

Article

Determining the Maximum Linear Mass of a Suspended Conveyor Belt Using PySR Symbolic Regression

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Abstract

Suspended conveyor belts are widely used in mining, including in systems with non-contact support such as magnetically suspended conveyors, where the maximum admissible linear mass of the loaded belt determines the required supporting forces. This paper presents a method for estimating the upper limit of the linear mass of a suspended belt for a given belt width and bulk material. Several cross-sectional configurations are analysed, and analytical expressions for the bulk cross-sectional area under limiting fill are derived. A numerical search over the troughing radius is then performed to find the radius that maximises the cross-sectional area and to select the configuration that provides the largest area. For this configuration, the extremum condition leads to a transcendental equation; so, symbolic regression with the PySR package is used to obtain an explicit approximation for the radius that maximises the area as a function of belt width and angle of repose. Substituting this expression into the standard formula for linear mass yields a closed-form estimate of the maximum admissible linear mass. Numerical examples show good agreement with the optimisation results and indicate that the formula is suitable for preliminary design of suspended and magnetically suspended belt conveyors.

Keywords: linear mass of the belt; maglev; troughing of the conveyor belt; cross-sectional area of the cargo; belt geometry optimization; symbolic regression; PySR



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1. Introduction

Conveyor systems play a pivotal role in the mining industry, enabling the continuous transportation of ore and overburden over long distances [1]. In light of escalating requirements for productivity and process sustainability, the enhancement of conveyor systems has become a strategic priority [2].

One promising avenue for advancing conveyor transport is the development of suspended-belt conveyors, in which the belt is supported by hangers, ropes, or other discretely spaced elements instead of conventional idler sets [3]. One variety of suspended conveyors is the conveyor with magnetic suspension of the belt [4]. Their operating principle relies on magnetic forces that support the belt without mechanical contact with structural supports [5]. This is achieved by generating a magnetic field that compensates the weight of the belt and the conveyed material [6]. The principal advantage of such systems is the reduction in friction, which directly lowers energy losses, increases the overall efficiency of the conveyor, and diminishes component wear. Eliminating belt-support

contact removes the need for idler rollers, reduces friction in the support zone, and extends equipment service life [7].

In magnetically levitated conveyors, the suspended belt passes above a series of discretely spaced magnetic modules (with permanent magnets or electromagnets) that create a supporting magnetic field and hold the belt within a prescribed air gap. The magnets are placed either under the belt edges or beneath its central part, and the spacing between modules defines the distance between neighboring suspension points. In such a configuration, each span of the suspended belt must sustain its own linear mass of belt and load without losing stability and without exceeding the allowable deflections and air gap. For magnetically levitated conveyors [8,9], as for other suspended-belt systems, one of the key design characteristics is the maximum permissible linear mass of the loaded belt. The stability of the suspended belt and the levitation margin are directly governed by the balance between the available lifting force and the total belt-and-load mass per unit length. Exceeding the allowable linear mass may lead to loss of stability or belt overturning, which results in shutdowns of conveying and potential equipment damage. Therefore, a method for calculating the maximum linear mass is required already at the preliminary design stage of such systems.

In most existing conveyor design methods, the problem of determining the limiting load and capacity is treated for belt conveyors with idler sets. Classical approaches are based on models of the cross-section of a troughed belt on idler supports [10–12]. In these models, the idler geometry (troughing angles, roller arrangement) is prescribed, and analytical relationships are derived for the cross-sectional area of the bulk load, the utilization factor of the belt width, the permissible fill level and, consequently, the conveying capacity and the load on the belt. In a number of standards and handbooks these relationships are provided in the form of ready-made formulas and charts, which makes it possible to estimate the limiting mass of the load and the belt loading for a given idler scheme.

However, for suspended and magnetically suspended conveyors [13,14] these approaches face fundamental limitations. First, in classical models the cross-sectional shape is rigidly determined by the idler geometry and is not treated as the result of maximizing the cross-sectional area. Second, the support spacing is not explicitly linked to the shape of the cross-section. Third, in many works the mass of the belt and the bulk per unit length is introduced as an input parameter, whereas the problem of determining the maximum permissible linear mass for a given belt width and material properties is not formulated explicitly.

In suspended-belt systems the cross-sectional shape is not the same as in the presence of idlers; instead, it is governed by the spacing between supporting elements and by the properties of the bulk material. As a result, the classical formulas for idler-supported conveyors do not provide a direct answer to the question of what maximum linear mass can be realized for a suspended belt of a given width and material under an admissible cross-sectional shape. This motivates the development of a method for calculating the ultimate attainable linear mass specifically for suspended belt conveyors, including those with magnetic levitation, as well as a compact analytical relationship linking the troughing parameters to this limit under realistic cross-sectional shapes of the bulk material.

Thus, the novelty of the present study lies in transferring the problem of determining the maximum linear mass from the context of idler-supported conveyors to the context of a suspended belt, where the cross-sectional shape and suspension parameters are treated as design variables. The proposed methodology is tailored to the suspended-belt type and is intended for integration into the design calculations of magnetically levitated conveyors while also being applicable to other suspended-belt systems.

The objective of this study is to develop a methodology for determining the maximum attainable linear mass of a loaded suspended conveyor belt for a given belt width and bulk-material properties [15]. The approach is based on analyzing the transverse geometry of the material layer on the belt, determining the troughing parameters at which the cross-sectional area attains its maximum, and constructing a compact analytical model that combines the bulk mass and the belt mass into a single expression for the maximum permissible linear mass.

A number of studies indicate that the configuration and operating modes of cutting-and-loading equipment directly affect the stability of material feed onto the conveyor, contact loads, and maintenance requirements. It has been shown that optimizing the layout of modules and their interfaces with conveying systems reduces wear of contact units and stabilizes conveying regimes [16]. In parallel, logistics chains are being digitalized: sensor networks, streaming analytics, and predictive maintenance provide end-to-end monitoring of conveyors, control of load distribution, and early detection of adverse operating regimes [17]. For magnetically levitated conveyors, these results are particularly important, because maintaining the prescribed air gap and balancing the lifting force against the linear mass require embedded measurements and real-time, data-driven control loops.

Another important aspect is the formation of the material stream on the belt in the loading zone. Experimental studies show that targeted design refinements of loading devices (for example, the use of an auxiliary blade on a shearer) improve cleanup and make the discharge stream more uniform, reducing impact overloads and fluctuations in the fill factor as material is transferred onto the belt [18]. For magnetic-levitation systems, this directly increases the stability margin of the suspended belt and reduces the likelihood of air-gap collapse or overturning by lowering peaks in the required lifting force per unit length.

