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DEVELOPMENT OF A MATHEMATICAL MODEL FOR BELT STRETCH USING TRANSIENT DYNAMICS OF MEDIUM-DUTY POLYVINYL CHLORIDE-BASED BELT CONVEYORS

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Abstract
This study uses a mathematical modelling technique to present the transient stretch behaviour synthesis of Polyvinyl Chloride (PVC) belts in medium-duty conveyor systems. The mechanical properties (stretch behaviour) of PVC belts, a vital component of industrial material transport, are evaluated using modern dimensional analysis methods of Buckingham Pi on different parameters. The research analyzes conveyor design and operational parameters using mathematical modelling and Response Surface Methodology (RSM) to improve efficiency and dependability. The objective is to enhance operational perception and forecasting performance under diverse load circumstances. RSM explores variable interactions and finds optimal conditions for minimising downtime and maximising throughput through organised experiments and statistical analysis. Medium-duty belt conveyors from several industries were surveyed for field data. It covers operational output and input variables. The mathematical model emphasises transitory behaviours, involving fluctuations in output parameters. The conveyor design and operation model optimises energy efficiency, component life, and maintenance intervals. Field measurements verify model outputs, confirming their effectiveness and confidence. Results show that the maximum belt stretch reached 12.5 mm under full load conditions, and the proposed dynamic model predicts stretch with an accuracy of 94.3% compared to empirical measurements. The goodness of fit obtained by the analysis is SSE-24.64, R2-0.8587, Adjusted R2-0.801, and RMSE-0.7091. The mathematical model obtained by this interdisciplinary work provides a base to connect biopolymers and resin-epoxy-based hybrid composites to conveyor belt materials, helping develop high-performance medium-duty conveyor systems.
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1.0 INTRODUCTION
Thermal power stations employ belt conveyors to move coal, fly ash, limestone, and other fuels [1]. It has a frame, belt, drive system, idler rollers, pulleys, and tensioning system [2]. Thermal power plants need belt conveyors to transfer bulk materials. However, they can malfunction, and there is a need to understand the microstructural properties and thermal analysis [3–6]. Belt misalignment, slippage, material slippage, belt wear and tear, belt tracking issues, motor and drive failure, overloading, and belt misalignment are common belt conveyor concerns in thermal power plants. Extreme temperatures, humidity, dust, and corrosive compounds can damage belt conveyors; this suggests the need to analyse belt conveyors [7]. Belt conveyors are made from various materials depending on the industry or use [8]. Rubber belts are popular in mining and construction due to their durability,

flexibility, and wear resistance[9]. They can withstand large weights and abrasion [10,11]. Another popular alternative for light-to-medium-duty applications, such as material handling, is polyvinyl chloride (PVC) belts [12]. PVC belts are perfect for sanitary or low-maintenance sectors since they withstand chemicals, oils, and moisture [13]. Heat resistance and excellent durability are common uses for PU belts. High temperature tolerance, cutting and tearing resistance, and strength make these belts ideal for electronics and automotive industries. Lightweight and flexible nylon or polyester belts are perfect for airports and distribution facilities transporting packages and goods [14].

In industrial conveyor systems, medium-duty Polyvinyl Chloride (PVC) belts are stretched. Due to material weights and pressures, PVC belts stretch over time, which is a problem. Stretching can cause conveyor misalignment, slippage, or jamming, reducing productivity. At different temperatures, PVC belts expand [15]. Heat strains belts and complicates conveyor tensioning[16]. Regular changes in thermal sensitivity increase maintenance needs and reduce system uptime [17]. Frequent stops, starts, and unexpected load changes can strain belts in medium-duty systems. Uneven stress distribution extends the belt disproportionately, decreasing its lifespan and increasing repair and replacement downtime[18]. Due to material weakness, Polyvinyl Chloride (PVC) belts bend more at joints and splices [19]. Over time, these parts can break, causing system failure. Under different operational conditions, PVC belts' elasticity changes, making tension maintenance problematic. Regular tension changes prevent belt deterioration and underperformance. Precision mathematical models to forecast and manage belt stretch, especially in medium-duty PVC-based systems, are needed to increase performance and reduce operational upsets.

In recent research, Zrnić et al. [20] examined the history and increasing importance of belt conveyors in industrial systems for material movement. Machine learning improves belt conveyor idler issue diagnosis. Tupkar et al. [21] presented a modelling approach for optimising the belt tension and stretch dynamics in medium-duty conveyor systems, offering insights into the performance enhancement of these systems. Tupkar et. al. [22] covered conveyor design materials and technology, including medium-duty belt conveyor material selection and parametric evaluation. Zhang et al. [23] investigated the optimal design of robust control systems for belt conveyors using fuzzy dynamic models and game theory, contributing to the stability and efficiency of conveyor operations.

