive unit, and high exploitation costs. On the other hand, the difficulties in making decisions on the construction of screw conveyors are caused

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by insufficient exploitation data of the existing systems. Implementing the diagnostic, measuring, and expert systems would allow collecting and processing of the data on the exploitation parameters of the screw conveyors, which are working under different conditions in the industry [10, 12-14].

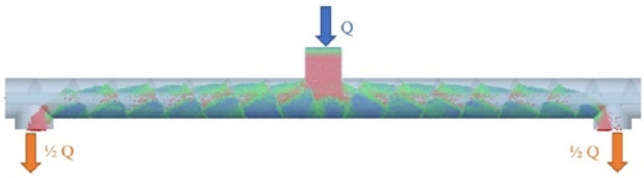


Fig. 1. A DEM simulation of a reversible conveyor

Nowadays, the design can be aided by advanced tools of virtual prototyping [4, 13, 17, 28]. Computer simulations are also used for studying the behavior of bulk materials during transportation by a screw conveyor. High computational powers of the workstations and highly developed numerical methods allow an accurate representation of the physical phenomena. As a result, the physical properties of a given bulk material and its interactions with a conveyor's components can be considered. In the simulations of bulk materials' behavior, the discrete element method (DEM) is used. Numerous simulation studies have confirmed the reliability of the results obtained in the simulations with comparison to the actual measurement results for different machines and devices used for the transportation of bulk materials [9, 24-25].

Screw conveyors have been a subject of research for years, studied theoretically, experimentally, and in computer simulations. The studies published so far have identified several phenomena observed during the transportation of a material by a screw conveyor. This, in turn, was used to determine how the physical properties of the transported materials, the geometry of the screw, the rotational speed of the shaft, and the conditions of material feeding influence the exploitation parameters of the device.

The authors of [15, 20-21, 25] have shown a good agreement between the results of DEM simulations and the results of experiments in determining a screw conveyor's efficiency. Besides, the research in [20] shows that theoretical models overestimate the values of mass efficiency compared to the actual results. The authors of [9] have shown a good agreement between the results of DEM simulations and the experiments in determining power demand. In [19], the authors used DEM to investigate the influence of filling rate, the rotational speed of the screw, the external diameter of the shaft, and the external friction coefficient of the material on the efficiency of a screw conveyor. The paper [11] shows the methodology for the calibration of a DEM material model during the simulation of the transportation of bulk materials by the screw conveyors of varying geometries (a screw with a constant pitch and external diameter on a regular shaft, a screw with changing external diameter, a screw with a varying pitch, a screw with a shaft of a changing external diameter). A good agreement was obtained between the efficiencies obtained in the simulations and experiments for all the studied variations of the screws, except for the screw with varying pitch – in this case, the simulated mass efficiency was underestimated by 24%. The authors explain this discrepancy with the size of DEM particles; they were too large compared to the screw pitch. In [27], the influence of the conditions of feeding the bulk material to the conveyor on the mass efficiency and power demand of the device was studied in laboratory conditions. It was shown that the efficiency of a screw conveyor increases with the rotational speed of a shaft, up to a value above which the centrifugal force causes the movement of the material towards the outside, which as a result limits the metering of the material from the hopper to the inside of the trough. It was also observed that the efficiency of the conveyor and its power demand are determined by the size of the trough inlet opening. Higher efficiency values were obtained for larger inlet openings. What is more, the paper [18] showed that the largest possible inlet opening together with a low rotational speed of the shaft provided the best efficiency because of the minimized power demand. The authors of [26] showed a correlation between the physical properties of the bulk material and the efficiency of the screw conveyor, based on the performed laboratory tests (shear cell test, compressibility test, permeability test, dynamic flow test). The papers [2,22,29] showed discrepancies between the experimental and theoretical efficiencies of a tubular screw conveyor. According to the theoretical models, the efficiency increases linearly with the increase of the rotational speed of the screw. In reality, the efficiency increases to a specific limit value of the rotational speed above which the efficiency curve flattens. It means that the further increase of rotational speed causes a smaller increase in efficiency. Paper [3] shows the results of the experiments on the power demand of a screw conveyor. It was observed that in the case of not aerated materials (sand and gravel), the power demand increases proportionally to the rotational speed of the screw. The increase of the rotational speed caused the decrease of the power demand for the transportation of an aerated material. It was caused by the decreased bulk density of the material after aeration. The authors of [23], based on the experiments' results, concluded that the smaller the ratio of the screw pitch and its external diameter, the greater the mass efficiency. The authors suggested that there is such a construction of a conveyor that ensures effective relation between efficiency and power demand. A good agreement between theoretically and experimentally obtained values of mass efficiency and power demand of a conveyor was observed. The calculations considered the working conditions and physical properties of the transported material (sand) very accurately, which, according to the authors, allowed such a good agreement.

