A New Numerical Method for Fast Prediction of Wheel Tread Wear for Stacker Cranes

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Abstract: With the development of the logistics industry, the demand for efficient, high-capacity material handling equipment, such as stacker cranes, has grown significantly. As a critical load-bearing component of stacker cranes, the wheel-rail contact system is subtracted to higher operational speeds and load capacities, which lead to increased contact stresses and wheel tread wear. The degraded wheel profile caused by wear can deteriorate wheel-rail interactions, exacerbate vibrations, and subsequently reduce the lifespan of stacker cranes. This paper proposes a numerical model based on co-simulation to predict wheel tread wear of stacker cranes. The model combines a multibody dynamics model of the stacker crane, a wheel-rail contact model, and a worn profile update model. Additionally, a wear superposition method, i.e., a simplified and practical method, is developed to calculate the accumulated wear, enabling the prediction of the wheel wear under different work cycles with limited simulation iterations. The results show the accumulated wheel tread wear depth across various work cycles of stacker cranes, providing quantitative predictions while significantly reducing simulation time.

1 INTRODUCTION

Stacker cranes are essential components of modern intralogistics systems, which enable automated storage and retrieval operations for a wide range of goods in automated pallet and small-parts warehouses. As rail-mounted, single-track material handling equipment, their performance heavily relies on the reliability of the wheel-rail system. Over the past decade, the rapid growth of e-commerce and globalisation has more than doubled the turnover of the logistics industry (Achouch et al., 2022). To meet this demand, warehousing operations have significantly enhanced material handling efficiency. However, this progress has pushed automated warehouse systems, particularly stacker cranes, to operate at their dynamic limits. The resulting increase in dynamic loads places substantial contact stresses on the wheel-rail system, accelerating wear and increasing the risk of damage (Laile & Fottner, 2021).

Wear is a primary damage type affecting the wheel-rail system, characterised by material loss due to adhesive and abrasive phenomena (Tunna et al., 2007). This material loss degrades the wheel and rail profiles, changing the position and size of the contact area. These changes influence the distribution of normal and tangential forces within the contact area, negatively impacting the system's dynamic response. Additionally, wear can lead to wheel out-of-roundness, causing shock loads and vibrations during operation. These effects may further damage other system components (Iwnicki et al., 2023).

Preventive maintenance is commonly conducted to mitigate the effects of wear, including grinding to restore the profiles of wheel and rail. Alternatively, some stacker crane operators choose to replace worn wheels entirely. Both approaches are scheduled based on fixed working hours or cycles (Große et al., 2018). Typically, preventive maintenance strategies rely on empirical data or manufacturer recommendations. However, this does not guarantee the prevention of premature wear failures or ensure that maintenance is performed only when necessary.

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This paper proposes a numerical solution for predicting the wheel wear behaviour of stacker cranes using a co-simulation approach that integrates a Simpack multibody model with a MATLAB-based wear prediction model. The method accounts for wheel profile changes due to wear, incorporating updated wheel profiles into subsequent simulation iterations. Additionally, a wear scaling strategy based on a normal distribution is developed, which enables the simulation of numerous real-world work cycles within fewer simulation runs. This approach significantly reduces simulation time while ensuring reliability.

2 RELATED RESEARCH

Wear is a gradual and slow process that occurs over significant wheel-rail relative displacements and under substantial load conditions. To accelerate simulation processes, it is commonly assumed that the wheel and rail profiles remain unchanged within a single simulation iteration. A multiplier is then applied to amplify material wear and update the profiles. This approach has been widely used in wear studies in the field of railways. Zhang et al. (Zhang et al., 2013) developed a simulation tool using Simpack's built-in wear model, where they applied a distance factor as a multiplier to scale wear results to a total distance of 10,000 km. However, Bosso et al. (Bosso & Zampieri, 2019) noted that using a high multiplier could lead to unrealistic wear concentrations in the initially calculated wear areas, resulting in overestimation. To address this, they proposed an interpolation smoothing method based on surface curvature to improve accuracy even with a high multiplier. Braghin et al. (Braghin et al., 2006) assumed that wear depth was uniformly distributed along the circumferential direction. They applied a moving average approach to smooth wear depth and updated the worn profile using cubic spline interpolation. Their study recommended updates for wear depth increments of 0.1 mm. Yang et al. (Yang et al., 2023) investigated wheel tread wear using a vehicle-track dynamics model based on a non-Hertzian contact algorithm. Their results showed that wear progressively expands in depth and width with increasing iterations, with wear propagation occurring faster in earlier iterations than in later ones.

