Stochastic Degradation Modeling of a Peristaltic Pump in a Biomedical Blood Autotransfusion System

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Abstract: *This study compares two stochastic models, Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device. Failure was defined as the reduction of flow rate below a critical threshold required for safe operation. Simulations showed that the Wiener Process consistently produced higher time-to-failure (TTF) values across all scenarios, with larger differences under low and moderate variability (σ = 0.05 and σ = 0.3) and smaller differences under high variability (σ = 0.8). The observed effect results from the deterministic component in Brownian Motion with Drift, which accelerates average degradation, while the Wiener Process is driven solely by random fluctuations, allowing greater variability in failure time. Findings indicate that, in biomedical applications, selecting an appropriate degradation model is crucial for accurate lifetime predictions and predictive maintenance planning, particularly in low-variability environments. Future work should integrate stochastic degradation models with statistical monitoring techniques to improve early fault detection accuracy and enhance lifetime estimation robustness under real operating conditions.*
Keywords: stochastic models; degradation; peristaltic pump; predictive maintenance; Wiener Process; Brownian Motion with Drift.

1.Introduction

Autotransfusion devices play a crucial role in the global healthcare setting, primarily due to their ability to reduce patient blood loss and to concentrate red blood cells for reinfusion, thereby minimizing the need for allogeneic blood transfusions (Conceição, 2004) [1]. The effective operation of these devices requires the integration of multiple components, such as a centrifuge for blood separation and a peristaltic pump for transferring fluid in different directions, as in the case of the AutoLog system, according to the device's user manual. It is noteworthy that the primary requirements for autotransfusion devices are to prevent contamination of the patient's blood and to ensure precise control of the flow rate of the fluids involved (Mello, 2024) [2].

Given these requirements, the peristaltic pump is well-regarded for meeting them, as it exhibits characteristics that ensure high reliability, such as the absence of direct contact between the pump mechanism and the system fluid, high flow rate accuracy, and ease of maintenance. These features demonstrate its effectiveness in the development of biomedical equipment (Santos et al., 2008) [3].

Peristaltic pumps, also classified as infusion pumps, are essential for the operation of autotransfusion devices. In this regard, it is important to highlight the relevance of maintaining these devices, as their failure may lead to severe patient complications such as venous spasms, pulmonary edema, and thrombophlebitis (Silva et al., 2025) [4]. In this context, predictive maintenance is characterized by the continuous monitoring of critical operational parameters of the equipment (Zhao et al., 2023) [5], providing essential data for decision-making aimed at preventing complete operational failure, thereby ensuring device reliability (Kardec et al., 2009) [6]. For this reason, condition-based maintenance is considered the most effective approach for peristaltic pumps (Zamzam, 2023) [7].

In parallel with maintenance strategies, degradation models serve as a valuable tool for enabling more efficient asset management, contributing to both resource optimization and safety (Park et al., 2006) [8], given their capability to represent how a system deteriorates or evolves over time, allowing the prediction of failures and degradation (Cai et al., 2023) [9]. This, in turn, can help reduce uncertainties in decision-making and future projections (Moratta, 2016) [10], as well as improve system reliability and durability (Zhang et al., 2024) [11].

When addressing degradation models, the Brownian motion with drift (Kadloor et al., 2012) [12] and the Wiener process (Zhang, 2018) [13] can be identified. Brownian motion is characterized as a stochastic model that simulates the degradation of a system or variable over time, incorporating a directional trend (Arias et al., 2023) [14], whereas the Wiener process is a stochastic model that describes system degradation in a purely random manner over time (Oliveira, 2023) [15]. Both models can be applied to the analysis of fluid flow in a peristaltic pump.

This study aims to develop, simulate, and compare the two presented stochastic models, with the purpose of predicting the time to failure (TTF) of the peristaltic pump in autotransfusion devices, as well as contributing to the understanding of the application of degradation models in the context of biomedical equipment.

2. Materials and Methods

The peristaltic pump is a mechanical device used in a wide variety of biomedical equipment, including autotransfusion systems, due to its ability to move fluids in a controlled manner while minimizing direct contact with moving parts, thus ensuring the integrity of the biological fluid. This study focuses on analyzing the gradual wear of the pump’s mechanical components, which can lead to reduced operational performance and eventual failure. To model the pump’s degradation process, two stochastic methods were compared: Brownian Motion with Drift, which incorporates a deterministic trend associated with the average wear rate, and the pure Wiener Process, which considers only the random component of the phenomenon, without a defined trend. This comparison aims to identify which approach more realistically represents the degradation evolution of the peristaltic pump.