Within this study, several cross-sectional configurations characteristic of suspended belts (configurations a–d) are considered. For each configuration, analytical expressions are derived for the cross-sectional area of the bulk load at limiting fill. A numerical search is then performed on a grid of belt widths and angles of repose to find the troughing radius at which the cross-sectional area is maximized and to identify the configuration that provides the largest area. It is shown that, in the range of parameters considered, one of the configurations yields the maximum area, and the corresponding extremum condition leads to a transcendental equation for the troughing radius that does not admit a simple closed-form solution.

To obtain an expression suitable for practical design, symbolic regression with the PySR package is applied to represent the optimal troughing radius as a function of belt width and angle of repose. Based on numerically determined values of the radius that maximize the cross-sectional area, a compact explicit approximation for the troughing radius is constructed. Substituting this expression into the standard formula for the linear mass, which accounts for the bulk density and the areal mass of the belt, yields a closed-form analytical expression for the maximum permissible linear mass of the loaded suspended belt.

The main results of this study are as follows: analytical expressions for the cross-sectional area at limiting fill are obtained; the configuration and troughing radius that provide the maximum area are determined numerically; using symbolic regression in PySR, an explicit approximation is constructed for the troughing radius at which the area is maximal; and, on the basis of this approximation, a closed-form expression is derived for the maximum permissible linear mass of a suspended belt, suitable for preliminary design of suspended and magnetically levitated conveyors.

2. Materials and Methods

2.1. Factors Governing the Maximum Mass per Unit Length

Mass per unit length is the total mass per one meter of the conveyor belt, comprising the mass of the belt itself and the mass of the conveyed material over that segment. Maximizing the material mass on the belt requires simultaneously: maximizing the cross-sectional area of the bulk load, S_g , and achieving a high fill factor, k .

The cross-sectional area S_g is determined by the belt's troughing geometry—namely, the belt width l , the suspension spacing AB , and the troughing radius R . Forming the belt into a trough increases carrying capacity relative to a flat belt [11,12,19]. The fill factor k represents the fraction of the available volume that is actually occupied by material; it depends on the angle of repose j , moisture content, particle-size distribution and particle shape, and the loading conditions [20–22]. For dry, free-flowing bulk materials, k typically reaches 0.85–0.95, whereas for sticky or coarse, blocky materials it is commonly 0.6–0.7 or lower.

The relationship between geometry and the mass per unit length is given by:

$$m_l = m_{belt} + \rho k S_g(l, j, R); \quad (1)$$

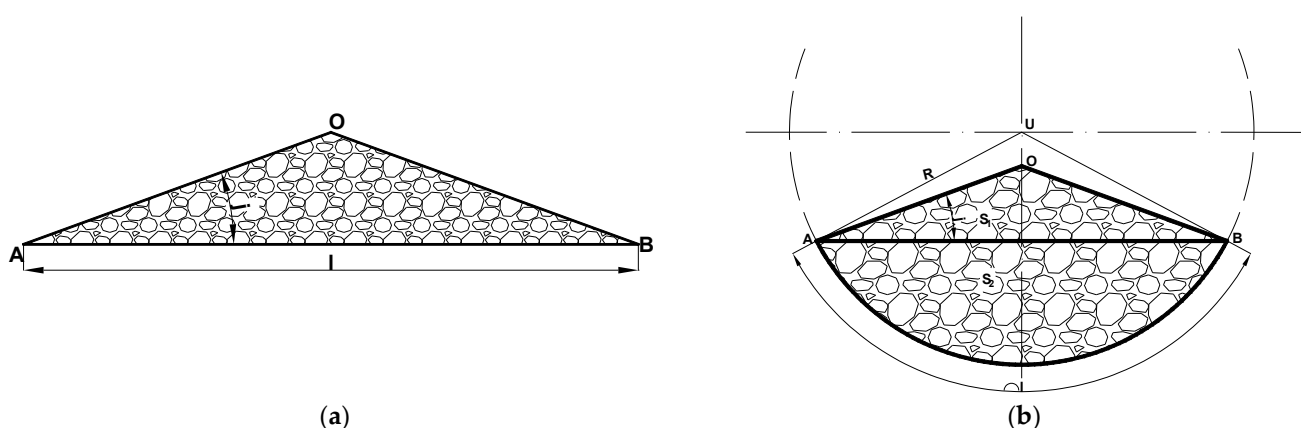
where m_l —linear mass, m_{belt} —is the bare-belt mass per unit length (without payload), ρ —is the bulk density of the conveyed material, k —is the fill factor, S_g —is the cross-sectional area of the bulk. Throughout all formulas, the angle j is expressed in radians (tabulated values given in degrees are converted to radians prior to use).

2.2. Cross-Sectional Geometry of the Bulk Load on the Belt

The cross-sectional [23] shape (Figure 1) is governed by the interplay among the belt width l , the suspension spacing AB , and the troughing radius R , and can be realized in four configurations, a–d [24,25].

 $a:l = AB$ (flat belt (no troughing));

$b:l > AB, AB < 2R, l < 2R, d = l$; the arc length between the suspensions equals the belt width

$$c:l > AB, AB = 2R, l > 2R, d < l;$$
$$d:l > AB, AB = 2R, l > 2R, d = l.$$
Figure 1. *Cont.*