The reviewed literature highlights various numerical methods for calculating wear in wheel-rail systems. However, most of these methods face the following challenges:

- Accurately determining wear depth distribution and updating the wheel-rail profile;
- Developing a practical approach to amplify wear accumulation

Furthermore, existing research primarily focuses on railway applications, with limited attention given to wheel-rail systems in logistics equipment such as stacker cranes. Compared to rail vehicles, stacker cranes exhibit bidirectional, intermittent movement patterns and operate under distinct load conditions. Additionally, stacker cranes use rimless wheels, which differ in dimensions from those used in railway applications (Yu & Fottner, 2024). These distinctive characteristics highlight the need for a comprehensive study of the wear behaviour of stacker crane wheel-rail systems. Given the lack of detailed experimental data on the wheel-rail wear behavior of stacker cranes, numerical methods provide a suitable approach for investigation.

3 NUMERICAL MODEL

The wheel wear prediction model for stacker cranes proposed in this paper consists of the following sub-models: a multibody dynamics model, a movement control model, a wheel-rail contact model, a wear calculation model and a worn profile update model. The overall framework is illustrated in Figure 1, where arrows indicate the flow of output results between submodel. Detailed descriptions of each submodel are provided in the following sections.

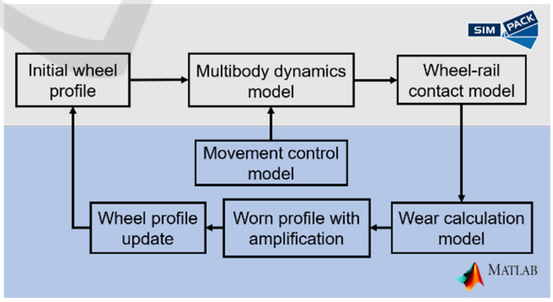

Figure 1: Overall framework of proposed wear prediction model based on co-simulation.

3.1 Multibody Dynamics Model of Stacker Crane

The multibody dynamics model of a single-mast stacker crane was developed using the multibody simulation software Simpack (Yu & Fottner, 2024).

Figure 2 illustrates the model structure along with a typical application scenario of stacker cranes.

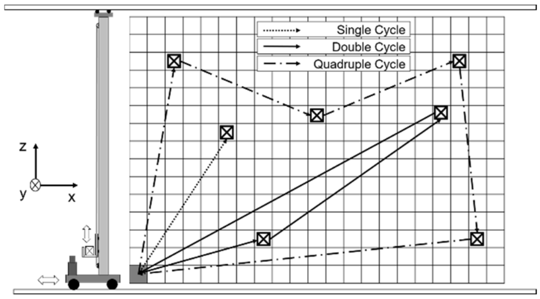

Figure 2: Schematic representation of stacker crane and its working scenario.

The model comprises a mast, a traverse, a lift carriage, two running wheels, and a rail. The wheel-rail system is modelled using Simpack's built-in Rail module. The initial wheel profile is rimless, while the rail uses the standard UIC60 profile, commonly used in railway applications. Key parameters for modelling the stacker crane system, such as mast height, average load capacity, operating velocity, and wheel diameter and width, are detailed in the study (Yu & Fottner, 2024).