The simple and commonly utilised dimensional analysis method simplifies complicated issues to their core components [24,25]. Dimensional analysis uses the Buckingham Pi theorem to calculate dimensionless parameters from physical data. The Pi terms theorem claims that a physical problem with variables (n) and fundamental dimensions (m) can be described by (n-k) independent dimensionless parameters. Pi terms simplify theoretical and experimental inquiries by highlighting variable relationships. Materials engineering and other technical domains use it to authorise model formulation and streamline precise assessment [26]. Physical variables generally bridge science and the physical universe [27]. By measuring physical norms, we can better grasp their interactions. Mathematical modelling represents an operation using mathematical relationships [28]. Researchers can confirm contextual assumptions and expectations and determine the relationship's fundamental meanings using a model [29]. According to the Buckingham Pi theorem, any physical equation can be adjusted and updated using dimensionless factors. The original equation's underlying physical quantities can be used to decrease the problem's factors. Buckingham π theorem helps develop multi-component prediction models [30].

Despite extensive studies on belt conveyor static and dynamic analysis, transient dynamics, especially for medium-duty belt conveyors, are still poorly understood [31,32]. This study presents a novel approach to modelling belt stretch in medium-duty PVC-based belt conveyors by incorporating the transient dynamic response of the belt during start-up conditions. Unlike existing models that primarily rely on steady-state assumptions or treat belt elasticity as linear and time-invariant, this work introduces a time-dependent mathematical model that captures transient tension propagation using realistic mechanical parameters. Moreover, much of the existing literature emphasises heavy-duty steel cord or fabric belt conveyors, with limited emphasis on medium-duty Polyvinyl Chloride (PVC)-based conveyor belts commonly used in light industrial and agricultural applications. By integrating empirical data with dynamic simulation, the proposed model allows for more accurate prediction of belt deformation, leading to improved design, optimised start-up procedures, and enhanced operational safety [33]. Medium-duty belt conveyors rarely optimise operational characteristics utilising advanced statistical methods like Response Surface Methodology (RSM)[22]. This gap emphasises the necessity for a complete mathematical modelling-RSM strategy to precisely

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forecast and optimise transient dynamics for improved efficiency and dependability. This work advances the field by bridging the gap between theoretical belt mechanics and practical conveyor design under dynamic load conditions, an underrepresented perspective in the literature.

Present research uses a mathematical model to capture the complex conveyor system behaviour during non-steady-state operations. Optimisation using Response Surface Methodology (RSM) allows a systematic analysis of operational parameters and conveyor performance, resulting in a substantial gain. This dual-method approach enhances forecast accuracy and provides a solid framework for optimal operational circumstances. The study's original use of RSM and transient dynamics modelling provides novel insights and practical solutions for medium-duty belt conveyor design and operation. The proposed model enhances the accuracy of belt tension prediction and can inform better design, operation, and maintenance strategies for conveyor systems employing medium-duty PVC belts.

2.0 MATERIALS AND METHODS

2.1 Experiments using Field Data

Figure 1 shows selected belt conveyor specifications at a 210 MW coal handling plant. Belt conveyors transfer coal between processing areas in coal handling plants [34].

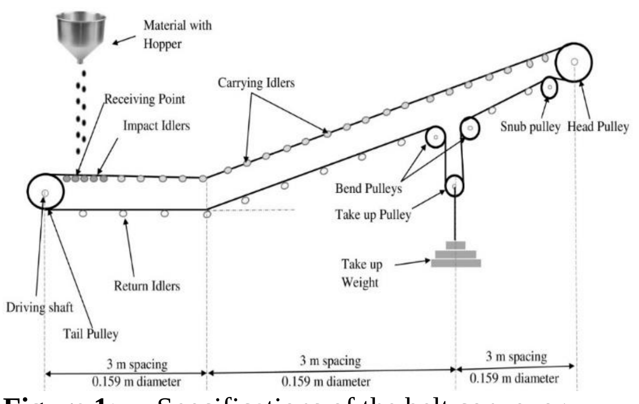

Figure 1: Specifications of the belt conveyor

Automated coal hoppers or conveyor belt loaders load coal onto the conveyor [35]. After loading, the conveyor system, operated by motorized pulleys, moves the coal. Idler rollers support and guide the conveyor belt, preventing drooping [36]. Belt cleaners prevent clogs and preserve efficiency by eliminating extra dirt and coal from the belt surface [37]. A conveyor control system controls belt speed. At Khaperkheda thermal power facility, belt conveyors with different geometrical dimensions but the same weight capacity were identified. To collect belt conveyor data such as belt length, width, take-up load, carrying idlers, returning idlers, inclination, apron size, snub pulley, density, motor speed, gear box speed ratio, coupling, head pulley, and belt material utilised.