Many papers correctly and purposefully indicated the influence of several factors connected with the transported material's properties, ways of manufacturing the material, or the construction and exploitation parameters of the screw on its work parameters. However, there are no clear guidelines for the constructors on how to include these factors in the designs using theoretical methods. The authors of some of the papers have confirmed the weaknesses of the theoretical methods for calculating the screw conveyors. The up-to-date simulation studies have shown a very good agreement between DEM simulations and experimental results regarding the mass efficiency of a screw conveyor. However, little attention is paid to the estimation of the power demand of a screw conveyor using the DEM method. Correct determination of power demand and efficiency of a screw conveyor allows the determination of exploitation characteristics, facilitating the choice of construction parameters and rotational speed to minimize the power demand and ensure effective transportation. There is also a lack of papers on the possibilities of optimizing the construction of the screw conveyors. This is why this paper shows the DEM simulation results of the transportation of cement performed to estimate the mass efficiency and power demand based on the experimental results. What is more, the results of multi-objective optimization of the exploitation parameters of a conveyor aimed at minimizing the power demand and maximizing the efficiency of a conveyor, performed with the use of the DEM method, are presented.

2. Methods of determining the exploitation parameters of a screw conveyor

The currently used theoretical methods allow the determination of mass efficiency of a conveyor and the drive power based on the adopted dimensions of the screw (pitch, external diameter), bulk density of the material, the rotational speed of the shaft, filling rate, and the progress resistance coefficient [1,16]. The basic method of determining a conveyor's mass efficiency and its power demand is described by Eq. (1) and (2).

$$Q = 60 \cdot \frac{\pi \cdot D_z^2}{4} \cdot n \cdot s \cdot \Psi \cdot \rho \cdot k_n, t/h \quad (1)$$

where:

D_z – external diameter of the screw, m,
n – rotational speed of the screw, rpm,
s – screw pitch, m,
ρ – bulk density of the material, t/m^3,
ψ – filling rate (within the range of 0.15-0.45, depending on the type of the material),
k_n – coefficient dependent on the angle of inclination of the conveyor (for a horizontal conveyor, the coefficient takes the value of 1),

$$P_H = \frac{c_o \cdot Q \cdot L}{367}, kW \quad (2)$$

where:

c_o – progress resistance coefficient of the transported material, dependent on the type of the material,
Q – efficiency of the conveyor, t/h,
L – length of the conveyor, m.

Eq. (3), proposed by CEMA (Conveyer Equipment Manufacturers Association), is very similar to Eq. (1), defined as per the basic method, i.e., mass efficiency is the function of the dimensions of the screw, rotational speed, and the filling rate of the trough. The CEMA method uses the imperial units, and the calculation models are shown in such a system. All the quantity units are taken according to CEMA [1]:

$$C = \frac{0.7854 \cdot \left(D_s^2 - D_p^2\right) \cdot P \cdot K \cdot 60 \cdot n \cdot W}{1728}, lbs/h \quad (3)$$

where:

C – mass efficiency, ft^3/h,
n – rotational speed of the shaft, rpm,
D_s – external diameter of the screw, in,
D_p – diameter of the shaft of the screw, in,
P – screw pitch, in,
K – filling rate percent,
W – bulk density of the material, lbs/ ft^3.

Eq. (4) expresses the power required for the transportation of material by a screw conveyor, without including the efficiency of the drive and friction in the bearings. Unlike the basic method, this equation includes the type and the shape of the screw flights.

$$hp_m = \frac{C \cdot L \cdot W \cdot N \cdot F_f \cdot F_m \cdot F_p}{1 \cdot 10^6}, hp \quad (4)$$

where:

C – mass efficiency, ft^3/h,
L – length of the conveyor, ft,
W – bulk density of the material, lbs/ft^3,
F_f – flight factor,
F_m – material factor,
F_p – paddle factor.

The equations for mass efficiency and power demand shown above are linear relations of the screw dimensions, filling rate of the trough, bulk density of the material, and empirical progress resistance coefficient. However, because of the limitations o these methods, the calculated exploitation parameters are not reliable. With an inaccurate calculation method, it is impossible to optimize the construction and exploitation parameters of a screw conveyor because of the significant risk of underestimating the results.

Unlike the theoretical methods, the numerical discrete element method allows reliable simulations of the bulk materials' behavior since it accounts for the interactions between the grains of the modeled material and the interactions between the material and the parts of the device. The modeled material is represented by a number of rigid spheres, whose behavior is described by various contact models [7, 9]. These models simulate the behavior of different materials, such as dry materials, strongly cohesive materials, or highly compressive materials. A DEM simulation accounts for the physical properties of the bulk material and, as a result, reflects its behavior very reliably. The material DEM model's basic inputs are the shape and size of a particle representing the actual grain of the material, the density of a particle, external and internal friction coefficients, and the restitution coefficient. It is worth noting that the material model's parameters in a DEM simulation are defined microscopically, i.e., for individual particles. Therefore, to reflect the macroscopic physical properties, the properties of individual particles must be chosen in a way that enables reflecting the behavior of the whole material. This process is called the DEM material model calibration and is further described by [5, 6, 7]. Having calibrated the model, we can simulate the transportation of the bulk material by a screw conveyor, determine its exploitation parameters (mass efficiency, power demand), and assess the filling rate of the trough, the behavior of the material in the feeding zone, and the abrasion wear of the flights.