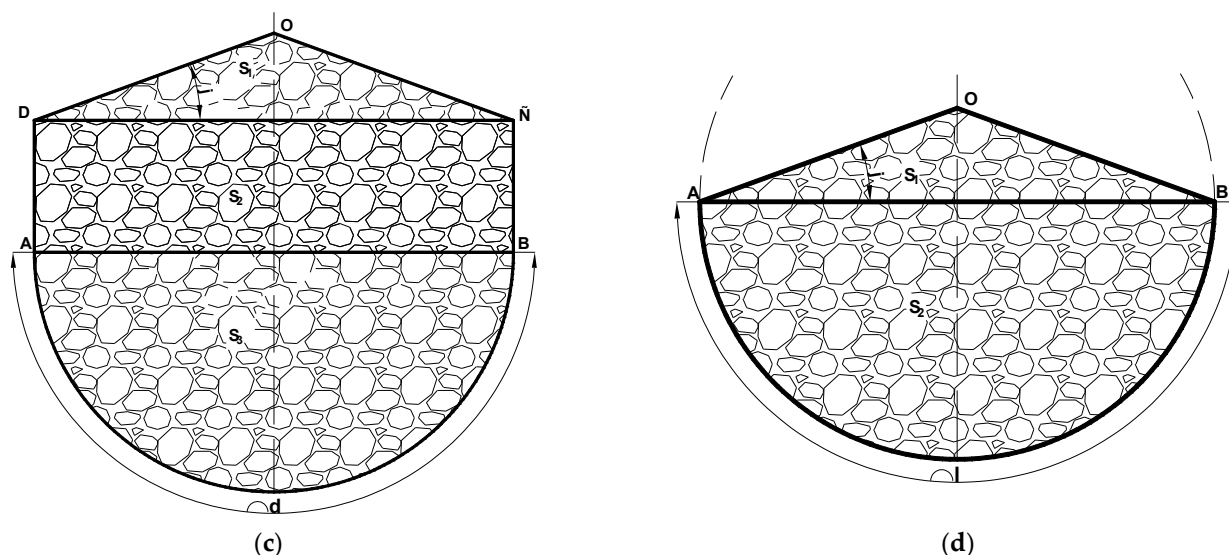


Figure 1. Variants of the cross-sectional shape of the load on the belt: (a)—flat belt; (b)—belt with a trough smaller than a semicircle; (c)—belt with a semicircular trough and a vertical section; (d)—belt with a semicircular trough. Notation: l —belt width; AB —suspension spacing; R —troughing radius; d —arc length between the suspensions O —apex of the bulk material heap, U —center of the belt trough circle.

Among the cross-sectional configurations (a–d), we sought the shape that maximizes S_g under limiting fill (accounting for the angle of repose j). For each variant, closed-form expressions $S_g^{(a-d)}(R)$ were derived. The optimal radius R_{opt} was obtained from the first-order condition $\partial S_g / \partial R = 0$ and verified as a maximum within the admissible domain. A comparative summary $S_{g,max}$ across a–d is provided in (Table 1).

Table 1. Comparison of the Maximum Cross-Sectional Area of the Bulk Load Across Configurations.

$l, \text{ mm}$	$j, ^\circ$	$S_{g(a)}, \text{ mm}^2$	$S_{g(b)}, \text{ mm}^2$	$S_{g(c)}, \text{ mm}^2$	$S_{g(d)}, \text{ mm}^2$
800	25	74,609	141,040	132,100	132,100
800	30	92,376	152,790	139,300	139,300
800	35	112,030	166,680	147,260	147,260
800	40	134,260	183,350	156,270	156,270
1000	25	116,580	220,370	206,400	206,400
1000	30	144,340	238,730	217,650	217,650
1000	35	175,050	260,440	230,100	230,100
1000	40	209,770	286,480	244,170	244,170
1500	25	262,300	495,830	464,400	464,400
1500	30	324,760	537,150	489,720	489,720
1500	35	393,870	585,980	517,730	517,730
1500	40	471,990	644,580	549,390	549,390
2000	25	466,310	881,470	825,610	825,610
2000	30	577,350	954,930	870,610	870,610
2000	35	700,210	1,041,700	920,400	920,400
2000	40	839,100	1,145,900	976,690	976,690

The optimal configuration is defined by the maximization of the cross-sectional area under limiting fill, i.e.,:

$$R_{opt}(l, j) = \arg \max_{R \in \mathcal{D}(l, j)} S_g(R|l, j) \quad (2)$$

where $\mathcal{D}(l, j)$ —denotes the admissible set of radii R , dictated by the geometry (Figure 1) and by design constraints (e.g., the relationships among AB , R , l). Throughout all equations, the angle j is expressed in radians.

2.3. Software Environment and Reproducibility

To obtain R_{opt} employed a one-dimensional optimization with multiple initial guesses (multi-start robust search) to avoid entrapment in local extrema; candidate solutions that violated geometric constraints (e.g., $AB \leq 2R$ for the relevant configurations) were rejected. For verification, we also computed $S_g(R)$ profiles on an R —grid and cross-checked the locations of the maxima (Figures 2 and 3).

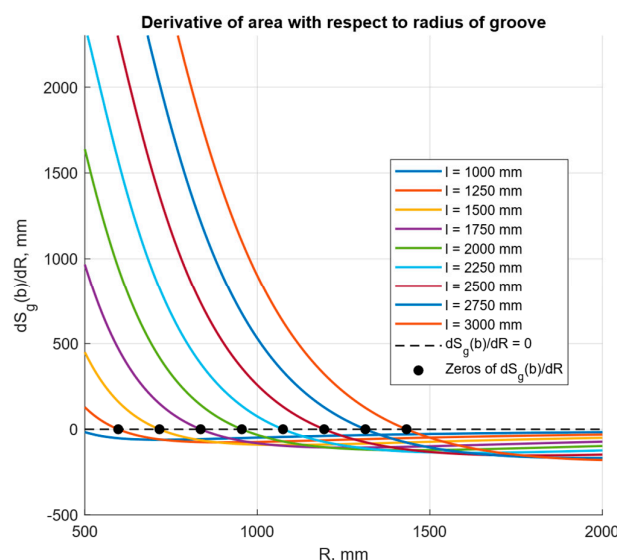


Figure 2. Derivative of the area with respect to the troughing radius.

Only for configuration b (troughing less than a semicircle) does the optimality condition lead to a transcendental equation that does not admit a simple closed-form solution for R_{opt} . For configurations a , c , and d , the maximizing radius and the corresponding maximum area can be obtained analytically; so, symbolic regression is not required for them. Consequently, PySR was applied exclusively to the dataset for configuration b in order to replace the numerical solution with a compact explicit formula suitable for engineering calculations.

For each (l, j) pair, maximum troughing radius R_{max} for configuration B was determined by numerically solving the transcendental equation for the maximum bulk cross-sectional area $S_g(b)$, whose derivation is presented in Section 3 (Results). Thus, the dataset used in the subsequent symbolic regression consists of the values $R_{opt}(l, j)$ obtained from this numerical solution of the cross-sectional-area maximization problem.

A data table comprising 1100 observations with three columns:

R_{opt}, l_1, j_1 . Ranges:

$l_1 \in [100, 10,000]$ (mm);

$j_1 \in [0.1745, 1.0472]$ rad (≈ 10 – 60°);

R_{max} —maximum troughing radius.

Missing or invalid entries were removed, yielding a final sample of 1100 rows. The dataset was randomly partitioned into training and test subsets in an 80/20 split using `random_state = 42`.