The degradation model based on Brownian Motion with Drift describes the wear evolution as the sum of a deterministic component and a random term. In this way, the drift represents the average degradation rate over time, while the stochastic term models the inherent random fluctuations of the process, such as variations in friction or minor operational irregularities. The equation representing the wear X(t) is commonly expressed as follows (Whitmore, 1997) [16]:

$$dX(t) = \mu\, dt + \sigma\, dW(t), \qquad (1)$$

Where μ is the drift coefficient, representing the average wear rate, σ is the intensity of the stochastic variability, and W(t) is the standard Wiener process. The development of this equation allows modeling the accumulated wear over time (Whitmore, 1997) [16]:

$$X(t) = X(0) + \mu(t) + \sigma W(t). \qquad (2)$$

This model is widely used to represent the physical degradation of mechanical components, as it accounts for both the average failure trend and the random variations that can accelerate or delay the process.

The pure Wiener process describes degradation as an evolution of a purely random characteristic, devoid of any systematic trend. In this model, the wear is represented by the following equation (Whitmore, 1997) [16]:

$$X(t) = X(0) + \sigma W(t). \qquad (3)$$

Besides stochastic models, to model the degradation of the peristaltic pump more realistically, it is necessary to consider the deterministic effects associated with pressure loss and random noise. Zhai et al. (2024) [17] represents the pressure loss by a quadratic function of time, which expresses the continuously increasing wear related to prolonged operation, as shown below:

$$P(t) = \alpha t^2. \qquad (4)$$

For the simulation of the peristaltic pump, parameters were adopted based on real data obtained through interviews with a perfusionist and the client who requested the project, ensuring greater practical adherence to the operating conditions of the peristaltic pump.

The pump flow rate under normal operating conditions is 600 ml/min, and this value was fixed in the developed model, while the equipment failure threshold was set at 480 ml/min, equivalent to 80% of the initial flow rate, which marks the point at which the equipment's performance is considered compromised. The time step was defined as 1 minute, a time resolution suitable for tracking the degradation evolution over the maximum simulated duration of 500 hours (30,000 minutes).

The intensity of the stochastic noise was simulated at three distinct levels, with values of 0.05, 0.3, and 0.8. This variation aimed to represent different operational magnitudes and mechanical imperfections inherent to the process. Table 1 presents the parameters used in the simulation.

Table 1. Simulation Parameters for Peristaltic Pump Degradation Modeling

Parameter	**Value(s)**
Initial Flow (q_0)	600 ml/min
Failure Threshold (L)	480 ml/min (80% of q_0)
Time step (dt)	1 minute
Maximum time	500 hours
Noise intensity (σ)	0.05; 0.3; 0.8