3.2 Movement Control Model

Since Simpack cannot model the complex movements of a stacker crane, this paper integrates an external movement control program developed by Rücker et al. (Rücker et al., 2020) in MATLAB/Simulink. The program determines the rack positions required for movement within a single work cycle based on the selected stacker crane operation mode. It then computes the corresponding acceleration, velocity, and displacement signals for each time step. These signals are then transmitted to the joint points of the multibody model via co-simulation, thereby enabling precise control of the stacker crane's movements. Figure 2 shows three typical operation modes of stacker cranes: single cycle, double cycle, and quadruple cycle. In practice, stacker cranes operate using a combination of these modes to improve efficiency (Siciliano et al.). However, for simplification, this study excludes such combinations from the simulation.

3.3 Wheel-Rail Contact Model

The wheel-rail contact model is a critical component of the wear prediction framework, as it defines the contact area and normal force distribution within the contact patch, significantly influencing wear results. This paper uses Simpack's Rail module for wheel-rail contact calculations (Vollebregt et al., 2011). The outputs from the contact model are transferred to the discrete outer surface of the wheel in MATLAB, where they are used for subsequent wear calculation and profile updates.

3.3.1 Wheel-Rail Contact Calculation in Simpack

Since the wheel and rail have quasi-identical material properties, the wheel-rail contact can be treated as an uncoupled normal and tangential contact problem that is solved sequentially (Sichani, 2013). The normal contact problem is addressed using Hertzian theory, while the tangential contact problem is solved using the FASTSIM algorithm based on Kalker's simplified theory. Results from the wheel-rail contact calculations in Simpack—such as the lateral contact point position and normal contact force—are used to determine the position and size of the elliptical contact area and the normal contact pressure within that area.

3.3.2 Discretization of the Outer Surface of Wheel

To further investigate wheel-rail contact and wear behaviour, the outer surface of the wheel tread should be discretized. This discretization divides the global contact problem into discrete cells on the wheel surface, enabling the local computation of worn material within each cell of the contact area.

The wheels on stacker cranes are generally rimless and can be approximated as cylindrical. When the wheel is unfolded along its axis, the outer surface can be represented as rectangular, where the length of the rectangle corresponds to the wheel's circumference and the width represents the wheel tread width. This rectangular surface is discretized into a grid of 1×1 mm square cell, as shown in Figure 3. For illustrative purposes, the figure does not represent the actual 1×1 mm cell size to scale.

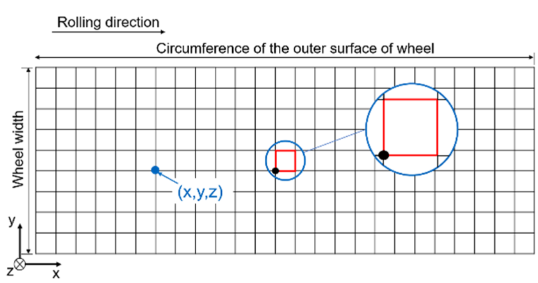

Figure 3: Discretization of wheel outer surface.

The three-dimensional coordinate information of each grid node, as shown in Figure 3, is stored in a MATLAB cell array. The x and y coordinates define the node's position on the wheel's outer surface, while the z coordinate represents the wear depth at that node. Each cell is referenced by its lower-left node, which serves as the reference point for subsequent contact area searches. As illustrated in Figure 3, the representative node for the cell highlighted in red is indicated by the black node at its lower-left corner.

3.3.3 Search for Contact Area on Discrete Wheel Surface

In this step, the wheel-rail contact area determined by Simpack is mapped onto the corresponding discrete wheel surface in MATLAB. Figure 4 shows the wheel-rail contact area at each time step during the stacker crane's movement. The blue elliptical region represents the contact area calculated by Simpack, while the grey cells depict the corresponding discrete representation of the contact area on the wheel's outer surface.

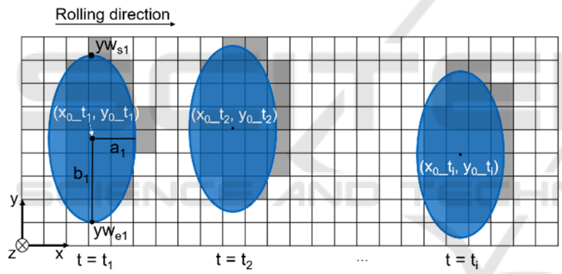

Figure 4: Search for contact area at each time step t_i.