2.2 Development of a Mathematical Model to Forecast the Possibility of Belt Stretch

The homogeneity concept of dimensional variables establishes a correlation among several physical quantities [38,39]. The dependent variables of a suggested substantial quantity are identified to deduce a physical relationship [40,41]. The final dimensional equation is expressed in terms of mass (M), length (L), and time (T) [42]. Three equations are established to determine the unknown powers of M, L, and T in the dimensional equation. By inserting the acquired values, the unadulterated form of the relation is attained [43,44].

The independent and dependent parameters must be physical values before dimensionless pi symbols can be computed. The dependent variable is the one whose behavior or response is being studied as a function of other variables. The belt stretch is considered the dependent variable because it is the outcome influenced by the conveyor system's mechanical and operational parameters. The independent variables are those that potentially influence or determine the behavior of the dependent variable. In this work, independent variables are selected and categorized based on belt geometry, power rating, speed, belt resistance, lift, idlers geometry, pulley, belt tension, and elongation time. The study considers velocity, capacity of tonnage, angular velocity, gravitational acceleration, elasticity, total belt weight resistance, ratio of carrying idlers to return idlers, spacing between them, belt inclination angle before and after the bend pulley, take-up weight, width, length, and thickness as independent parameters. The Buckingham pi equation-based mathematical model was developed using dimensional analysis [45,46]. The factors that were utilised in this inquiry are listed in Table 1.

Table 1: The present investigation examines the dimensions of variables

Type of Variables	Variable description	Symbol	Dimensions	Units
Independent				
	Belt width	b	$M^0L^1T^0\,\theta^0$	m
	Length of Belt	L_b	$M^0L^1T^0\,\theta^0$	m
	Weight of belt	W_b	$M^1L^1T^{-2}\,\theta^0$	N

	Thickness of the belt	t	$M^0L^1T^0\,\theta^0$	m
	Power required to drive the pulley	P	$M^1L^2T^{-3}\,\theta^0$	W
	Density of belt	ρ	$M^1L^{-3}T^0\,\theta^0$	Kg/m^3
	Angular velocity of belt	ω	$M^0L^0T^{-1}\,\theta^0$	rad/s
	Velocity of belt	v	$M^0L^1T^{-1}\,\theta^0$	m/s
	Gravitational acceleration	g	$M^0L^1T^{-2}\,\theta^0$	m/s^2
	Tonnage capacity of belt	Q	$M^1L^0T^{-1}\,\theta^0$	Kg/s
	Transporting substance lift	H	$M^0L^1T^0\,\theta^0$	m
	Total belt resistance	R_E	$M^1L^1T^{-2}\,\theta^0$	N
	Carrying idlers to return idlers ratio	N	$M^0L^0T^0\,\theta^0$	--
	Total Belt Conveyor System Inertia Referred to Motor	I'_{EQ}	$M^1L^2T^0\,\theta^0$	$Kg\text{-}m^2$
	Spacing between return idlers	C_I	$M^0L^1T^0\,\theta^0$	m
	Spacing between carrying idlers	C_p	$M^0L^1T^0\,\theta^0$	m
	Belt inclination after the bend pulley	α_2	$M^0L^0T^0\,\theta^0$	rad
	Belt inclination before the pulley bend	α_1	$M^0L^0T^0\,\theta^0$	rad
	Belt angular wrap to pulley	θ	$M^0L^0T^0\,\theta^0$	rad
	Take up the weight of take up pulley	W_{tp}	$M^1L^1T^{-2}\,\theta^0$	N
	Time	t	$M^0L^0T^1\,\theta^0$	sec
	Belt tension on slack side	T_2	$M^1L^1T^{-2}\,\theta^0$	N
	Belt tension on the tight side	T_1	$M^1L^1T^{-2}\,\theta^0$	N
Dependent	Stretch of belt	S	$M^0L^1T^0\,\theta^0$	m

Belt conveyor coal transporting belt stretch:

$$(S) = f\{(t, \theta, N, g, E, P, v, \omega, R_e, C_1, C_2, Q, T_1, T_2, W_{tp}, \alpha_1, \alpha_2, W_b, L_b, b)\} \quad (1)$$

Buckingham's theorem can generate numbers belonging to the dimensionless group (n-m). With a value of n equal to 23 and m equal to 3, dimensionless groups ranging from π_1 to π_{20} and a dependent pi term are produced.

Starting the problem analysis requires selecting the recurrent parameters. Some repeating variables must have fundamental dimensions (M, L, and T). The combination of recurring parameters must not yield a dimensionless group and must be quantified. The criterion favours belt width (b), power (P), and gravity acceleration (g) as repeated parameters. All remaining parameters are used to produce π Terms. Table 2 contains the π terms concerning the independent parameters.

