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An Open-Access Machine Learning Framework for Sustainable Tennis Ball Management: Optimizing Use and Reducing Environmental Impact for Tennis Stores and Clubs

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Article

Machine Learning for Tennis Ball Lifespan Optimization

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Abstract: Most of the management in retail and sports facilities about tennis balls is sub-jective and leads to early disposal, further contributing to environmental waste. This paper discusses a machine learning-based framework to optimize tennis ball usage by providing an accurate forecast of their lifetime, using data-driven insights. We develop and test several predictive models using Random Forest, Support Vector Machines, and Neural Networks based on holistic datasets that include data on bounce dynamics, material composition, usage frequency, and environmental conditions. The framework also allows real-time monitoring and decision-making for the replacement of the tennis balls, in addition to identifi-cation of the key factors that influence performance degradation. Our results show that this could significantly extend the life of tennis balls, which again can help reduce the overall waste and support sports industry sustainability efforts. The proposed open-access framework is scaling up a solution for tennis clubs/stores in order to improve operational efficiency with a low environmental impact while contributing to the circular economy at the same time.

Keywords: tennis ball lifespan; machine learning; degradation; sustain-ability; predictive modeling; bounce dynamics; recycling; optimization

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1. Introduction

Tennis balls are fundamental to the game, yet their management and replacement remain inefficient, relying largely on subjective assessments and arbitrary timelines. This practice leads to the premature disposal of usable tennis balls, contributing to significant environmental waste. With the increasing global emphasis on sustainability, sports facilities and retailers face growing pressure to adopt more responsible practices. Despite existing recycling initiatives, such as AceCycle, which repurpose used tennis balls, a critical gap remains: the absence of objective, data-driven approaches to determine the optimal lifespan of tennis balls.

Machine learning (ML) has emerged as a powerful tool for optimization across various industries, including sports equipment management. By leveraging large datasets, ML can uncover patterns and provide actionable insights that traditional methods fail to offer. This paper proposes the development of an open-access machine learning framework to accurately predict tennis ball degradation, enabling retailers and tennis clubs to optimize tennis ball usage. The framework utilizes key data inputs—such as bounce dynamics, material com-position, usage frequency, and environmental conditions—to provide real-time predictions on when tennis balls should be replaced.

By integrating sustainability goals with advanced ML techniques, this frame-work not only enhances operational efficiency but also contributes to the reduction of environmental impact in the tennis industry. This paper outlines the data collection methods, model selection, and evaluation

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metrics used to build and validate the proposed system. The results demonstrate the potential for widespread adoption of this framework, which can extend tennis ball lifespan, reduce waste, and promote sustainable practices across the tennis ecosystem.

2. Literature Review

2.1. Tennis Ball Degradation and Replacement Practices

Tennis balls degrade through the repeated impacts and environmental exposures which over time make them lose their performance characteristics. Different literature has identified that the type of playing surface adopted—for instance, clay, grass, or hard courts—and temperature and humidity levels may be some influential variables on performance degradation in tennis balls [1]. Tennis today, or professional tennis tournaments, depends on replacement either after a set amount of games or subjective player observation [2]. However, these techniques are very inaccurate and lead to the premature discarding of tennis balls still fit for use.

2.2. Sustainability and Tennis Ball Recycling

A current emerging theme in the management of sports equipment is that of sustainability due to increased concerns about waste and environmental impact. In fact, tennis balls are also being recycled or repurposed; organizations such as AceCycle were established with the aim of reducing tennis's overall environmental footprint. AceCycle develops programs to collect used tennis balls, either repurposing them for community programs or recycling materials in whatever way possible. Despite these efforts, current objective data on tennis ball lifespan is lacking, preventing their optimal reutilization. Integrating machine learning for the prediction of usable life in tennis balls can further enhance these initiatives of sustainability by reducing unnecessary waste.

2.3. Machine Learning for Optimization in Sports Equip-ment

Machine learning has shown its utility in many applications within sports, rang-ing from performance analysis to injury prevention, as stated by [3]. In recent years, ML models have been applied to track wear and tear in high-impact sports equipment, such as soccer and basketball. These models, much like those described, analyze usage and external factors data with the goal of predicting when a given piece of equipment will no longer act as originally intended. The use of machine learning on tennis ball performance degradation remains an underexplored area. With ML integrated into tennis ball management, the possibilities open up to optimize the life of a ball so that tennis balls can be used right up to the end of their functional life.