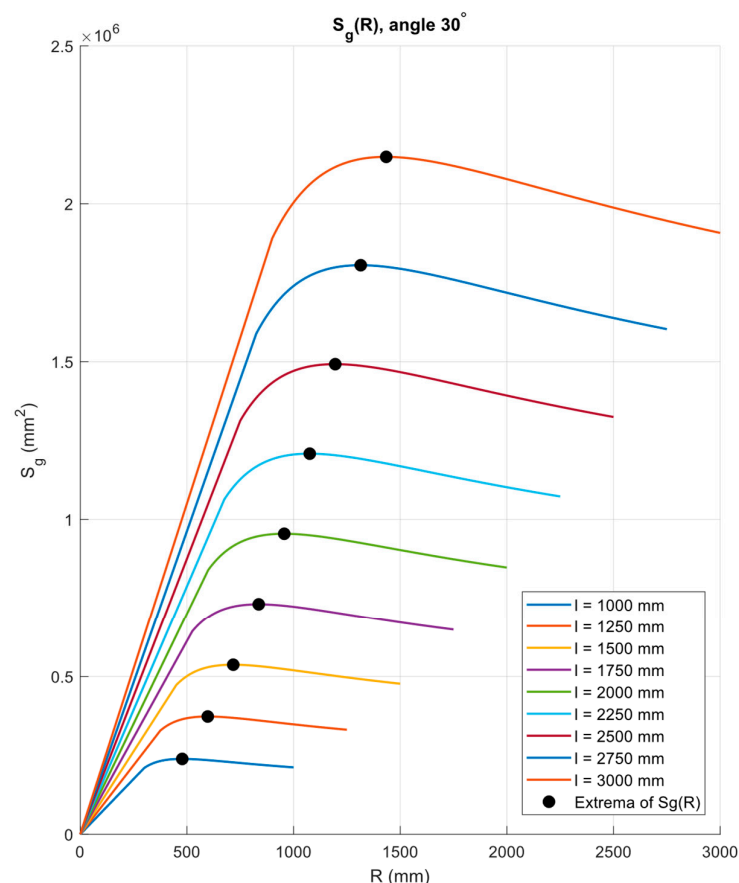


Figure 3. Dependence of $S_g(R)$.

To approximate the mapping $R_{opt} = f(l, j)$ employed PySR (SymbolicRegression.jl). The operator set comprised:

$\{+, -, \times, \div, \text{pow}, \sqrt{}, \exp, \log, \text{square}, \text{cube}, \text{inv}\}$, where $\text{inv}(x) = 1/x$. Training employed a complexity cap $\text{maxsize} = 20$ and a parsimony penalty $\text{parsimony} = 10.0$. The evolutionary search settings were: $\text{niterations} = 100$, $\text{populations} = 10$, $\text{population_size} = 100$, and a wall-time $\text{limittimeout_in_seconds} = 600$. Variable names were— l, j . Model quality was assessed on the test set using R_{opt} . In addition, physical plausibility was verified via monotonicity checks: R_{opt} increases with l at fixed j and decreases with j at fixed l .

Approximation quality was evaluated on the test set, yielding $R^2 \approx 0.999$ and a typical relative error in $R_{opt} < 0.1\%$. In addition, we verified dimensional consistency (unit balance) and scale homogeneity, checked monotonicity with respect to l and j , and assessed robustness via a stress test that removed 5–10% of the data (stress-test).

Python [3.13.7], PySR [1.5.9], NumPy [2.3.2], Pandas [2.3.2], Scikit-learn [1.7.1]; PySR interfaced Julia [1.11.6]. Randomness was controlled by setting the pseudo-random seed = 42. The complete training code and data-preparation scripts are available in the repository [26].

3. Results

3.1. Computation of the Maximum Cross-Sectional Area of the Bulk Load

To determine the maximum cross-sectional area of the bulk load [27], we first compute the areas for all geometric configurations [28]. We begin with variant *a* (flat belt, $l = AB$). In this case, the cross-section is an isosceles triangle with base l and base angles j . Its area is:

$$S_{g(a)} = \frac{l^2}{4} \times \tan(j); \quad (3)$$

Under configuration b , the bulk cross-sectional area is the sum of the triangular wedge $S_{1(b)}$ and the circular-segment area $S_{2(b)}$.

The triangular component $S_{1(b)}$ is given by:

$$S_{1(b)} = R^2 \times \sin^2\left(\frac{l}{2R}\right) \times \tan(j); \quad (4)$$

the circular-segment area $S_{2(b)}$ is given by:

$$S_{2(b)} = \frac{R}{2} \left(l - R \times \sin\left(\frac{l}{R}\right) \right); \quad (5)$$

the total cross-sectional area $S_{g(b)}$ is given by:

$$S_{g(b)} = R^2 \times \sin^2\left(\frac{l}{2R}\right) \times \tan(j) + \frac{R}{2} \left(l - R \times \sin\left(\frac{l}{R}\right) \right); \quad (6)$$

to determine the value of R at which $S_{g(b)}$ attains its maximum, we differentiate $\frac{dS_{g(b)}}{dR}$ and set the derivative to zero. Differentiation yields:

$$\frac{dS_{g(b)}}{dR} = \tan(j) \times \sin\left(\frac{l}{2R}\right) \left[2R \times \sin\left(\frac{l}{2R}\right) - l \times \cos\left(\frac{l}{2R}\right) \right] + \frac{1}{2} \left[l \left(1 + \cos\left(\frac{l}{R}\right) \right) - 2R \times \sin\left(\frac{l}{R}\right) \right]; \quad (7)$$

solving the stationarity condition $\frac{dS_{g(b)}}{dR} = 0$ yields the troughing radii R , at which the bulk cross-sectional area attains its maximum. Because a closed-form solution is precluded by the equation's transcendental nature, the optimal R is determined numerically. Computations were carried out for an angle of repose $j = 30^\circ$ and belt widths l , ranging from 1000 to 3000 mm in 250 mm increments (Figure 2). The resulting optima form the basis for the subsequent approximation and the construction of compact, generalizable relationships.

As an illustrative case, for a belt width of 2000 (mm) the derivative $\frac{dS_{g(b)}}{dR}$ vanishes at $R = 0.955$ (m), we therefore take this value as the optimal radius for maximizing the area. Substituting (with the same j and l) into Equation (15) yields the corresponding maximum cross-sectional area of the bulk for configuration (b).

As an additional check, we numerically located the maximizer of $S_{g(b)}(R) = \max$ (Figure 3) for each case $j = 30^\circ$ considering belt widths l from 1000 (mm) to 3000 (mm) in 250 (mm) increments.

The function $S_{g(b)}(R)$ attains its maximum for a belt width $l = 2000$ (mm) at $R = 0.955$ (m) we therefore take this value as the optimum for configuration (b).