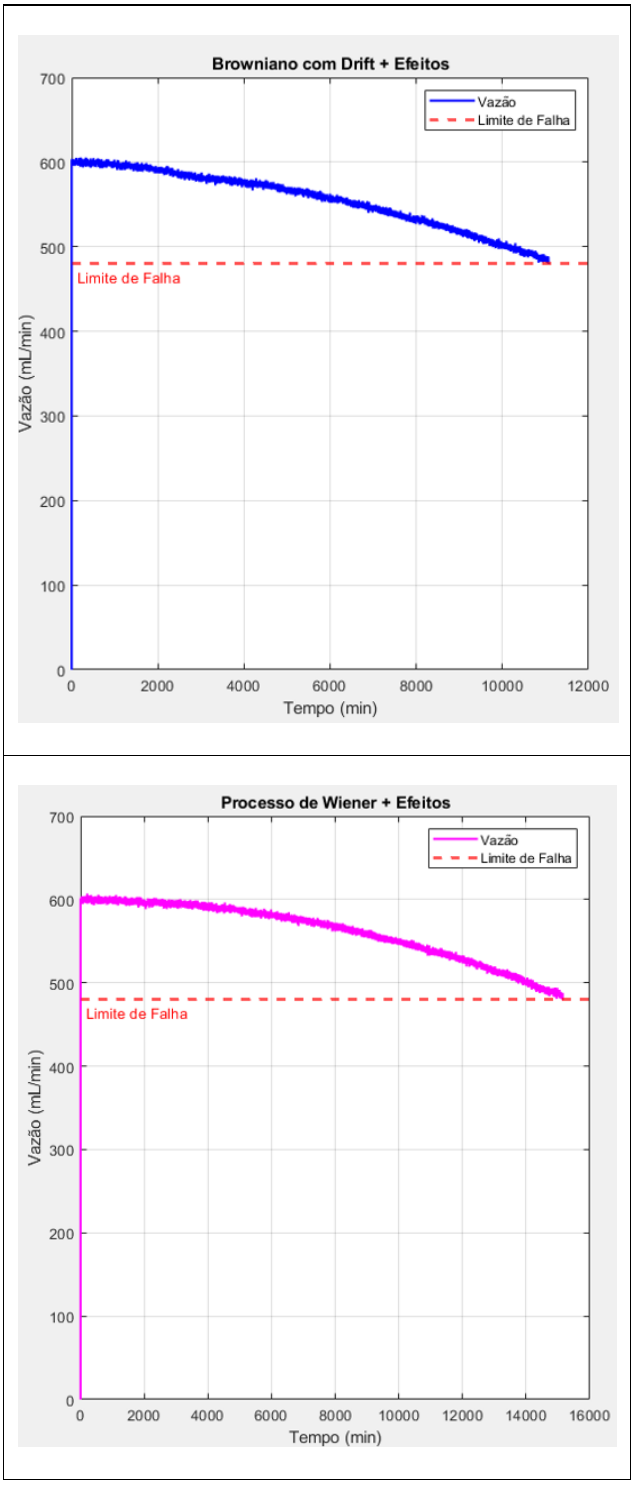
The computational simulation was implemented in MATLAB to model the degradation of the peristaltic pump using two distinct stochastic models: Brownian Motion with Drift and the pure Wiener Process. For each model, multiple individual degradation trajectories over time were generated, incorporating the effects of stochastic noise and deterministic components. The simulation progressed iteratively until the pump flow reached the established failure threshold or the maximum operating time was reached. During the process, the time to failure (TTF) was recorded for each simulation, allowing for a quantitative analysis of the useful life and comparison of the performance of the two models under different variability conditions.

3. Results

This section presents the results of the simulations aimed at evaluating the time to failure (TTF) of a peristaltic pump used in autologous blood transfusion equipment, considering different levels of uncertainty in the degradation process. Two stochastic models were analyzed: Brownian Motion with Drift and the pure Wiener Process. The models were applied to three distinct scenarios of stochastic variability (σ = 0.05; 0.3; and 0.8). The use of these models is relevant for medical applications in which the continuous and safe operation of the pump is highly critical for the integrity of the transfusion procedure and the patient, enabling the anticipation of interventions and reducing the risk of unexpected failures.

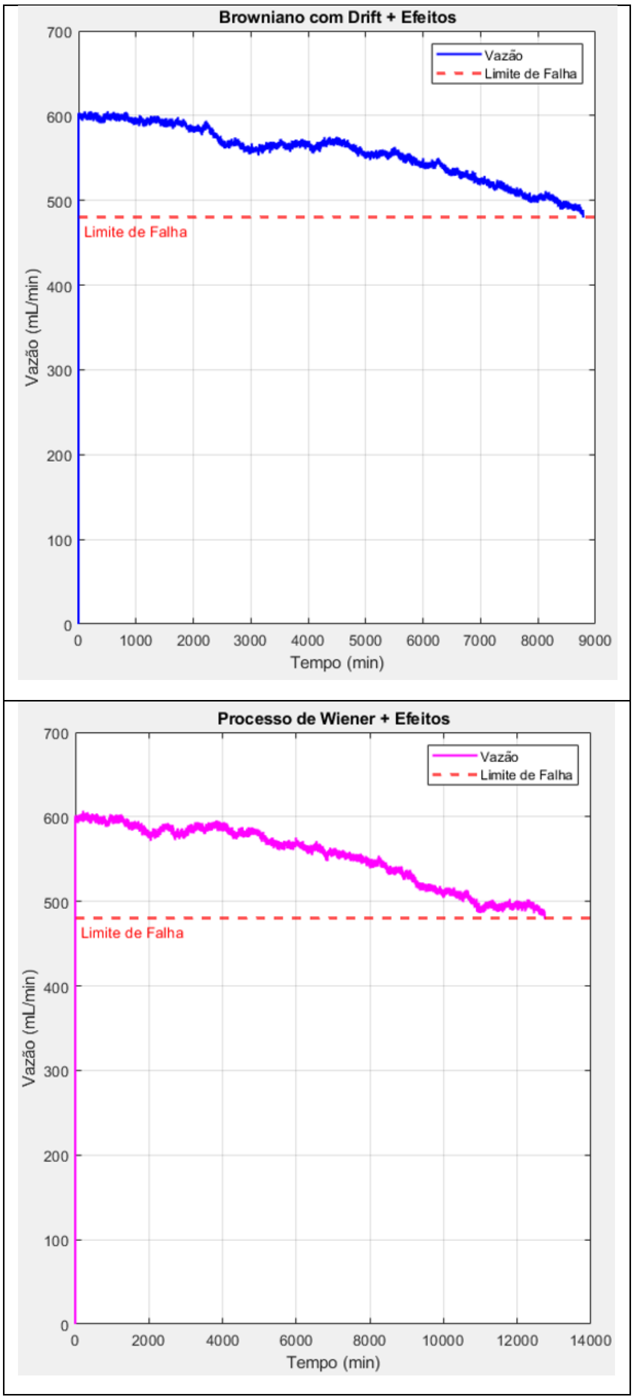
In the scenario with σ = 0.05, characterized by a low level of variability, the estimated TTF was 11,070.00 minutes (184.50 h) for the Brownian Motion with Drift model and 15,174.00 minutes (252.45 h) for the pure Wiener Process. At this level of uncertainty, it is observed that the pure Wiener model presented a time to failure greater than that obtained with the Brownian Motion with Drift. Figure 1 presents the simulation results for σ = 0.05.