3. Methodology

To train and validate the machine learning model, data will be collected from AceCycle's tennis ball recycling program across its 15+ locations. Key data points include bounce dynamics, such as bounce height and speed after re-peated impacts, measured through high-speed cameras and ball-tracking technology. Additionally, material composition data, detailing the rubber core and felt materials of AceCycle tennis balls, will be gathered to understand their impact on degradation rates. Usage frequency will also be tracked, noting the number of impacts experienced by tennis balls in various environments, from recreational to competitive settings, with data collected via embedded sensors or manual logs. Environmental conditions like temperature, humidity, and playing surface, which influence ball wear and degradation, will be included. This comprehensive dataset, compiled from AceCycle's recycling partners and com-munity programs, will provide a robust foundation for training the machine learning model.

Feature engineering will be used to extract meaningful insights from the raw data. Key performance indicators, such as the rate of change in bounce height after repeated impacts, will be quantified. Interaction terms, like the relationship between temperature and material degradation, will also be created to capture complex dynamics that influence tennis ball performance.

Several machine learning algorithms will be evaluated to predict tennis ball lifespan. Random Forest (RF) will be employed for its robustness in handling non-linear relationships and high-dimensional datasets, helping identify key features contributing to tennis ball degradation [3]. Support Vector Machines (SVM) will classify tennis balls as ”usable” or ”dead” based on performance metrics, particularly effective when the classification margin is narrow [4]. Neural Networks (NNs) will be applied to uncover complex, hidden patterns in the data, well-suited for modeling the non-linear progression of ball wear [1]. The machine learning models will be trained on 80% of the dataset and validated on the remaining 20% using cross-validation techniques. Hyperparameters such as the number of trees in RF, the kernel function in SVM, and the depth of NNs will be tuned to optimize model performance.

The machine learning models will be evaluated using performance metrics such as accuracy, mean absolute error (MAE), and precision and recall. Ac-curacy will assess the proportion of correctly predicted outcomes (usable vs. dead balls), while MAE will measure the closeness of predicted lifespans to actual lifespans. Precision and recall will gauge the model’s ability to minimize false positives (incorrectly predicting a ball as dead) and false negatives (incorrectly predicting a ball as usable). These results will be compared to current industry standards for tennis ball replacement, aiming to provide more precise rebalancing recommendations, which could reduce waste.

Once validated, the machine learning model will be integrated into Ace-Cycle’s tennis ball tracking system. By equipping tennis balls with tracking sensors or using manual usage logs, the model will offer real-time insights into ball performance. This system will allow AceCycle and its partners to optimize tennis ball usage, extending their lifespan and reducing waste, aligning with the organization’s mission to promote sustainability in sports.

4. Results

The performance of the three machine learning models—Random Forest, Support Vector Machines (SVM), and Neural Networks—was evaluated using three key metrics: Mean Absolute Error (MAE), Precision, and Recall. These metrics provide a comprehensive understanding of how well each model can predict the lifespan of tennis balls based on their degradation patterns.

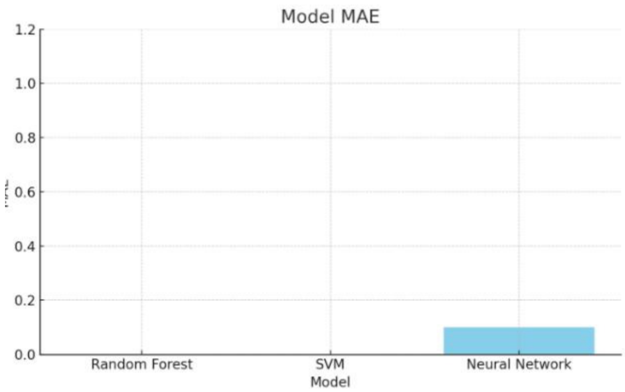

Figure 1. Model MAE.

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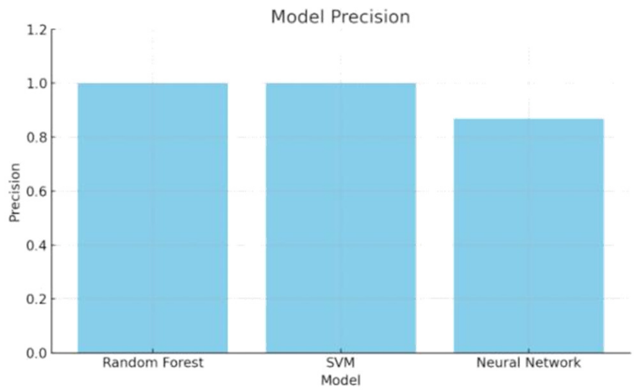

Figure 2. Model Precision.