As shown in Figure 4, the position and size of the elliptical contact area are determined by the wheel's lateral contact positions $y_{\mathrm{w,s}}$ and $y_{\mathrm{w,e}}$ at the contact point, as well as the semi-axis lengths a and b of the elliptical contact area.

To discretize the elliptical contact area (blue region in Figure 4) onto the grid, it is necessary to identify which grid cells (grey region in Figure 4) lie within the contact area. This paper uses the positional relationship between a point and an ellipse, as defined in Equation (1), where (x_0, y_0) represents the centre of the elliptical contact area, (x, y) the lower-left node of a cell. Specifically, the formula determines whether the lower-left node of a cell lies inside or on the boundary of the ellipse. If it does, the corresponding cell is considered part of the contact area.

$$\frac{(x-x_0)^2}{a^2}+\frac{(y-y_0)^2}{b^2} \leq 1 \tag{1}$$

3.4 Wear Calculation Model

This paper applies the Archard wear model to calculate the volumetric worn material on the wheel. The wear depth is then determined using the wear distribution model developed in this study.

3.4.1 Archard Wear Model

In the Archard wear model, the volume of worn material is directly proportional to the normal contact force and the sliding distance, while inversely proportional to the hardness of the softer material in the wheel-rail pair. This relationship is expressed by Equation (2),

$$V_{\mathrm{wear}} = k \cdot \frac{F_{\mathrm{N}} \cdot s}{H} \tag{2}$$

where V_{wear} is the worn volume, k the wear coefficient, F_{N} the normal contact force, H the hardness of the softer material in the wheel-rail material pair in MPa, and s the sliding distance. The wear coefficient k is a dimensionless factor that depends on normal contact pressure and sliding velocity, as shown in Figure 5 (Jendel, 2002). The values of k were experimentally determined under dry and clean wheel-rail contact conditions. For simplification, this paper uses the mean values of the wear coefficients for different regions, i.e. $k_{\mathrm{I}} = k_{\mathrm{III}} = 5\times10^{-4}$, $k_{\mathrm{II}} = 35\times10^{-4}$, and $k_{\mathrm{IV}} = 350\times10^{-4}$.

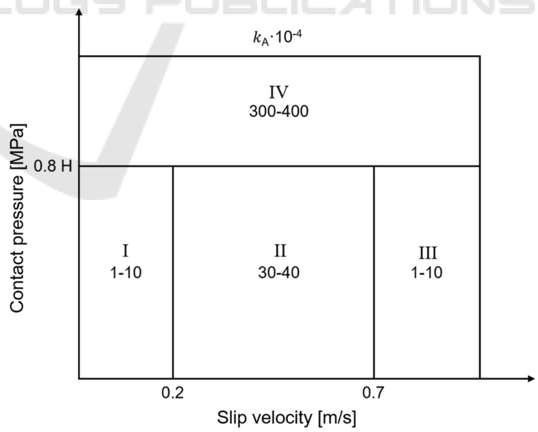

Figure 5: Archard wear chart (Jendel, 2002).

3.4.2 Wear Depth Distribution

According to Hertzian theory, normal contact pressure follows a parabolic distribution across the contact area. The maximum pressure $P_{\max}$ occurs at the centre of the contact area, as expressed in

Equation (3) (Mostofi & Gohar, 1980), and gradually decreases toward the edges of the contact area.

$$P_{\max} = \frac{3}{2} \cdot \frac{F_{\mathrm{N}}}{A} \tag{3}$$

According on the Archard wear model, wear volume is proportional to the normal contact force. As a result, wear depth across the contact area is also expected to follow a parabolic distribution (Heinrich & Klüppel, 2008). Building on this assumption, we developed a parabolic wear depth distribution model based on the Euclidean distance between discrete nodes and the centre of the contact area. The Euclidean distance is calculated using Equation (4):

$$d = \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{4}$$

where x and y are the coordinates of any node within the discretized contact area, x_0 and y_0 the coordinates of the contact area centre, d the Euclidean distance between these two points. When $d = 0$, meaning the node is located at the centre of the contact area, the wear depth reaches its maximum value. Conversely, when d reaches its maximum value $d_{\max}$, indicating the node is at the edge of the contact area, the wear depth becomes zero.