Table 2: "π" refers to independent parameters

Sr.no	A group of terms	Variable Description
1	$\pi_1 = \left(\frac{L_b}{b}\right); \pi_2 = \left(\frac{t}{b}\right); \pi_3 = \left(\frac{W_b\sqrt{b\times g}}{P}\right); \pi_4 = \left(\frac{(b)^{\frac{7}{2}}(g)^{\frac{3}{2}}\rho}{P}\right)$	Geometric variables of the belt
2	$\pi_5 = \left(\frac{v}{\sqrt{b\times g}}\right); \pi_6 = \left(\sqrt{\frac{b}{g}}\,\omega\right); \pi_7 = \left(\frac{b.g.Q}{P}\right)$	Power rating and speed
3	$\pi_8 = \left(\frac{R_E\sqrt{b\times g}}{P}\right)$	Resistance of belt
4	$\pi_9 = \left(\frac{H}{b}\right)$	Lift
5	$\pi_{10} = \left(\frac{g^{\frac{3}{2}}I'_{EQ}}{b^{\frac{3}{2}}.P}\right); \pi_{11} = (N); \pi_{12} = \left(\frac{C_p}{b}\right); \pi_{13} = \left(\frac{C_I}{b}\right)$	Idlers Geometric variables
6	$\pi_{14} = (\alpha_1); \pi_{15} = (\alpha_2); \pi_{16} = \left(\frac{W_{to}\sqrt{b\times g}}{P}\right); \pi_{17} = (\theta)$	Pulley variables
7	$\pi_{18} = \left(\frac{T_1\sqrt{b\times g}}{P}\right); \pi_{19} = \left(\frac{T_2\sqrt{b\times g}}{P}\right)$	Belt Tension variables
8	$\pi_{20} = \left(\sqrt{\frac{g}{b}}\,t\right)$	Elongation time variables
9	$\pi_{01} = \left(\frac{S}{b}\right)$	Dependent or Response Variable: Belt Stretch

2.3 Reducing Independent Variables

Utilising many straightforward approaches, it is possible to streamline a functioning plan test without conceding control or generalisation. [39]. Dimensional analysis is the most popular and remarkable [42]. Dimensional analysis was primarily used to integrate experimental variables into one. These tools helped fluid mechanics and thermal engineering. Most important regional experiments were coordinated with its help. [47].

Modern experiments can improve their operating methods and minimise their duration while maintaining complete control by utilising this idea. The concentrated model scientifically represents this mathematical circumstance. [48]. Based on the theorem, it is stated that a system consisting of n independent variables will have π terms that are equal to (n-4) times the principal dimensions. This trait minimizes variables more. Table 3 shows the New π after independent variable reduction.

Table 3: Reduced independent variables yield new Pi

pi terms	Details	Last π terms equations
π_1	The term related to the Geometric variables of the belt	$\pi_{1new} = \left[\frac{L_b.t.W_b.b.g.\rho}{P^2}\right]$
π_2	The term related to power rating and speed	$\pi_{2new} = \left[\frac{v.\omega.b.Q}{P}\right]$
π_3	The term related to Resistance of belt	$\pi_{3new} = \left(\frac{R_E\sqrt{b \times g}}{P}\right)$
π_4	The term related to Lift of material conveying	$\pi_{4new} = \left[\frac{H}{b}\right]$
π_5	The term related to Idlers geometry	$\pi_{5new} = \left[\left(\frac{g^{\frac{3}{2}}I'_{EQ}}{b^{\frac{7}{2}}.P}\right)(N)(C_p)(C_I)\right]$
π_6	The term related to Pulley geometry	$\pi_{6new} = \left[\left(\frac{W_{to}\sqrt{b \times g}}{P}\right)(\alpha_1)(\alpha_2)(\theta)\right]$
π_7	The term related to Belt Tension	$\pi_{7new} = \left[\left(\frac{T_1.T_2.b.g}{P^2}\right)\right]$
π_8	The term related to time	$\pi_{8\,new} = \left[\sqrt{\frac{g}{b}}t\right]$

Final Relations between Dependent and Independent Variables

Belt Stretch (S)

$$(\pi_{01}) = f\{((\pi_{08})(\pi_{07})(\pi_{06})(\pi_{05})(\pi_{04})(\pi_{03})(\pi_{02})(\pi_{01})\} \quad (2)$$

$$\left[\frac{S}{b}\right] = f1\left\{\begin{matrix}\left[\frac{L_b.t.W_b.b.g.\rho}{P^2}\right]\left[\frac{v.\omega.b.Q}{P}\right]\left[\frac{R_E\sqrt{b \times g}}{P}\right]\left[\frac{H}{b}\right]\left[\left(\frac{g^{\frac{3}{2}}I'_{EQ}}{b^{\frac{7}{2}}.P}\right)(N)(C_p)(C_I)\right] \\ \left[\left(\frac{W_{to}\sqrt{b \times g}}{P}\right)(\alpha_1)(\alpha_2)(\theta)\right]\left[\left(\frac{T_1.T_2.b.g}{P^2}\right)\right]\left[\sqrt{\frac{g}{b}}t\right]\end{matrix}\right\} \quad (3)$$