We now derive the area for configuration (c) which decomposes into:

S_1 —the area of the triangular repose wedge above the inner chord DC ;

S_2 —the area of the rectangular insert between the parallel chords DC and AB of height H (where $l = d + 2H$);

S_3 —the area of the semicircle of radius R , bounded by the chord AB (since $AB = 2R$).

Accordingly, the total area is:

$$S_{g(c)} = R^2 \times \tan(j) + 2R \left(\frac{l}{2} - \frac{\pi}{2} R \right) + \frac{\pi}{2} R^2 = R^2 \times \tan(j) + R \times l - \pi R^2 + \frac{\pi}{2} R^2 = R^2 \left(\tan(j) - \frac{\pi}{2} \right) + R \times l; \quad (8)$$

recognizing that this is a quadratic function of R , the coefficient of R^2 : $a = \tan(j) - \frac{\pi}{2}$. If ($a < 0$) the parabola opens downward and, therefore, the maximum is attained at:

$$R_{opt} = -\frac{l}{2(\tan(j) - \frac{\pi}{2})} = \frac{l}{2(\frac{\pi}{2} - \tan(j))}; \quad (9)$$

however, boundary constraints also apply: the radius cannot exceed $\frac{l}{\pi}$ otherwise the pile height becomes negative. Consequently:

$$H = \frac{l}{2} - \frac{\pi}{2}R \geq 0 \Rightarrow R \leq \frac{l}{\pi}; \quad (10)$$

since $R_{opt} > \frac{l}{\pi}$, while $R \leq \frac{l}{\pi}$, the maximum is attained at the boundary:

$$R = \frac{l}{\pi}, H = 0; \quad (11)$$

this yields the expression for the maximum cross-sectional area:

$$\begin{aligned} S_{g(c)} &= \left(\frac{l}{\pi}\right)^2 \left(\tan(j) - \frac{\pi}{2}\right) + \frac{l}{\pi} \times l = \frac{l^2}{\pi^2} \times \tan(j) - \frac{l^2}{2\pi} + \frac{l^2}{\pi} \\ &= \frac{l^2}{\pi^2} \times \tan(j) + \frac{l^2}{2\pi}; \end{aligned} \quad (12)$$

since, for configuration c the maximum occurs at $H = 0$, the side portions of the belt do not rise above the chord AB , and the trough is formed solely by the semicircular arc. In this limit, the belt geometry becomes identical to configuration d , for which the arc length equals the belt width l , and $AB = 2R$. Consequently, at $H = 0$, the optimal configuration for c collapses to d , and the maximum cross-sectional area in both cases is determined by the same geometry. Accordingly, the closed-form expression for the maximum area derived for configuration c , is equally valid for configuration d .

To compare the configurations on an equal footing, the cross-sectional area was computed for all four variants (a–d) over a grid of belt widths $l = 800, 1000, 1500, 2000$ mm and angles of repose $j = 25^\circ, 30^\circ, 35^\circ, 40^\circ$. For every (l, j) combination, configuration B produced the largest cross-sectional area, while configurations c and d yielded slightly lower values and configuration a consistently gave the smallest area. The numerical results are summarized in Table 1 and show that configuration B provides the highest degree of belt filling (maximum achievable loading of the cross-section); therefore, in the subsequent analysis it is taken as the representative cross-sectional shape corresponding to the maximum loading of the belt.

Accordingly, the maximum cross-sectional area is attained under configuration $B \Rightarrow$ hence, at $R = R_{opt}$ $S_{g(b)} = S_{max}$.

The optimal troughing radius R_{opt} was determined numerically for belts of varying width l and angle of repose j (Figure 4). The computations spanned belt widths from 100 mm to 10,000 mm in 100 mm increments and angles of repose from 10° to 60° in 10° , increments, thereby covering typical operating conditions of mining conveyance systems. Although, in practice, most conveyors employ belt widths up to 2000–3000 mm and most bulk materials exhibit angles 50° , [29] extending the modeling range improved the generality of the derived relations and their robustness by supplying a broader training domain for the symbolic-regression algorithm. The resulting dataset size is thus justified by the need for faithful modeling and ensures the applicability of the results across a wide spectrum of engineering scenarios.

To derive an analytical dependence of the optimal troughing radius R_{opt} on belt width l and angle of repose j employed symbolic regression using the PySR library [30]. This approach automatically discovers compact, interpretable mathematical expressions that approximate the data without prescribing the functional form a priori [31,32].

As input, we used a dataset comprising over one thousand l, j combinations with their corresponding R_{opt} , obtained via numerical optimization of the bulk cross-sectional area.

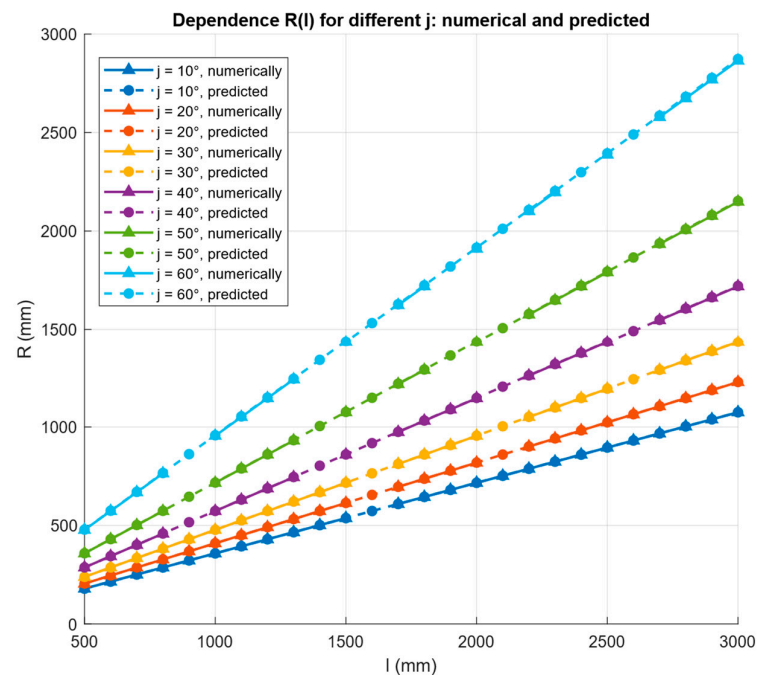


Figure 4. Comparison of data obtained numerically and using the dependence derived by symbolic regression method.