3. Experimental and simulation studies on the exploitation parameters of a screw conveyor

The experiment aimed to measure the actual exploitation parameters of a screw conveyor, such as mass efficiency and power demand, depending on the rotational speed of the screw. The experiment was performed on a laboratory line designed for determining the exploitation parameters of a screw conveyor. The visualization of the laboratory line is shown in Fig. 2.

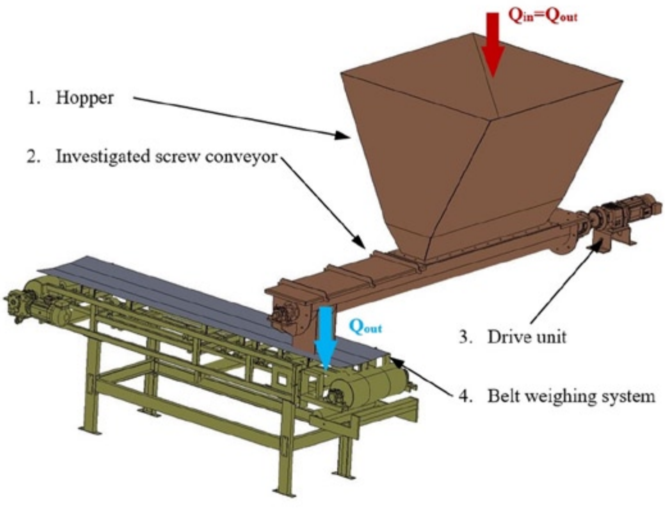


Fig. 2. Visualization of the laboratory line.

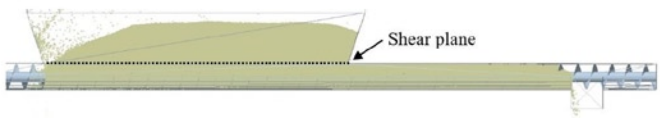
The experimental laboratory line was equipped with a hopper of 4 m^3 volume. The screw conveyor under study, with an external diameter of 160 mm and the screw pitch of 75 mm, was mounted on a shaft of a 70 mm diameter. A helical gear unit with a frequency converter supplied the power. The material from the screw conveyor was transported to a weighing unit type WMTP B-650, which allowed the measurement of the efficiency within the range up to 10 Mg/h, with an accuracy of 0.5%. The material from the weighting unit was then transported to a belt conveyor that fed the elevator transporting the material back to the hopper and closing the loop. The power demand was measured as the power consumption of the drive unit at a given rotational speed. Dimensions and exploitation parameters of the screw conveyor under study are shown in Table 1.

Table 1. Dimensions and exploitation parameters of the screw conveyor under study.

Parameter	Value
D_z – external diameter of the screw	160 mm
d_w – diameter of the screw shaft	70 mm
P – screw pitch	75 mm
L – length of the conveyor	4000 mm
n – the range of the rotational speed	20 – 70 rpm
α – the angle of inclination of the conveyor	0°

In order to minimize the increase of the power demand caused by the shear in the layer of the material at the interface of the hopper and the trough, the amount of the material was chosen to fill the trough without accumulating in the hopper as shown in Fig. 3.

a)



b)

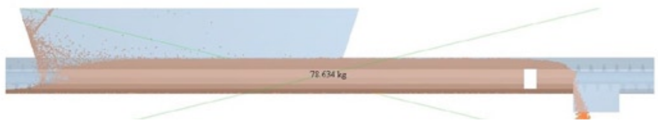


Fig. 3. a) Shear layer at the interface of the hopper and the trough
b) Filling rate of the trough during the experiment

The efficiencies of the belt conveyors and the bucket conveyor used for the closed-loop of the transported material were chosen to fill the trough, without the aforementioned accumulation of the material in the hopper. A Portland cement was used in the experiment, as it is a representative bulk material used in the cement, energy, and chemical industry plants. The granulation of the Portland cement is very fine, within 1μm to 50 μm. Its physical properties are very similar to the materials such as gypsum, limestone powder, and raw material powder. In the experiment and in the simulations, the assumption was made that the transported material is dry and non-cohesive. The physical properties of the Portland cement are shown in Table 2.

Table 2. Physical properties of the Portland cement

Physical property	Value
Bulk density, kg/m^3	1050
Moisture, %	0.2
The angle of repose, °	35.9
External friction coefficient	0.52

The DEM simulation model of the screw conveyor reflected the actual object used for the experiment. In order to ensure similar working conditions, the model included the hopper, the trough, and the central working unit – the screw, as shown in Fig. 4.