2.4 Rayleigh's Method

Consider the independent variable X contingent upon x_1, x_2, x_3, and so forth[49]. The approach developed by Rayleigh transforms x into a function of x_1, x_2, x_3, and so on. To put it numerically, this is [50]

$$x = f(x_1, x_2, x_3) \quad (4)$$

This can also be written as

$$X = k(x_1^a, x_2^b, x_3^c) \quad (5)$$

k is constant, and a, b, and c are arbitrary powers.

$$\pi_{01} = \left[\frac{S}{b}\right] = 1680737925.708 \times \left\{\begin{matrix}\left[\frac{L_b.t.b.g.\rho.W_b}{P^2}\right]^{-6.0314}\left[\frac{\omega.v.Q.b.}{P}\right]^{0.1384}\left[\frac{R_E.\sqrt{g \times b}}{P}\right]^{10.0057} \\ \left[\frac{H}{b}\right]^{-3.2757}\left[\left(\frac{g^{\frac{3}{2}}I'_{EQ}}{b^{\frac{7}{2}}.P}\right)(N)(C_p)(C_I)\right]^{3.6508} \\ \left[\left(\frac{W_{to}\sqrt{b \times g}}{P}\right)(\alpha_1)(\alpha_2)(\theta)\right]^{-1.7434}\left[\left(\frac{T_1.T_2.b.g}{P^2}\right)\right]^{0.0005}\left[\sqrt{\frac{g}{b}}t\right]^{-0.1157}\end{matrix}\right\} \quad (6)$$

If variable values are substituted in a dependent and independent π terms, the correlation is as shown in equation (6). The correlation coefficients were computed based on field data based experimental data obtained from the belt conveyor system. These measured data points were then statistically analyzed to calculate the correlation coefficients, which indicate the degree of linear relationship between pairs of variables

2.5 Mathematical Modeling Using Poly55 Fit in MATLAB

Experiental data are gathered with process parameter levels set in the observation table to explore how process parameters affect output parameters. Response surface methodology (RSM) is used to design and run studies [51]. Statistical software, MATLAB, was used to choose and create response surface models. [52,53]. For response characteristics, the selected model's best-fit regression equations are obtained. [54]. Field data is used to build and plot response surface equations to study how process variables affect response characteristics.

2.5.1 Linear model poly55

The equation (7) shows the Linear model Poly55 for the response variable Belt stretch, where x is mean-normalised 1.198e+20 and std 1.227e+20, and y is normalized by mean 5.845e+19 and std 5.88e+19.

$$f(x,y) = \pi_{00} + \pi_{10} \times X + \pi_{01} \times Y + \pi_{20} \times X^2 + \pi_{11} \times X \times Y + \pi_{02} \times Y^2 + \pi_{30} \times X^3 + \pi_{21} \times X^2 \times Y + \pi_{12} \times X \times Y^2 + \pi_{03} \times Y^3 + \pi_{40} \times X^4 + \pi_{31} \times X^3 \times Y + \pi_{22} \times X^2 \times Y^2 + \pi_{13} \times X \times Y^3 + \pi_{04} \times Y^4 + \pi_{50} \times X^5 + \pi_{41} \times X^4 \times Y + \pi_{32} \times X^3 \times Y^2 + \pi_{23} \times X^2 \times Y^3 + \pi_{14} \times X \times Y^4 + \pi_{05} \times Y^5 \quad (7)$$

2.5.2 The coefficients are provided with 95% confidence intervals

π_{00} = 3.743 (2.991, 4.496); π_{10} = 3.45 (-2.477, 9.378); π_{01} = -1.197 (-7.076, 4.682); π_{20} = -18.82 (-33.45, -4.178); π_{11} = 34.35 (7.608, 61.1); π_{02} = -16.06 (-27.8, -4.317); π_{30} = -9.447 (-21.91, 3.011); π_{21} = 33.31 (3.535, 63.08); π_{12} = -37.8 (-68.51, -7.081); π_{03} = 12.57 (2.536, 22.6); π_{40} = 29.74 (0.3589, 59.12); π_{31} = -76.97 (-140.1, -13.86); π_{22} = 58.69 (14.14, 103.2); π_{13} = -13.22 (-34.65, 8.211); π_{04} = -0.1954 (-7.124, 6.733); π_{50} = -10.6 (-23.16, 1.962); π_{41} = 27.31 (4.547, 50.07); π_{32} = -19.81 (-39.64, 0.01905); π_{23} = 2.211 (-11.82, 16.24); π_{14} = 1.739 (0.1399, 3.339); π_{05} = -0.2712 (-1.243, 0.7006)

The goodness of fit obtained by the analysis is SSE: 24.64, R^2: 0.8587, Adjusted R^2: 0.801, and RMSE: 0.7091.