Data processing involved preliminary cleaning, normalization of column names, type casting, and splitting the dataset into training (80%) and test (20%) subsets [33]. Model training employed a set of basic operators—addition, subtraction, multiplication, division, and exponentiation—together with unary functions (square root, logarithm, exponential, and reciprocal) [34]. The algorithm was configured to search for expressions that balance accuracy and parsimony, enforcing a complexity cap and a parsimony penalty to discourage overly complex formulas and overfitting [35].

As a result, the algorithm yielded a relation that best captures the system’s behavior while satisfying the expected monotonicity criteria. The optimal troughing radius is accurately described by:

$$R_{\text{opt}} = \frac{l}{\pi - 2.0029 \times j}; \quad (13)$$

The derived analytical dependence $R_{\text{opt}}(l, j)$ is based on a geometric analysis of the circular segment and the triangle formed by the belt chord and the radius of curvature, and it approximates the numerical solutions of the underlying transcendental equation for the maximum cross-sectional area. Figure 4 presents a comparison between the numerical values of R_{opt} and the results obtained from this analytical relation, while Table 2 shows representative examples of the agreement between the numerical and predicted values for various combinations of belt width l and angle of repose j .

Table 2. Comparison of Numerical and Predicted R_{opt} .

L (mm)	j (rad.)	Numerical R_{opt} (mm)	Predicted R_{opt} (mm)	Error
100	0.1745	35.8069	35.814	~0.02%
200	0.1745	71.6188	71.628	~0.01%
100	0.2618	38.1954	38.198	~0.01%
5000	0.9599	4092.55	4099.7	~0.17%
10000	0.2618	3819.72	3819.8	~0.002%

For a quantitative assessment of the approximation accuracy, standard metrics were computed using the same computed values of $R_{\text{opt}}(l, j)$ that were employed for training the PySR model, namely the root-mean-square error:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (R_i^{\text{pred}} - R_i^{\text{num}})^2}, \quad (14)$$

the mean absolute error:

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |R_i^{\text{pred}} - R_i^{\text{num}}|, \quad (15)$$

and the coefficient of determination:

$$R_{\text{det}} = 1 - \frac{\sum_{i=1}^N (R_i^{\text{num}} - R_i^{\text{pred}})^2}{\sum_{i=1}^N (R_i^{\text{num}} - \bar{R}^{\text{num}})^2}, \quad (16)$$

where R_i^{num} are the numerical values of R_{opt} , R_i^{pred} are the values computed from the derived formula, and $\bar{R}^{\text{num}}$ is the sample mean. For the obtained relation, the metrics are $\text{RMSE} \approx 6.76$ mm, $\text{MAE} \approx 4.13$ mm, and $R_{\text{det}} \approx 0.99999$. These indicators confirm the suitability of the formula for engineering calculations.

Verification of physical plausibility showed that the model correctly reproduces the expected trends: for a fixed angle j , the optimal radius R_{opt} increases monotonically with increasing belt width l , whereas for a fixed l , the value of R_{opt} decreases as the angle of repose j increases. This is consistent with the expected behaviour of the system: at larger angles of repose the heap becomes steeper and lower in height; so, a smaller trough radius is sufficient to contain the bulk material.

A universal formula has been derived for computing the maximum cross-sectional area of the bulk load on the belt.

$$\begin{aligned} S_{\text{max}} &= \frac{l^2}{(\pi-x)^2} \times \cos^2\left(\frac{x}{2}\right) \times \tan(j) + \frac{l^2}{2(\pi-x)} \left(1 - \frac{\sin(x)}{\pi-x}\right) \\ &= \frac{l^2}{(\pi-2.0029 \times j)^2} \times \cos^2\left(\frac{2.0029 \times j}{2}\right) \times \tan(j) + \frac{l^2}{2(\pi-2.0029 \times j)} \left(1 - \frac{\sin(2.0029 \times j)}{\pi-2.0029 \times j}\right); \end{aligned} \quad (17)$$

recognizing that AB denotes the suspension spacing, we derived the spacing at which the belt's bulk cross-sectional area attains its maximum:

$$AB_{\text{opt}} = \frac{2l \times \cos(1.00145 \times j)}{\pi - 2.0029 \times j}; \quad (18)$$

We then determine the optimal suspension spacing, AB_{opt} and compare it with the numerically obtained spacing (Figure 5) for belt widths l ranging from 1000 to 3000 (mm) in 250 (mm) increments, at an angle of repose $j = 30^\circ$.

From Equation (17), for $l = 2000$ (mm) and $j = 30^\circ$ $AB_{\text{opt}} = 1.6396$ (m), A direct numerical search shows that S_g attains its maximum at $AB = 1.6540$ (m). The relative difference of 0.87% indicates close agreement and corroborates the validity of Equation (18) for engineering use.

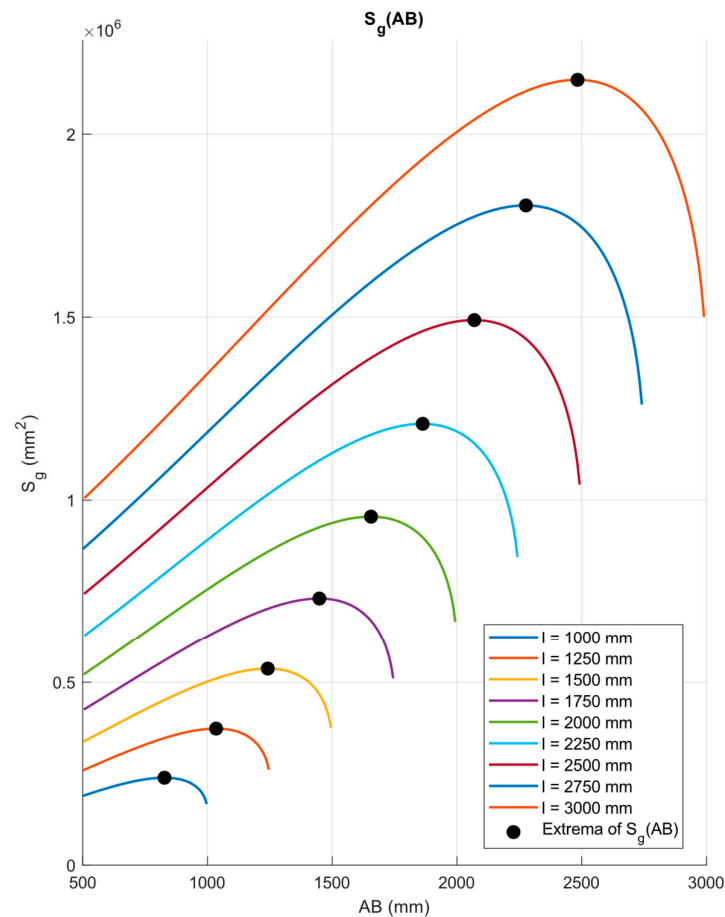


Figure 5. Dependence of the cross-sectional area on the distance between supports AB.