Figure 1. Comparison between the two stochastic models for σ = 0,05.



In the scenario with σ = 0.3, which represents a moderate process variability, the TTF was 8,786.00 minutes (146.43 h) for the Brownian Motion with Drift model and 12,744.00 minutes (212.40 h) for the Wiener process. As in the previous scenario, the Wiener process showed higher values compared to the Brownian Motion with Drift. The figure presents the simulation results for σ = 0.3.

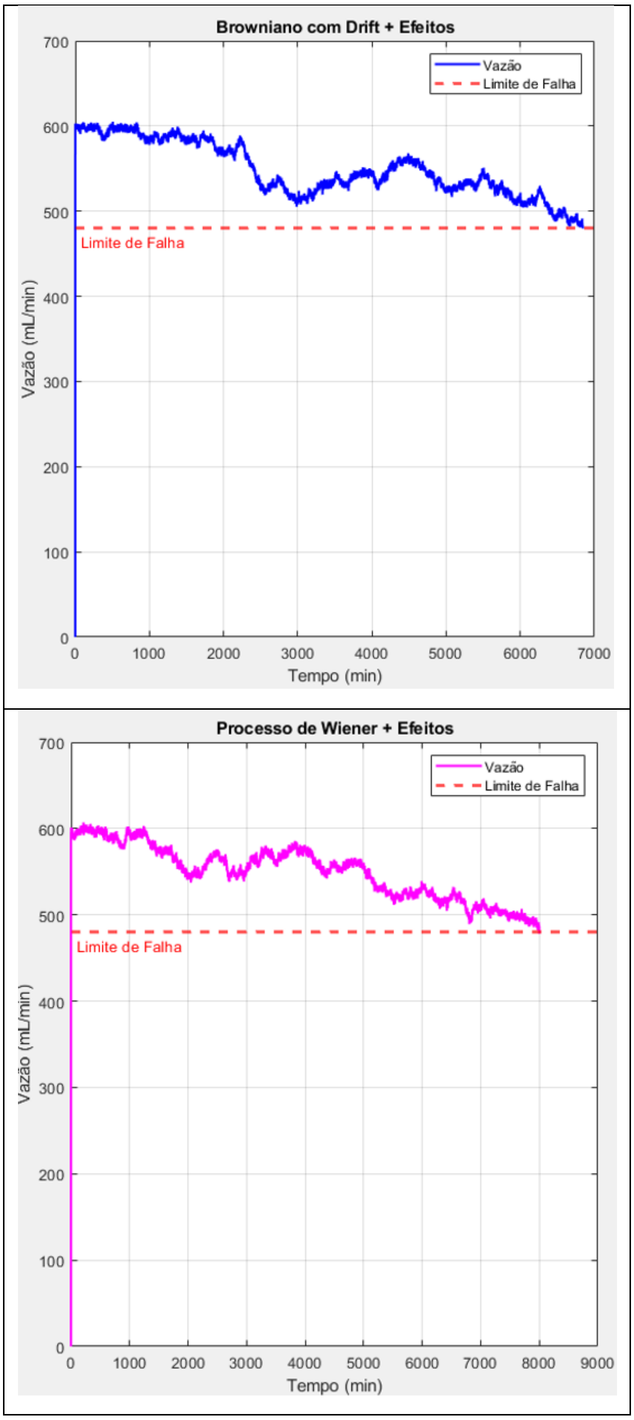
Figure 2. Comparison between the two stochastic models for σ = 0,3.