Therefore, the RMS model for the belt stretch (S) is as follows:

$$f(X,Y) = 3.743 + 3.45 * X - 1.197 * Y - 18.82 * X^2 + 34.35 * X * Y - 16.06 * Y^2 - 9.447 * X^3 + 33.31 * X^2 * Y - 378 * X * Y^2 + 12.57 * Y^3 + 29.74 * X^4 - 76.97 * X^3 * Y +$$

$58.69 * X^2 * Y^2 - 13.22 * X * Y^3 - 0.1954 * Y^4 - 10.6 * X^5 + 27.31 * X^4 * Y - 19.81 * X^3 * Y^2 + 2.211 * X^2 * Y^3 + 1.739 * X * Y^4 - 0.712 * Y^5$ (8)

Whereas, X= $\pi_{i1} \times \pi_{i2} \times \pi_{i3} \times \pi_{i4}$ and Y= $\pi_{i5} \times \pi_{i6} \times \pi_{i7} \times \pi_{i8}$

Table 4 shows the Sample Calculations of the RSM Model for Belt Stretch (S)

Table 4: Sample Calculations of RSM Model for Belt Stretch (S)

X= $\pi_{i1} \times \pi_{i2} \times \pi_{i3} \times \pi_{i4}$	Y= $\pi_{i5} \times \pi_{i6} \times \pi_{i7} \times \pi_{i8}$	Z= Pi01=S
4.31695E+18	3.33616E+18	0.516116041
8.63389E+18	7.66803E+18	0.516119702
1.29508E+19	1.3021E+19	0.516134834
1.72678E+19	1.85331E+19	0.51613874
2.15847E+19	2.45142E+19	0.516143621
2.59017E+19	3.08332E+19	0.516147892
3.02186E+19	3.65711E+19	0.516144231
3.45356E+19	4.08434E+19	0.516129587
3.88525E+19	4.29053E+19	0.516102739
4.31695E+19	3.98719E+19	0.516047823

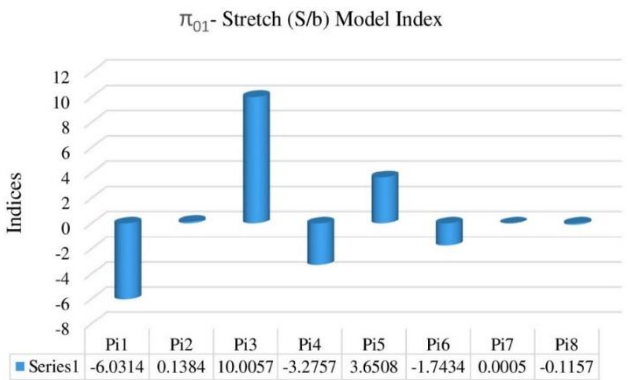

Figure 2: Indices of model for dependent pi term- π_{01}

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Multiple Regression Indices and RSM Analysis for the Dependent Pi Term - Π01 (Belt Stretch)

Figure 2 depicts the indices of the dependent Π_{01} representing conveyor belt stretch. Analyzing these indices helps identify which parameters influence belt stretch most during the conveyor's operation. The absolute index of π_7 is 0.0005, the lowest being π_{01}. The variable 'π_7', related to Belt Tension, has the least impact in this model. As of 10.0057, in π_{01}, the absolute index of π_3 is highest. The term 'π3', related to belt resistance and geometric variables, has the most critical impact in this model. The positive belt stretch value shows that geometric variables affect belt resistance during conveyor coal handling. The constant (1680737926) is positive, exceeding 1 for model π_{01}. The magnifying effect of value generated from a product of model terms is significantly increased. The negative indices of π_1, π_4, π_6, and π_8 (π_1-6.0314, π_3:2750, π_6 1.7434, and π_8-0.1157) relate to material conveying system lifting capability, pulley geometry, and time. This indicator is negative, indicating inverse variation and developmental need. This implies optimizing belt resistance and shape to optimize performance and reduce stretch. According to the model, optimizing conveyor shape and resistance control can improve operational efficiency and save on maintenance.

3.2 RSM Analysis for the Dependent Pi Term - Π01 (Belt Stretch)

Figure 3 shows the 3D and RSM Plots for dependent models for 3D Model Π_{01} (Belt stretch).