3.2. Determination of the Payload Mass per Unit Length

Having determined the maximum cross-sectional area of the bulk on the belt, $S_g = \max$ the next step is to compute the mass of the conveyed material per unit belt length (per meter). The characteristics of the bulk cargo are presented in Table 3.

Table 3. Bulk Material Properties.

Conveyed Material	Bulk Density	Static Angle of Repose j	Maximum Permissible Conveyor Incline (Uphill) b_{max}
Coal:			
brown dry	0.6–0.9	35–45	16–18
brown wet	0.8–1.0	40–50	18
raw	0.8–1.1	30–45	18
Gravel:			
wet washed	1.8–1.9	40–50	20
unsorted	1.3–1.5	35–40	18
sorted dry	1.2–1.45	30–35	18
expanded clay	0.6–0.8	30–40	13–15
granite	1.5	35–45	18

Over a 1 m belt segment, the bulk volume is numerically equal to the cross-sectional area, S_g (m^3/m); so, the payload mass per unit length is obtained by $V = S_g \cdot 1$ [36]. When sizing the magnetic suspension, [37] we employ $S_{g,max}$ to obtain a conservative (upper-bound) [38] estimate of the payload mass per meter.

3.3. Accounting for the Belt Mass

In addition to the payload, the belt's self-weight contributes to the mass per unit length of the conveyor [39]. Accurate determination of the total mass per unit length therefore requires explicit inclusion of the belt mass.

The belt mass per unit length m_{belt} (kg/m) depends on its construction—most notably the carcass (reinforcement) type and the thickness of the rubber covers. The two principal belt families—textile (fabric-reinforced) and steel-cord—differ markedly in weight: textile belts generally have a lower specific mass, whereas high-strength steel-cord belts are heavier.

For textile (fabric-reinforced) belts handbook data typically report the belt mass per unit length m_{belt} as an areal mass (areal density) in units of (kg/m²) (see Table 4). To obtain m_{belt} in (kg/m), multiply the areal mass by the belt width l (in meters).

Table 4. Areal mass of textile (fabric-reinforced) belts (kg/m²) as a function of fabric type and ply count [40].

Fabric Type	Cover Grade	3 Plies	4 Plies	5 Plies	6 Plies	8 Plies
TK-200-2	3-1	9.10	10.00	11.00	11.90	12.90
TK-200-2	5-2	14.10	15.70	16.30	17.70	18.90
TK-200-2	4.5-3.5	16.80	18.40	19.80	21.60	23.20
TK-200-2	6-2	15.40	17.00	18.60	20.20	21.80
TK-200-2	6-3.5	18.20	19.80	21.40	23.00	24.60
TK-200-2	8-2	18.20	19.80	21.40	23.00	24.60
TK-300	4.5-3.5	21.00	23.00	24.80	27.00	29.60
TK-300	6-2	19.30	21.30	23.30	25.30	27.20
TK-300	6-3.5	22.80	24.80	26.80	28.80	30.70
TK-300	8-2	22.80	24.80	26.80	28.80	30.70
TK-300	5-2	17.60	19.60	20.20	22.10	23.80
TLK-200-2	6-2	16.10	17.90	19.80	21.60	23.90
TLK-300	6-3	16.40	18.40	20.40	22.30	24.60
TLK-400	6-4	16.10	17.90	19.80	20.90	22.70

3.4. Practical Application and Worked Example

In the preceding sections, a closed-form expression for the maximum bulk cross-sectional area $S_{g,max}(l, j)$ for configuration b (Equation (17)) was obtained. Substituting this function into the general relation between cross-sectional area and mass per unit length (Equation (1)) yields Equation (19), which defines the maximum attainable mass per unit length of the loaded suspended belt:

$$m = \rho \times k \times \left[\frac{l^2}{(\pi - 2.0029 \times j)^2} \times \cos^2\left(\frac{2.0029 \times j}{2}\right) \times \tan(j) + \frac{l^2}{2(\pi - 2.0029 \times j)} \left(1 - \frac{\sin(2.0029 \times j)}{\pi - 2.0029 \times j}\right) \right] + m_{belt}; \quad (19)$$

As shown in Section 2.3, the approximation used to construct Equation (19) reproduces the underlying numerical model with a typical relative error of less than 0.1%; so, the values of m_{max} computed from Equation (19) inherit this level of accuracy.

As a detailed example, consider a conveyor with a textile (fabric-reinforced) belt TK-300 (four plies, with 4.5/3.5 mm covers) transporting run-of-mine coal. TK-300 is a widely used standard belt type in mining belt conveyors; so, this example highlights that the proposed methodology can be directly applied to conventional off-the-shelf belts when designing suspended, including magnetically levitated, conveyor systems. Let the belt width be $l = 2.0$ m, the bulk density $\rho = 1100$ kg/m³, the angle of repose $j = 45^\circ$, the operational factor $k = 0.95$, and the linear mass of the empty belt $m_{belt} = 23.0$ kg/m.

$$m = 1100 \times 0.95 \times \left[\frac{4}{2.4607} \times 0.5 + \frac{4}{3.1376} \left(1 - \frac{1}{1.56887} \right) \right] + 23.0 \times 1 = 1331.3 + 23.0 \approx 1.35 \times 10^3 \text{ kg/m} \quad (20)$$

The maximum attainable mass per unit length in this example is about $m_{\max} \approx 1.35 \times 10^3 \text{ kg/m}$. This value can be used directly as the design load for determining the required specific lifting force of the magnetic suspension.

To illustrate the behavior of Equation (19) over a wider range of parameters, additional calculations of $m_{\max}$ were carried out for various combinations of belt width l , bulk density ρ , and angle of repose j . In all the examples below, the same operational factor $k = 0.95$ and linear mass of the empty belt $m_{\text{belt}} = 23.0 \text{ kg/m}$ are used. The examples are summarised in Table 5.

Table 5. Examples of maximum linear mass $m_{\max}$ for different combinations of parameters.