In the scenario represented by high variability, modeled with σ = 0.8, the estimated TTF was

6,842.00 minutes (114.03 h) for the Brownian Motion with Drift model and 8,002.00 minutes (133.37 h) for the Wiener process. In this case, there was a reduction in the TTF difference between the two models. Figure 3 presents the simulation for the σ = 0.8 scenario.

Figure 3. Comparison between the two stochastic models for σ = 0,8.



4. Discussion

The comparative analysis between the stochastic models of Brownian Motion with Drift and the pure Wiener Process reveals a consistent pattern: in all simulated scenarios, the Wiener Process exhibited higher time-to-failure (TTF) values compared to the Brownian Motion with Drift model. This difference is more pronounced in low and moderate variability scenarios (σ = 0.05 and σ = 0.3) and decreases as process variability increases (σ = 0.8).

The study was conducted considering the degradation of a peristaltic pump used in a biomedical device, where failure is defined as the reduction of flow rate below a critical threshold required for the safe and effective operation of the system. In this context, understanding the influence of the chosen stochastic model is crucial for accurately estimating the component's lifetime and for planning predictive maintenance actions.

The observed behavior can be explained by the intrinsic characteristics of each model. In Brownian Motion with Drift, the deterministic term (drift) tends to guide the degradation trajectory more consistently toward the failure threshold, accelerating the average wear process. In contrast, in the pure Wiener Process, evolution is governed solely by the stochastic term, allowing more significant oscillations around the mean value, which in some cases delays reaching the failure threshold.

In the high variability scenario (σ = 0.8), the TTF difference between the models is considerably reduced. This occurs because increasing the σ parameter amplifies the random effect in both models, making the drift's influence relatively less dominant and bringing the simulated trajectories closer together. In this regime, the impact of random fluctuations prevails over the deterministic component, resulting in more irregular and less predictable degradation trajectories.

From a practical perspective, these results indicate that for peristaltic pumps in biomedical applications, the choice of stochastic model can significantly affect lifetime predictions, particularly in processes with low or moderate variability. Under high variability conditions, the influence of the chosen model decreases, although it may still be relevant depending on the reliability requirements of the system.

5. Conclusion

The comparative study between Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device, demonstrated that the choice of stochastic model directly affects the estimation of time-to-failure (TTF). In all scenarios analyzed, the Wiener Process yielded higher TTF values, with the difference being more pronounced under low and moderate variability conditions and less significant in high variability scenarios.

The findings suggest that, for biomedical applications where reliability and operational safety are critical, selecting an appropriate degradation model is essential for accurate lifetime predictions and effective predictive maintenance planning. Furthermore, the influence of the chosen model is more relevant in processes with lower variability, whereas in highly variable environments, the random component tends to dominate, reducing the differences between the approaches.

As a recommendation for future work, it is suggested to explore hybrid systems, combining stochastic degradation models with statistical monitoring techniques, such as control charts, to enhance early fault detection accuracy and improve lifetime estimation robustness in real operating conditions.

References

[1] CONCEIÇÃO, Mário José da. Transfusão sanguínea em crianças e os métodos para evitá-la: uma reavaliação. Revista Brasileira de Anestesiologia, v. 54, n. 2, p. 276–282, mar./abr. 2004. Disponível em: https://www.scielo.br/j/rba/a/YXYJ9fR84HSQ5SsnTZFFBgc/. Acesso em: 1 jul. 2025.

[2] MELLO, Marco Antonio Araújo de. Avaliação da recuperação de sangue intra e pós-operatória em pacientes submetidos à cirurgia cardíaca com circulação extracorpórea. 2024. Dissertação (Mestrado em Saúde e Desenvolvimento na Região Centro-Oeste) – Faculdade de Medicina, Universidade Federal de Mato Grosso do Sul, Campo Grande, 2024.Hirsh, H., Coen, M.H., Mozer, M.C., Hasha, R. and Flanagan, J.L, "Room service, AI-style," IEEE intelligent systems, 14 (2). 8-19. Jul.2002.