If the contact area is divided into cells of size $\Delta x \times \Delta y$, the wear depth Δz can be expressed by Equation (5), where Δs represents the sliding distance between two time-steps, and $P(\Delta x, \Delta y)$ the contact pressure within a cell.

$$\Delta \mathrm{z} = k \cdot \frac{P(\Delta x, \Delta y) \cdot \Delta s}{H} \tag{5}$$

By combining Equation (2), (3) and (5), the wear depth distribution z in the contact area is given by Equation (6):

$$z = \frac{3}{2} \cdot \left(1 - \frac{d}{d_{\max}}\right)^{1/2} \cdot \frac{V_{\mathrm{wear}}}{A} \tag{6}$$

3.5 Worn Profile Amplification and Update

Wear is a slow and gradual process that develops over long-term wheel-rail contact. The operational lifespan of a stacker crane's wheel can reach up to 10^8 rotations. However, simulating the complete wear process over its entire lifecycle is impractical due to the enormous computational resources and time required. To address this, the wear results must be magnified to effectively represent long-term wear behaviour. The calculated wear depth is subtracted from the initial wheel profile to model the changes in the wheel profile due to wear. The updated wheel profile is then used in subsequent simulation iterations.

Chapter 2 reviews relevant research on magnification of wear results. A common approach is to linearly scale the wear results of a single simulation iteration using a user-defined multiplier factor. For example, if 10 simulated cycles correspond to 1,000 actual working cycles, a multiplier factor of 100 is applied. While higher multiplier factors can significantly reduce simulation time, they may also lead to unrealistically concentrated wear distribution within the contact area. Additionally, they can generate excessively steep or discontinuous updated wheel profiles, leading to instability in subsequent numerical iterations.

When the stacker crane moves along a linear rail, wheel lateral displacements vary due to movement-induced excitation. These displacements shift the contact position, subsequently altering the wear position. According to the wear distribution model, wear is concentrated at the centre of the wheel-rail contact area, with intensity decreasing toward the edges of the contact area. Based on this principle, subsequent wear is assumed to accumulate in both lateral and longitudinal directions along the initial wear profile. Each accumulation includes a lateral displacement y_{disp} at each node within the contact area, while the wear depth at the original position is simultaneously added onto the displacement position. The lateral displacement y_{disp} follows a normal distribution, as expressed in Equation (7):

$$y_{\mathrm{disp}} \sim N(\mu, \sigma) \tag{7}$$

where $\mu = 0$, indicating that subsequent wear accumulates at the centre of the initial wear area. The value of σ determines the spread of the wear distribution across the wheel surface, where a higher σ results in a more evenly distributed wear pattern across the wheel tread. N is the wear amplification factor, representing the number of iterations in the accumulated wear process described above. After wear depth amplification, the wheel profile is updated and used as the initial profile for the subsequent dynamics simulation iterations.

4 MODEL VERIFICATION AND RESULTS DISCUSSION

This section performs a verification of the proposed model by comparing it with Simpack's built-in wear calculation model. While Simpack includes a built-in wear calculation model, it does not account for the progressive expansion of the worn area over extended simulation iterations, resulting in an overestimation of wear accumulation (Bosso & Zampieri, 2019). However, since experimental validation with real measurements is planned for future work, the current results should be regarded as a verification rather than a comprehensive validation.

To evaluate the developed wear calculation model, the unaccumulated result is compared with the Simpack's calculation result, which serves as the baseline. The simulation parameters provided by (Yu & Fottner, 2024) are used for comparison. The simulated stacker crane has a height of 30 meters and an average load capacity of 2,000 kg. The wheels, made of 42CrMo4 steel material with a Poisson's ratio of 0.3, have a diameter of 500 mm. The wheel-rail friction coefficient is 0.2. The simulation was conducted for 100 work cycles using the double-cycle operation mode.