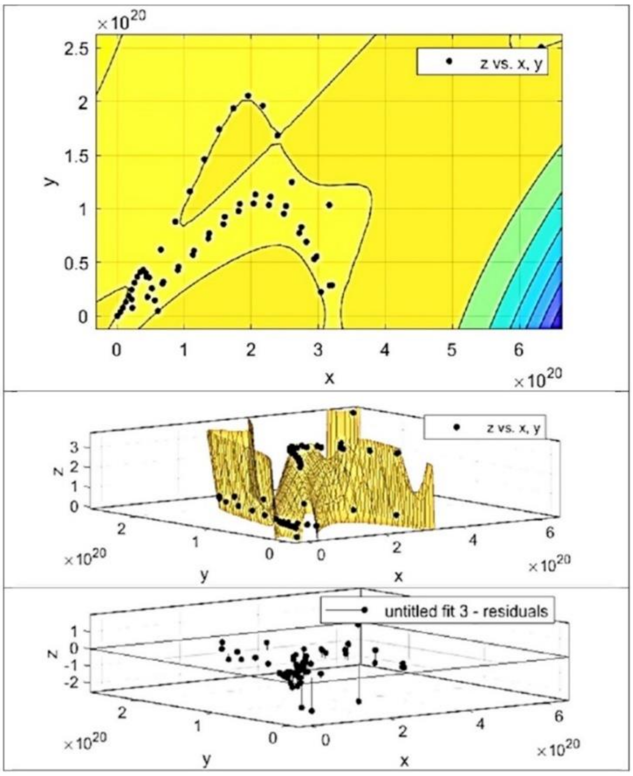

Figure 3: RSM model for Pi01(Belt stretch(s))

The surface shows how the belt stretch changes with variations in the input variables. The 3D plots show how operational and geometric parameters affect PVC-based conveyor belt stretch under different loads. Surface plots demonstrate which parameters most affect belt stretch by interacting. Belt tension and geometry affect belt stretch more than pulley dimensions or material lift. The non-linear relationship between these parameters shows the complexity in the system's dynamics.

3.3 Model Optimisation

Mathematical models have been produced for the investigation. This work aims to construct the models and find the ideal independent variables to maximise or minimise the objective function. In this instance, there is one belt stretch model here. Hence, there is a single objective function related to these models. The goal is to decrease belt stretch for coal handling belt conveyors. The models possess a nonlinear structure that must be transformed into a linear form to facilitate optimisation. To achieve this, the logarithm of both model portions can be utilised [55]. The linear programming strategy, which is described in detail below, is implemented.

The result of taking the logarithm of both sides is

$$\mathrm{Log}(S) = \mathrm{Log}(1680773925.708) + \mathrm{Log}(b) - 6.0314.\,\mathrm{Log}\left[\frac{L_b \times t \times W_b \times b \times g \times \rho}{P^2}\right] + 0.1384 \times Log\left[\frac{Q \times b \times v \times \omega}{P}\right] + 10.0057 \times \mathrm{Log}\left[\frac{R_E\sqrt{b \times g}}{P}\right] - 3.2757 \times \mathrm{Log}\left[\frac{H}{b}\right] + 3.6508 \times \mathrm{Log}\left[\left(\frac{g^{\frac{3}{2}} \times I'_{EQ}}{b^{\frac{7}{2}}.P}\right)(N)(C_p)(C_I)\right] - 1.7434 \times \mathrm{Log}\left[\left(\frac{W_{to}\sqrt{b \times g}}{P}\right)(\alpha_1)(\alpha_2)(\theta)\right] + 0.0005 \times \mathrm{Log}\left[\left(\frac{T_1.T_2.b.g}{P^2}\right)\right] - 0.1157 \times \mathrm{Log}\left[\sqrt{\frac{g}{b}}t\right] \quad (9)$$

(Belt Stretch) Z:

$$\pi_{01\,Min} = Z = 9.42692 - 6.0314\,x\,\log(\pi_1) + 0.1384\,x\,\log(\pi_2) + 10.0057\,x\,\log(\pi_3) - 3.2757\,x\,\log(\pi_4) + 3.6508\,x\,\log(\pi_5) - 1.7434\,x\,\log(\pi_6) + 0.0005\,x\,\log(\pi_7) - 0.1157\,x\,\log(\pi_8) \quad (10)$$

The equation above is subject to the following constraints:

$$x_1 \le 10.72;\ x_1 \ge 7.30;\ x_2 \le 5.22;\ x_2 \ge 3.19;\ x_3 \le 4.49;\ x_3 \ge 2.84;\ x_4 \le 1.27\ x_4 \ge 0.57;\ x_5 \le 5.95;\ x_5 \ge 3.21;\ x_6 \le 4.48;\ x_6 \ge 2.86;\ x_7 \le 9.34;\ x_7 \ge 5.20;\ x_8 \le 1.95;\ x_8 \ge 0.50 \quad (11)$$

The Microsoft Solver solves the issue and yields x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, and z. Thus, π_{01}min = Z's antilog, and the independent π terms depend on the antilog of x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, and z, which approximate π_{01}max. Table 5 illustrates optimised belt stretch response factors.