Only the screw conveyor and the hopper were included in the simulations, without the remaining equipment of the closed transportation loop. The constant amount of the material was ensured by the use of the periodic boundary condition. It means that the material from the end of the trough was fed back to the hopper, creating the closed loop. The parameters of the DEM model are shown in Table 3.

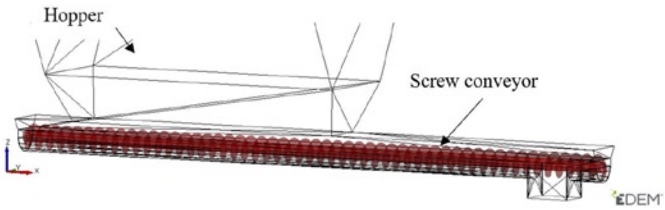


Fig. 4. The geometrical model under study

Table 3. Parameters of the material model of the cement used in the DEM simulations

Parameter	Value
Size of a DEM particle	3 mm
The shape of a DEM particle	Sphere
Shear modulus (G) for the interaction between the particles	1.0e+7 MPa
Shear modulus (G) for the interactions between the particles and the walls	1.0e+7 MPa
Poisson ratio	0.25
The density of a DEM particle	1675 kg/m^3
Coefficient of restitution	0.5
Internal friction coefficient	0.25
Rolling resistance coefficient between the particles	0.1
External friction coefficient	0.52
Rolling resistance coefficient between the particles and the walls	0.01
Timestep	2.66e-5 s
Number of particles used in the simulation	422, 000

4. Results

Fig. 5 shows the mass efficiency as a function of the rotational speed of the screw shaft, obtained in experiments, simulations, and using the theoretical models. In the calculations, typical values of the filling rate of the trough were adopted. In the basic theoretical model, the filling rate was set to $\psi = 0.25$ and the inclination coefficient $k_n = 1.0$. In the CEMA method, the filling rate coefficient was set to

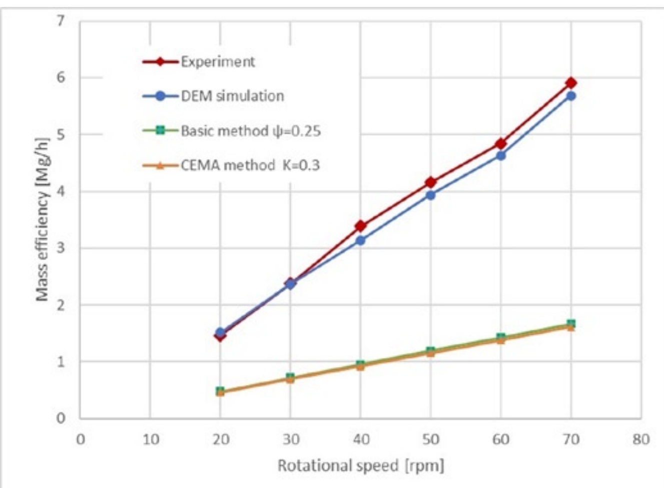


Fig. 5. Mass efficiency as a function of the rotational speed of a screw shaft

K = 0.3. The results obtained in the CEMA method were converted from the imperial units to the SI units.

In Fig. 5 we can see a good agreement between the DEM simulations and the experiment results. The efficiencies obtained in the basic theoretical method and CEMA are also very similar. However, with the adopted values of the filling rate, the theoretical values are much lower than those obtained in the DEM simulations and the experiment.

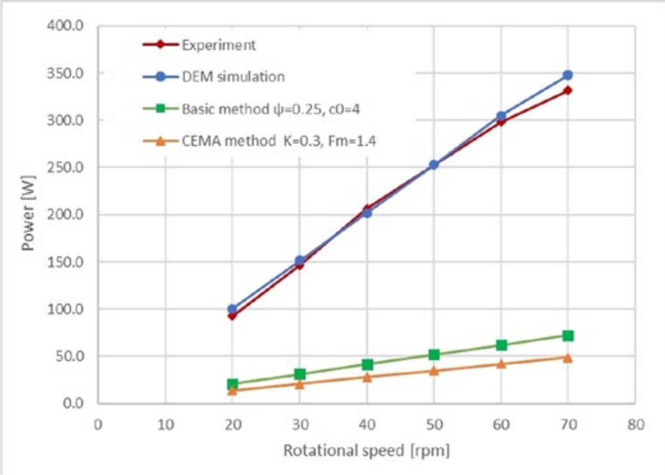


Fig. 6. Power demand as a function of the rotational speed of the screw shaf

Fig. 6 shows the power demand as a function of the rotational speed of the screw shaft in a similar way. The actual power required for the transportation of the cement with a defined rotational speed was determined as a difference of the total power measured during the transportation of the material and the power of an empty conveyor. For the theoretical calculations, in the Portland cement case, the resistance coefficients were taken to be $c_0 = 4.0$ for the basic method and $F_m = 1.4$ for the CEMA method.