[3] SANTOS, Angeline Rodrigues dos; NEILSON, Marc Lucas Hallak. Bomba peristáltica de duto flexível: reprojeto e melhorias. 2008. Trabalho de Conclusão de Curso (Graduação em Engenharia Mecatrônica) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2008.

[4] SILVA, Mayados S. et al. Reliability analysis of hospital infusion pumps: a case study. BioMedical Engineering OnLine, v. 24, n. 55, 2025. Disponível em: https://link.springer.com/article/10.1186/s12938-025-01389-2. Acesso em: 1 jul. 2025.

[5] ZHAO, Yixin et al. Condition-based maintenance for a multi-component system subject to heterogeneous failure dependences. Reliability Engineering and System Safety, v. 239, 2023. Disponível em:

https://www.sciencedirect.com/science/article/pii/S0951832023003976. Acesso em: 1 jul. 2025.

[6] KARDEC, A.; NASCIF, J. Manutenção: Função Estratégica. 3. Ed. Rio de Janeiro: Editora Qualitymark, 2009.

[7] ZAMZAM, Aizat Hilmi; HASIKIN, Khairunnisa; WAHAB, Ahmad Khairi Abdul. Integrated failure analysis using machine learning predictive system for smart management of medical equipment maintenance. Engineering Applications of Artificial Intelligence, v. 125, 2023. Disponível em:https://www.sciencedirect.com/science/article/pii/S0952197623008990. Acesso em: 1 jul. 2025.

[8] PARK, Chanseok; PADGETT, William J. Stochastic degradation models with several accelerating variables. IEEE Transactions on Reliability, v. 55, n. 2, p. 379–390, jun. 2006. DOI: 10.1109/TR.2006.874937.

[9] CAI, Yue; TEUNTER, Ruud H.; DE JONGE, Bram. A data-driven approach for condition-based maintenance optimization. European Journal of Operational Research, v. 311, p. 730–738, 2023. DOI: 10.1016/j.ejor.2023.05.002.

[10] MAROTTA, Raphael Damasceno. Modelagem da degradação da superestrutura ferroviária e otimização na alocação de recursos para manutenção. 2016. Trabalho de Conclusão de Curso (Graduação em Engenharia de Produção) – Universidade Federal de Juiz de Fora, Juiz de Fora, 2016.

[11] ZHANG, Xiaohong et al. Multiple-failure mode division and condition-based maintenance decision making for systems with multi-indicator performance degradation. Computers & Industrial Engineering, v. 191, p. 110118, 2024. Disponível em: https://www.sciencedirect.com/science/article/pii/S0360835224002390. Acesso em: 1 jul. 2025.

[12] KADLOOR, Sachin; ADVE, Raviraj S.; ECKFORD, Andrew W. Molecular communication using Brownian motion with drift. IEEE Transactions on Nanobioscience, v. 11, n. 2, p. 89–99, 2012.

[13] ZHANG, Zhengxin et al. Degradation data analysis and remaining useful life estimation: A review on Wiener-process-based methods. European Journal of Operational Research, v. 271, n. 3, p. 775–796, 2018.

[14] ARIAS, Enrique; MORETT, Guilherme. Confecção de um modelo mecânico análogo para o estudo do movimento browniano e da difusão molecular. Revista Brasileira de Ensino de Física, São Paulo, v. 45, e20230008, 2023.

[15] OLIVEIRA, Solange Conceição de. Modelagem baseada em equações diferenciais estocásticas não-lineares para dinâmica de preços. 2023. Tese (Doutorado em Modelagem Matemática e Computacional) – Centro Federal de Educação Tecnológica de Minas Gerais, Belo Horizonte, 2023.

[16] WHITMORE, George Alex; SCHENKELBERG, Fred. Modelling accelerated degradation data using Wiener diffusion with a time scale transformation. Lifetime data analysis, v. 3, n. 1, p. 27-45, 1997.

[17] ZHAI, Qingqing; LI, Yaqiu; CHEN, Piao. Modeling product degradation with heterogeneity: A general random-effects Wiener process approach. IISE Transactions, p. 1-14, 2024.