$l, \text{ m}$	$\rho, \text{ kg/m}^3$	$j, ^\circ$	k	$m_{\text{belt}} \text{ kg/m}$	$m_{\max}, \text{ kg/m}$
1.5	1100	30	0.95	23.0	584.3
2.0	1100	30	0.95	23.0	1020.9
2.0	1100	40	0.95	23.0	1220.5
1.5	1800	30	0.95	23.0	941.5
2.0	1800	30	0.95	23.0	1655.9
2.0	1800	40	0.95	23.0	1982.5

The numerical values in Table 5 were obtained by substituting the corresponding parameters into Equation (19). The table clearly demonstrates the expected trends: $m_{\max}$ increases with increasing belt width and bulk material density, and it also depends significantly on the angle of repose. These dependencies must be taken into account when specifying the required lifting capacity of the magnetic suspension system.

4. Discussion

This work proposes a reproducible methodology for determining the maximum attainable mass per unit length of a suspended conveyor belt with magnetic levitation. The methodology combines an analytical description of the cross-section for the key geometric configurations (*a–d*) and its optimization with respect to the troughing radius R and the derivation of an interpretable closed-form law for $R_{\text{opt}}(l, j)$ via symbolic regression. We show that the maximum cross-sectional area is achieved under configuration *b*, which follows from more complete utilization of the belt width l subject to the geometric constraints on AB and R . Configurations *c* and *d* yield the same maximum in the boundary case $H = 0$, whereas configuration *a* underperforms due to the absence of troughing.

The resulting compact law is:

$$R_{\text{opt}} = \frac{l}{\pi - 2.0029 \times j} \quad (21)$$

It faithfully reflects the underlying physics: at fixed j the optimal radius increases monotonically with belt width l , at fixed l decreases as the angle of repose j grows. This accords with intuition: a wider belt requires a gentler curvature to retain the pile, whereas a larger angle of repose (steeper flanks) permits a less pronounced trough. Comparison with the numerical solution demonstrates high approximation accuracy, and the monotonicity checks confirm the physical soundness of the result across the entire training domain. An important corollary follows from $AB = 2R \sin\left(\frac{l}{2R}\right)$ substituting $R_{\text{opt}}(l, j)$, yields a closed-form expression for the optimal suspension spacing that links trough geometry to the suspension layout.

The practical significance of these results is that maximizing the cross-sectional area $S_{g,max}$ at a given belt width l and angle j yields a direct increase in throughput without enlarging the conveyor envelope. Combining $R_{opt}(l, j)$ with the area model $S_g(R)$ and accounting for the fill factor k and bulk density ρ , the total mass per unit length is:

$$m_l = m_{belt} + \rho k S_g(l, j, R); \quad (22)$$

which, in turn, determines the required specific lifting force of the magnetic system. A representative example for a TK-300 textile belt transporting run-of-mine coal yields a total mass per unit length of approximately 1354,3 kg/m and a corresponding specific lifting force of about 13,28 kN/m, establishing realistic requirements for the magnetic suspension and an adequate margin for levitation stability. At the operational level, this translates into reduced wear, lower friction, and improved overall reliability of the conveying line.

This study has recognized limitations. First, the angle of repose j is treated as deterministic and constant, whereas in practice it depends on moisture content, particle-size distribution, particle shape and interparticle cohesion, and under belt motion may differ from the static value (i.e., a dynamic angle). Second, the fill factor k is modeled in aggregate; its dependence on loading regime, vibration, belt speed, and the geometry of the loading device can lead to deviations from the assumed values. Third, the calculations neglect the belt's bending and transverse stiffness, local edge deformations, and potential loss of slope stability under impact loading.

The foregoing simplifications were adopted deliberately to obtain an upper bound on the mass per unit length, appropriate for the preliminary design stage of the magnetic suspension. Under the stated assumptions—a deterministic, stationary angle of repose j , a high (aggregate) fill factor k , an idealized trough geometry without sagging or local edge deformation; and quasi-static operation without impact disturbances—the quantity m_l attains its maximum, i.e., the worst-case for the suspension in terms of the required specific lifting force. This conservative stance ensures that adequate margins in lifting force and levitation stability are specified when selecting the parameters of the magnetic system.

In this study, a quasi-static geometrical–analytical formulation is considered, which makes it possible to obtain an upper estimate of the maximum admissible linear mass of a suspended belt for given material parameters and belt width. Dynamic effects, as well as electromagnetic processes in the suspension system, are deliberately not modelled here: the analytical framework presented is intended as an initial stage that defines the limiting static level of loading. In subsequent work, it will serve as the basis for magnetic modelling tasks and for dedicated laboratory experiments aimed at verifying and refining the limiting linear mass of the suspended belt under realistic operating conditions.

The proposed methodology provides a principled means of selecting the trough geometry and suspension parameters for magnetically levitated conveyors. The combination of analytical geometry with symbolic regression yields compact formulas that deliver high accuracy across a wide range of operating conditions and are readily integrated into standard engineering design and verification procedures.

5. Conclusions

This study presents a reproducible approach to determining the maximum linear mass of a magnetically suspended conveyor belt, combining an analytic description of the cross-sectional geometry for configurations *a–d*, optimization with respect to the troughing radius R , and symbolic regression (PySR) to obtain a compact, interpretable law $R_{opt}(l, j)$. The dataset was formed from the numerical solution of the cross-sectional area maximization problem. In PySR, we used a physically meaningful set of operations and arbitrary exponents, limited the depth of expression trees, and selected models using error–complexity

penalties; candidate formulas were further filtered by a priori physical criteria (monotonicity ($\partial R_{\text{opt}}/\partial l > 0$, $\partial R_{\text{opt}}/\partial j < 0$, correct limiting behavior), with a train/validation split to control overfitting. The resulting $R_{\text{opt}}(l, j)$ exhibits the expected monotonicity (increasing with l , decreasing with j), agrees well with numerical calculations, and provides a closed-form link to the suspension spacing AB_{opt} ; the maximum cross-sectional area is achieved in configuration B because it makes the fullest use of the belt width under the geometric constraints on AB and R; in the boundary case $H = 0$, configuration c reduces to d, whereas a predictably underperforms due to the absence of troughing. Incorporating R_{opt} into the computational loop together with the area model $S_g(R)$ and belt/material parameters yields design-ready equations for the maximum linear mass and the required lifting force per unit length.

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Data Availability Statement: Additional information, in particular the training code and the database for model development, is available at <https://github.com/sgordin990-create/DETERMINING-THE-MAXIMUM-LINEAR-MASS-OF-A-CONVEYOR-BELT-BASED-ON-PYSR-SYMBOLIC-REGRESSION> (accessed on 23 September 2025).

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Abbreviation

The following abbreviation is used in this manuscript:

PySR Python Symbolic Regression (SymbolicRegression.jl)

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