Fig. 6 shows that the power demand of a crew conveyor during the cement's transportation determined in DEM simulations is in good agreement with the actual results of the experiment. The theoretical calculations underestimated the results significantly compared to experiments and DEM simulations. What is more, there is a discrepancy between the results of the basic and CEMA methods. For the adopted values of the material's progress resistance coefficient inside the trough, the CEMA method resulted in lower values.

The use of DEM simulations facilitated the assessment of the filling rate of the trough at different values of the rotational speed. Fig. 7 shows the filling rate of the trough at the rotational speed equal to 20, 50, and 70 rpm.

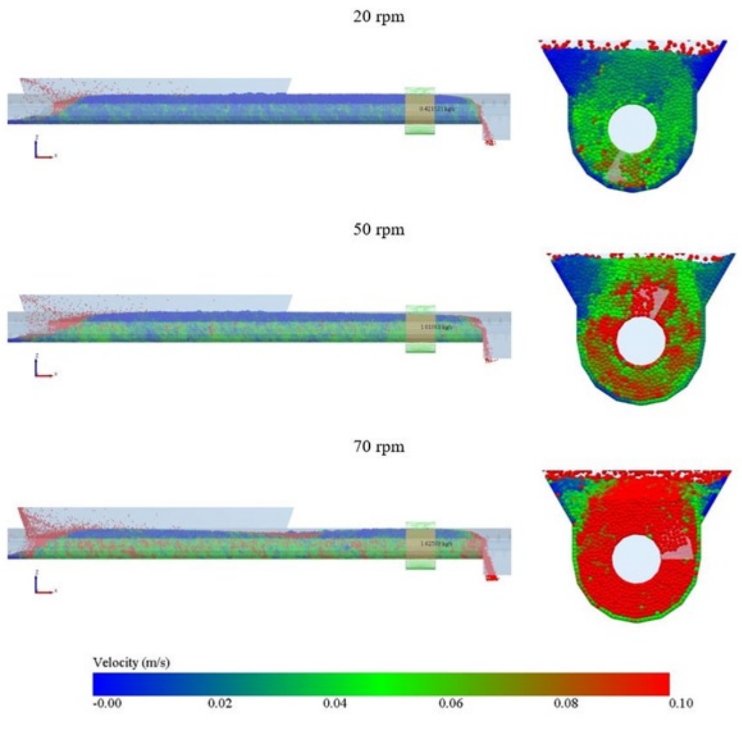


Fig. 7. Filling rate of the trough together with the distribution of the velocity of the material in the cross-section through the trough

The presented distributions of the filling rates of the trough show that the trough is filled in 100% through the whole length of the screw conveyor. Based on the above results, the filling rate coefficients were corrected to $\psi = 0.9$ for the basic method and K = 1.0 for the CEMA method, which significantly improved the consistency between the theory and the experiment. Fig. 8 shows the comparison of the results of mass efficiency for the corrected filling rate coefficients.

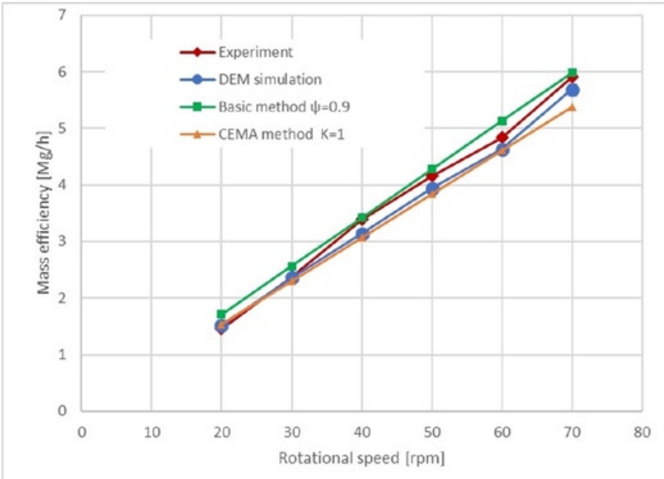


Fig. 8. Mass efficiency results for the corrected values of filling rate coefficients

With the corrected values of filling rate coefficients both theoretical methods resulted in values very similar to the results of the DEM simulations and the experiment.

A similar procedure was repeated to determine the power required for the transportation of the material by a screw conveyor. The mass efficiencies calculated for the corrected values of the filling rate coefficients were used, and the progress resistance coefficients were chosen in such a way that allowed a good agreement with the actual results of experiments. For the basic method, the coefficient c_0 was determined to be $c_0 = 5.5$, and for the CEMA method, the coefficient $F_m = 3.1$. Fig. 9 shows the comparison of the power demand with the corrected resistance coefficients.

Fig. 9 implies that using the corrected progress resistance coefficients results in a good agreement between the results obtained during the laboratory tests and determined in the DEM simulations.

5. Multi-objective optimization

Decision-making is an integral part of the design process. The constructors decide which solutions are the most effective for specific criteria, such as efficiency, power, durability, etc. Usually, these criteria (objectives) are conflicting, e.g., designing a durable device with a minimized use of materials, achieving the best possible efficiency with minimum power demand, etc. In most cases, such solutions cannot be found. This is because the minimization of one objective causes the maximization of the other. We can say that the objectives are conflicting, but one dominates the other [7]. Hence, the optimization results can be divided into dominated and non-dominated solutions.