Figure 6 shows wheel wear depth at different lateral positions for two simulation results. The red dashed line represents the result obtained using Simpack's built-in Archard wear model, while the blue solid line corresponds to the MATLAB-based wear calculation model developed in this paper. As shown in the figure, the maximum wear depth calculated by the proposed wear model is slightly higher than that calculated with the Simpack model. Additionally, the wear distribution predicted by the proposed method shows a minor shift away from the centre of the contact area compared to the Simpack result.

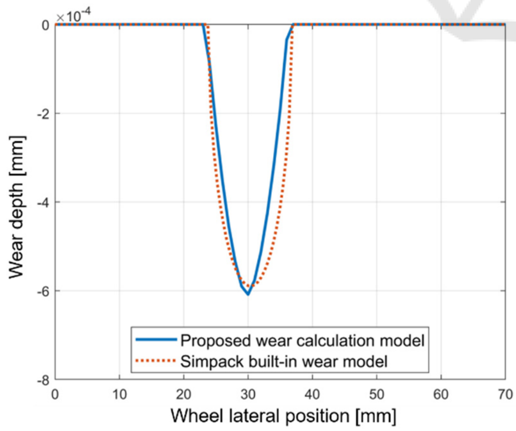

Figure 6: Comparison between the proposed wear model and Simpack built-in wear model.

Table 1 compares the maximum wear depth and its corresponding lateral position. The results indicate that the wear calculation model developed in this paper is highly consistent with Simpack's built-in model results. This consistency emphasises the reliability of the proposed MATLAB-based wear calculation model, establishing it as a robust foundation for subsequent wear amplification and wheel profile updates.

Table 1: Comparison of two wear calculation models for the maximum wear depth and the lateral position it occurs.

	Proposed wear model	Simpack's built-in wear model
Maximum wear depth/ 10^{-4} mm	6.08	5.89
Wheel lateral position/ mm	30.00	30.55

To verify the developed wear amplification method, an amplification factor of $N = 100$ is selected. Similarly, a distance factor of 100 is applied in the Simpack wear model to enable a direct comparison with the wear amplification approach proposed in this study. The results, shown in Figure 7, compare the two methods. The red dashed line represents the Simpack result, while the blue solid line corresponds to the result from the wear amplification developed in this paper. The results indicate that the amplified wear depth calculated in Simpack is significantly higher than that obtained using the proposed method. Additionally, the wear area predicted by Simpack is narrower.

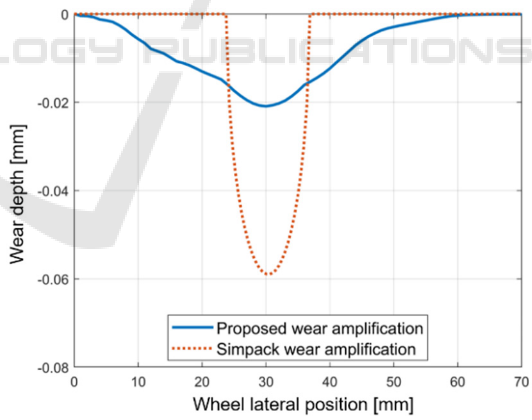

Figure 7: Comparison of wear amplification results with a factor of 100 for one simulation iteration.

The significant differences arise from the fundamentally different methods of wear superposition. In Simpack, the distance factor directly amplifies the results of a single simulation run, keeping the wear zone consistent with the initial wear profile. Consequently, subsequent wear is proportionally amplified along the same profile. In contrast, the amplification method proposed in this paper accounts for the lateral expansion of the wear profile as wear accumulates over time. This approach considers the dynamic redistribution of wear, providing a more refined representation of the wear process over multiple iterations.

At this stage, the impact of the worn profile update on simulation results is analysed. To simulate the long-term work cycles of a stacker crane within a finite number of simulation runs, a wear amplification factor of N = 100 is applied, with the profile updated every hundred simulated work cycles. Each profile update represents one simulation iteration, equivalent to 10,000 actual work cycles of stacker cranes. In this simulation, fifteen wear iterations are performed to analyse the wear behaviour under profile updates, with the results presented in Figure 8.