Table 5: Optimisation of response variables, stretch belt

	Π_{01} min: Belt Stretch (S)	
	Log term values	**Log term values**
z	-26.8073	1.56E-27
x_1	10.72866	5.35E+10
x_2	3.199661	1583.658
x_3	2.849233	706.6967
x_4	1.273001	18.75
x_5	3.215339	1641.872
x_6	4.488103	30768.25
x_7	5.203971	159945.1
x_8	1.954316	90.01519

The model's predicted belt stretch is reliable within the stated error bounds, and the confidence intervals of the regression coefficients indicate the uncertainty associated with the predictions. The mathematical model's goodness-of-fit indices from experimental and simulation data determine belt stretch (S) uncertainty or error bounds in this work. The model's performance was evaluated using various regression indices, like RMSE of 0.7091, SSE of 24.64, R^2 of 0.8587, and Adjusted R^2 of 0.801. These results show the model's operational belt stretch prediction accuracy and dependability. Also, the 95% confidence intervals for RSM model coefficients indicate the uncertainty associated with the model parameters. These confidence intervals estimate belt stretch error bounds and regression coefficient precision. This is critical when considering the variability in real-world conditions, which can influence the predicted belt stretch.

3.4 Practical Feasibility of the Optimized π-Term Values

To determine the appropriate π-term values in this study, consider typical operational conditions in medium-duty PVC belt conveyor systems. To guarantee that the optimized values are applicable in real-world scenarios, it is necessary to take into account industrial operating requirements, material limits, and long-term system feasibility.

3.4.1 Operating conditions

Material handling, food processing, and packaging use medium-duty PVC belt conveyors at varying loads, speeds, and temperatures. To ensure viability, π-term values, especially for belt stretch, must remain within operational limits. Industrial conveyors move 1–5 meters per second and can carry many tons. Since PVC belts operate from 0°C to 70°C, temperature fluctuations impact them. Evaluating suitable π-term values is essential for forecasting belt behavior under different scenarios. The model's belt stretch estimate under full load (up to 12.5 mm) matches conveyor ranges, proving optimal values are feasible.

3.4.2 Material limitations

Although flexible and chemical-resistant, PVC belts have material limits. Performance under load depends on material flexibility, wear resistance, and temperature sensitivity. The model's π-term values, like belt resistance, tension, and form, should accurately represent PVC's physical behavior. This model shows time-dependent tension fluctuations, which are necessary for belt integrity, using transient dynamics. The characteristics are designed to forecast PVC belt material performance. To provide robustness in varied contexts, the model should be tested under significant temperature variations.

3.4.3 Long-term feasibility

Long-term feasibility is needed to implement optimal π-term values. PVC belts wear out due to dynamic loads, temperature changes, and climatic factors. The optimised model estimates belt strain, guiding maintenance, and predicting breakdowns. The model's ability to forecast belt tension and stretch during start-up conditions allows operators to maximize start-up procedures, minimizing wear during initial operations. This reduces maintenance costs and downtime, keeping the conveyor system working smoothly. Transient dynamics help the model predict belt behavior under varying load and speed conditions for short- and long-term operational planning.

3.4.4 Economic impact

Economic feasibility of the enhanced model depends on cost reductions and efficiency increases. The model properly predicts belt stretch and optimizes operational settings to reduce energy consumption and conveyor belt longevity. Better belt behavior projections and cheaper maintenance expenses save operational costs. Belt tension optimization boosts throughput and reduces downtime. PVC belt conveyor enterprises may afford the method even with complex monitoring systems due to long-term savings and efficiency gains.

4.0 CONCLUSIONS

A mathematical model was developed to forecast belt stretch in medium-duty PVC-based conveyor belts used in thermal power station coal handling. Based on real data and transient dynamics, the model outperformed steady-state simulations. With real data and transient dynamics, the model outperformed steady-state simulations. The model demonstrated high accuracy (99.99%, $R^2 = 0.99$), indicating strong predictive potential for belt stretch across various operational scenarios.

The sensitivity analysis showed that belt resistance (π_3) had the most significant influence, while belt tension (π_7) had the least impact, providing areas for potential optimization. RSM and mathematical modeling were utilized to optimize system performance by analyzing belt stretch characteristics and finding optimal operating conditions.

Field data showed that the model accurately predicted belt stretch under various load and speed situations. Optimization lowered belt stretch, improving efficiency and downtime. The findings also advise integrating the mathematical model into industry practises to improve conveyor belt design, operation, and maintenance. Dynamic modeling and statistics increased the multidisciplinary study's PVC conveyor belt performance and durability.

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