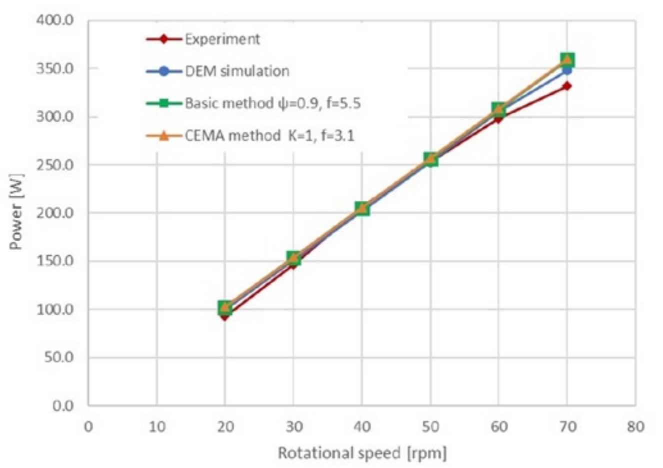


Fig. 9. The power demand for the corrected values of the resistance coefficients as a function of the rotational speed of the screw

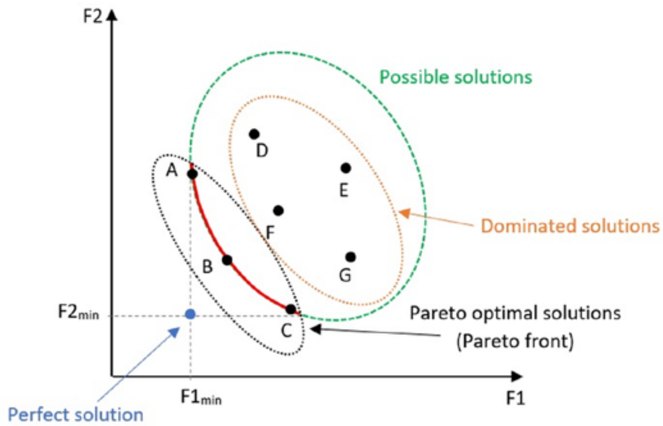


Fig. 10. Sets of dominated and non-dominated solutions

The dominated solutions are the ones, for which both criteria can be improved. In Fig. 10 these are the solutions D, E, F, and G. The choice of such solutions is unjustified since there are better solutions in terms of $F1_{min}$ and $F2_{min}$. Such solutions are called non-dominated or Pareto optimal [7]. This means that a solution that improves one of the criteria without degrading the other does not exist. Figure 10 shows a set of solutions A, B, and C called a Pareto front; the elements of such a set are Pareto optimal. A perfect solution is such a vector of variables, for which all the objective functions take the minimum value. Finding such a point is practically very rare since each objective function takes its minimum for a different set of variables [7].

In the case of the above example, we can specify three variants. Solution A reaches the minimum of the objective function F1 and the maximum of the objective F2, Pareto optimally. Solution B takes middle values of F1 and F2, and solution C reaches the minimum of F2 and the maximum of F1, Pareto optimally. From this example, we can see that in multi-objective optimization, the decision-maker can choose a solution from the Pareto front depending on their preferences.

Mathematically, a general decision-making model takes the following form:

$$F(x) = f(x_1, \ldots, x_n) \rightarrow min, max$$
$$g_i(x_1, \ldots, x_n) \geq 0, i = 1, \ldots, m \tag{5}$$

where:

F(x) – objective function (criterion), which should be minimized or maximized,

$x_1, \ldots x_n$ – variables,

$g(x_1, \ldots x_n)$ – constraints.

The value of the objective function (criterion) can be defined as a measure of the decision to be made. Depending on the requirements, this function can be either minimized or maximized. The variables describe alternative decisions. In many cases, the decision must be made considering numerous criteria F1(x), F2(x), …, which comes to the problem of multi-objective optimization.

6. Results of the multi-objective optimization of the exploitation parameters of a screw conveyor

Based on the calibrated DEM material model, several simulations were performed for different constructions of a screw conveyor and different rotational speeds in order to determine the efficiency characteristics and power demand. Table 4 shows the construction parameters of the screw conveyors under study.

Table 4. Construction details of the simulated screw conveyors.

Construction No.	D – external diameter, mm	d – internal diameter, mm	s – screw pitch, mm
1	150	60	100
2	150	60	150
3	150	60	200
4	200	60	100
5	200	60	150
6	200	60	200

The simulations were performed for the rotational speeds within the range of 20 to 80 rpm. In order to ensure identical working conditions in each case, the amount of material in the hopper and the trough was constant and equal to 150 kg, as shown in Fig. 11.