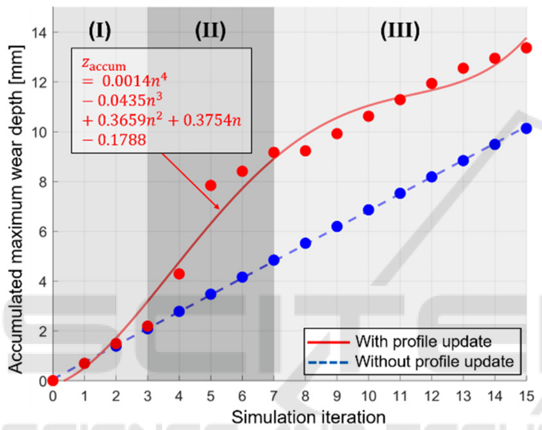

Figure 8: Comparison of results with/without worn profile update regarding multiple simulation iterations.

The blue dashed line shows that wear behaviour without profile updates follows a quasi-linear trend throughout the iteration process. In contrast, when profile updates are considered, the wheel wear process demonstrates three distinct wear regimes as work cycles increase, as shown by the red solid curve. These regimes can be categorized as early stable wear (I), mid-rapid wear (II), and late stable wear (III).

The red curve in Figure 8 represents a fourth-degree polynomial fit to the red discrete points. The fitting result is expressed by the equation next to the red line in Figure 8, where z_{accum} is the accumulated maximum wear depth on the wheel tread in mm, n the number of simulation iterations, each corresponding to 10,000 actual work cycles of stacker cranes.

To quantitatively analyse wheel wear behaviour, the wear rate is determined at different work cycle stages. It represents the average maximum wear depth per 10,000 actual work cycles at each stage. The summarized results are shown in Table 2.

Table 2: Wheel wear rate under different work cycles.

Number of actual work cycles	Predicted wear rate/ (mm/10^4 work cycles)
0 – 30,000	0.73
30,000 – 70,000	2.8
> 70,000	0.56

During the initial operation stage (work cycles less than 30,000), wear has just begun and has minimal impact on the wheel profile. In the middle operation stage (work cycles between 30,000 and 70,000), wear may alter the wheel profile, leading to a mismatch between the wear and rail profiles. This mismatch reduces the contact area, accelerating wheel wear. In the later operation stage (work cycles more than 70,000), the wheel-rail profiles form a better match, reducing the wheel wear rate.

5 CONCLUSION AND OUTLOOK

This paper presents a numerical investigation into the wheel wear prediction for stacker cranes. A co-simulation framework is developed by integrating the Simpack multibody model with a MATLAB-based wear calculation model. Additionally, a wear amplification approach is introduced to simulate the lifecycle of a stacker crane's wheel within a feasible number of simulation iterations. Instead of applying a simple linear multiplier to the wear results, the proposed approach accounts for the wear amplification along the traverse contact position, providing a more refined estimation of long-term wear progression. The developed wear calculation model is compared with Simpack's built-in wear model. Results indicate that the proposed approach produces a similar wear depth distribution to Simpack's model, while significant differences are observed when applying a wear amplification factor of 100. This discrepancy occurs because the wear accumulation method proposed in this paper considers the lateral expansion of the contact area due to wear.

This paper also investigates the influence of worn profile changes on wheel wear behaviour across different operation stages. It is found that the wheel wore slowly first, then wore rapidly and finally slowed again. The proposed calculation method enables a quantitative prediction of stacker crane wheel wear at various work cycle stages, providing specific research significance and practical value for the maintenance planning of stacker cranes.

Future research will focus on experimental validation of the proposed method to further ensure its reliability and accuracy. Real-world wheel wear data from stacker cranes will be used to assess the consistency between simulated and observed wear behaviour. These experiments are excepted to provide valuable insights for validating the proposed wear amplification method, thereby enhancing its practical applicability in industrial fields.

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