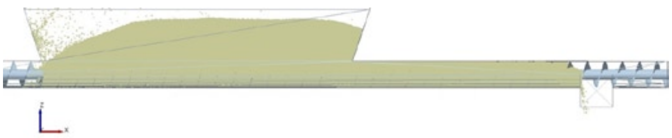


Fig. 11. Simulated transportation of the material by a screw conveyor

Fig. 12 shows the simulated mass efficiency values for each construction of the conveyor as a function of the rotational speed of the screw.

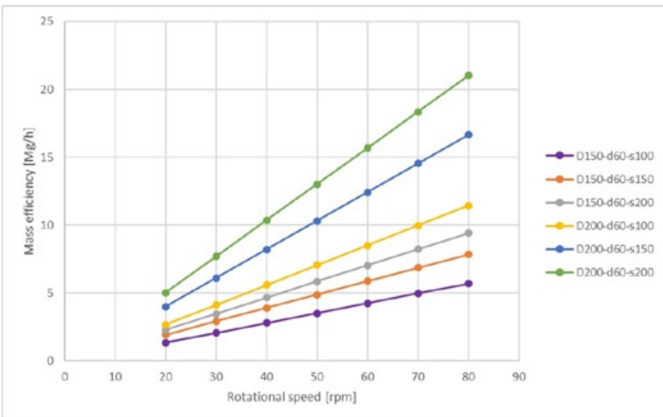


Fig. 12. Mass efficiency of the simulated screw conveyors as a function of the rotational speed of the screw shaft

As it is indicated by the above graphs, the efficiency increases linearly within the studied range of the rotational speed of the shaft. For individual rotational speeds, the efficiency increases with the increase of the screw pitch and the flights' external diameter.

Fig. 13 shows the power demand required for cement transportation by a screw conveyor at defined rotational speeds of the screw shaft.

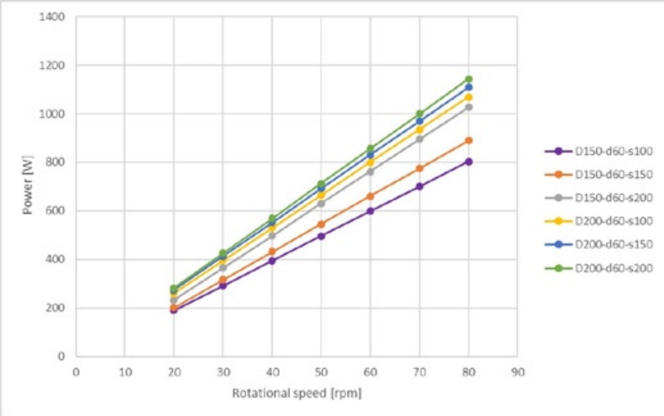


Fig. 13. Power demand of the simulated screw conveyors as a function of the rotational speed of the screw shaft

Similarly, like in the case of mass efficiency, the power demand of each conveyor increases together with the increase of the rotational speed. We can see that also in this case at a constant rotational speed, the power demand increases with the increase of the screw pitch and the flights' external diameter.

Both characteristics show how the construction parameters of the screw conveyors and the rotational speed of the shaft influence the mass efficiency and power demand. The interpretation of the results does not determine which option is the best possible to maximize the efficiency with simultaneous minimization of the power demand. Therefore, in order to be able to choose the best construction, we can perform multi-objective optimization.

The exploitation parameters of a screw conveyor, i.e., mass efficiency and power demand are determined by the construction parameters, such as the external diameter of a screw and screw pitch. According to the principles of multi-objective optimization, the following objective functions were determined:

F1 – power required for the transportation of the material (6)

$$F1(x) = f(x_1, x_2, x_3) \rightarrow min \tag{6}$$

F2 – mass efficiency of a conveyor (7)

$$F2(x) = f(x_1, x_2, x_3) \rightarrow max \tag{7}$$

With such objective functions, the following variables were taken into account:

x_1 – external diameter of the screw,
x_2 – screw pitch,
x_3 – the rotational speed of the screw.

The constraints g(x) were adopted as follows: rotational speed within 40-60 rpm, screw pitch within 100-200 mm, and the external diameter of the screw flights within 150-200 mm. This relation is described by Eq. (8):

$$g(x) = f(x_1, x_2, x_3) \tag{8}$$

For such an optimization task, the optimization of a screw conveyor's construction parameters can be performed. Table 5 shows the defined objective functions and constraints.

Table 5. Defined objective functions and constraints.

F1(x)	F2(x)	g(x)
Power demand → minimum	Efficiency → maximum	g(x_1) ∈ <100; 200 mm> g(x_2) ∈ <150; 200 mm> g(x_3) ∈ <40; 60 rpm>

Figure 14 shows the possible solutions in the space of objective functions, together with a perfect solution.

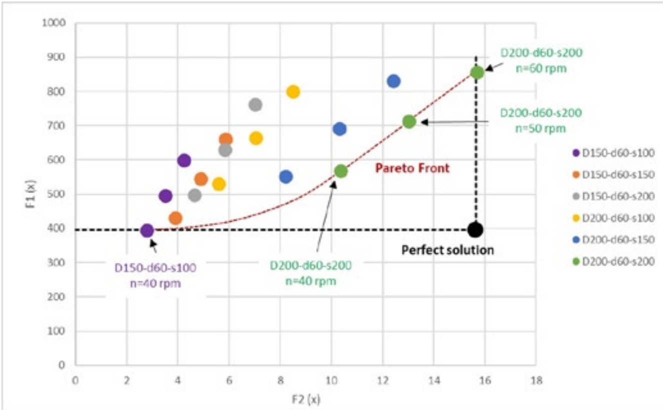


Fig. 14. Possible solutions of the optimization and a Pareto front

The Pareto front was obtained for three values of the rotational speed (40, 50, and 60 rpm), the external diameter of the conveyor D_{out}=200 mm and the screw pitch s=200 mm, and for the rotational speed equal to 40 rpm for a screw conveyor of the external diameter of D_{out}=150 mm and the screw pitch s=100 mm. Obtaining a perfect solution in terms of (6) and (7) is impossible due to the adopted constraints. As can be easily seen, these functions are conflicting, and the increase in efficiency caused the increase of the power demand.

When one of the objective functions is minimized, and the other one is maximized, the optimal solutions of (6) and (7) can be found by solving Eq. (9):

$$\max\left(\frac{F1(x)}{F2(x)} : x \in D\right) \tag{9}$$

where:
D – the set of possible solutions,
$F2(x) \neq 0: x \in D$

For each construction of a screw conveyor, the ratios of F1(x) – power demand and F2(x) – mass efficiency were determined. The values of the obtained ratios are shown in Table 6.

Table 6. Ratios of the objective functions

Construction details	F1(x)/F2(x)
D150-d60-s100	0.0071
D150-d60-s150	0.0090
D150-d60-s200	0.0093
D200-d60-s100	0.0106
D200-d60-s150	0.0149
D200-d60-s200	0.0183

The maximum ratio of the objective functions F1(x) and F2(x) was obtained for the screw conveyor of the external diameter D_{out}=200 mm and the screw pitch s=200 mm. It means that this construction is the optimal solution of (6) and (7) with the adopted constraints.

7. Conclusions

Designing screw conveyors requires much attention and caution from the constructors. The conveyors' construction parameters (external diameter, screw pitch) and the rotational speed of the screw significantly influence the exploitation parameters, i.e., efficiency and power demand. The goal is to ensure the required mass efficiency at the defined filling rate of the trough and the rotational speed of the screw, and to allow efficient transportation of the material. On the other hand it is important to ensure some capacity reserve in cased a temporary increase of the material fed to the conveyor. As shown in the so-far research and by the experiments' results, theoretical calculation methods are not sufficient since they do not provide reliable results of mass efficiency and power demand required for the transportation of the material. The theoretical methods are based on the assumption that mass efficiency and power demand are the functions of the dimensions of the screw, bulk density, filling rate of the trough, and empirical progress resistance coefficient of the bulk material inside the trough. Such methods simplify the physical properties of the transported materials. They do not include their interaction with the trough and the screw and the bulk density change during the transportation. Keeping in mind all the limitations of these methods and the fact that the results are very often far from reality, the constructors rarely risk optimizing the construction of the screw conveyors.

As shown in the simulations, the results of the mass efficiency ad power demand obtained in the numerical discrete element method (DEM) are in good agreement with the experiments' results. This method reflects the behavior of a bulk material during transportation by a screw conveyor since it includes the physical properties of the materials and their interaction with the components of the screw conveyors. Large possibilities offered by the DEM method for modeling bulk materials make it a universal tool aiding the design of screw conveyors. In order to obtain reliable results of the simulation, the input parameters of the DEM material model must be calibrated carefully, based on the actual physical properties of the bulk material. Computer simulations allow the determination of mass efficiency and power demand of a screw conveyor and the estimation of filling rate of the trough, assessment of the behavior of the bulk material in the feeding zone, and the abrasion wear of the flights. With such a reliable tool, the construction parameters of the screw conveyor can be optimized to decrease its power demand (and, as a consequence, exploitation costs caused by the electric energy consumption) with the maintained high efficiency. As it was shown by the results of the performed multi-objective optimization, the transportation is more effective with a conveyor of a larger external diameter of the flights and larger screw pitch (the efficiency is maximized, and the power demand is minimized). Obtaining a perfect Pareto solution was not possible due to the adopted constraints. Nevertheless, the multi-objective optimization facilitates the decision on the choice of the construction parameters and the rotational speed of the screw.

Further research on the optimization of the construction of screw conveyors should include additional objectives concerning minimization of flights' abrasion wear and minimization of the conveyor's mass. Together with the minimization of the power demand and maximization of the efficiency, these functions may allow such construction that will reduce the costs of producing, exploitation (e.g. replacement of the worn flights), and the power supplied to the device while working.

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