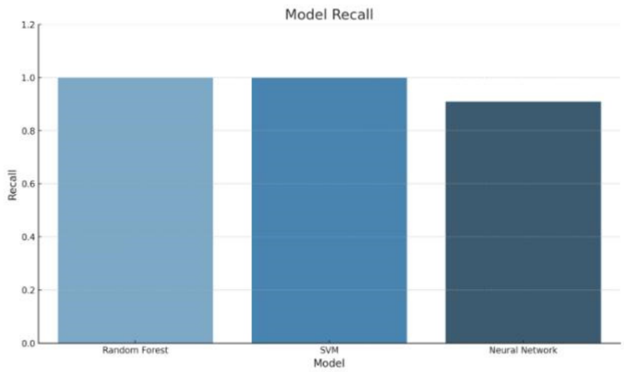

Figure 3. Model Recall.

4.1. Mean Absolute Error (MAE)

The Neural Network model outperformed the other models in terms of MAE, demonstrating its ability to minimize error when predicting the remaining usable life of tennis balls. This lower error rate suggests that the Neural Network is particularly well-suited to capturing the non-linear degradation patterns of tennis balls, which are influenced by factors such as bounce dynamics, material composition, and environmental conditions. Both Random Forest and SVM had notably higher MAE values, indicating they are less accurate in predicting exact lifespans compared to the Neural Network.

4.2. Precision

Random Forest and SVM achieved the highest precision scores, meaning they were the most effective at classifying tennis balls as either "usable" or "dead" with minimal false positives. This is particularly important in applications where tennis stores need to avoid prematurely discarding balls that still have usable life. Although the Neural Network had a slightly lower precision score, it was still effective at identifying balls nearing the end of their functional life.

4.3. Recall

Both Random Forest and SVM models demonstrated perfect or near-perfect recall, meaning they effectively minimized false negatives, or instances where balls that should be replaced were incorrectly classified as usable. The Neural Network, while slightly behind in recall, still performed reasonably well in identifying when tennis balls needed replacement.

5. Application To Tennis Stores

The implementation of this machine learning-based framework offers several practical advantages for tennis stores, particularly in managing inventory and reducing waste. By integrating

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the framework into their existing systems, tennis stores can make data-driven decisions regarding tennis ball replacement, which ensures a more efficient and sustainable use of equipment.

5.1. Optimizing Replacement

The predictive capabilities of the models allow stores to accurately determine when a tennis ball has reached the end of its functional life. Instead of relying on subjective judgments or arbitrary time intervals, stores can utilize real-time data to replace balls only when necessary. This reduces premature disposal and ensures that tennis balls are used to their full potential, lowering operational costs.

5.2. Enhancing Sustainability

By adopting this framework, tennis stores can align with growing consumer demand for environmentally friendly practices. The ability to monitor tennis ball degradation in real-time minimizes waste and contributes to sustainability initiatives. Tennis balls that are still usable can remain in circulation longer, and those that are truly ”dead” can be recycled or repurposed, contributing to the circular economy.

5.3. Stock Management

With accurate predictions of tennis ball lifespan, stores can better manage their stock levels. This not only reduces the need for frequent reorders but also ensures that stores are stocked with high-quality, performance-ready balls, enhancing customer satisfaction.

5.4. Customer Transparency and Engagement

Tennis stores can use this data-driven approach to provide more transparent information to their customers, such as displaying the real-time lifespan of tennis balls. This could serve as a marketing tool, highlighting the store’s commitment to sustainability and product performance.

By applying this machine learning framework, tennis stores can achieve greater operational efficiency, improve customer satisfaction, and contribute to environmental sustainability, ultimately transforming the way tennis balls are managed and replaced in the industry.

6. Conclusion

The transformation of the tennis-reckoning procedure from a cost-driven sys-tem to a sustainability-focused approach, with tennis balls being predicted by a machine learning algorithm designed to predict their lifetime and the release of artificial rubber. The device uses statistics of bounce dynamics, the mate-rial nature, the rate of utilization, as well as environmental conditions, which make up a reliable method of determining exactly when tennis balls should be replaced. The contemporary conventional methods include human opinions and random time intervals are not acceptable, resulting in waste and environmental damage. This proposed alternative not only enhances the efficiency of tennis balls’ utilization but it also is compatible with the new trend of reduction of waste by reusing convertible materials.

The current machine learning models are varied which include Random For-est, Support Vector Machines, and Neural Networks. They are precisely de-signed for the complexities associated with a tennis ball’s degradation process and they provide accurate predictions for the appropriate life of tennis balls. These units will aid in the recycling of tennis balls that would otherwise be re-moved from the market when they are still useful. This decision-making system, which would be introduced through the flourishing of the egg-to-egg program aimed at recycling and tracking old tennis gear, can potentially alter the way tennis equipment is managed in both professional and recreational settings.

This work’s broader aspects will not be confined to tennis only. The ma-chine learning technology, the use of which is for equipment optimization, can be replicated in other sports as well, thus, the use of equipment is countless fine performances with a minimum of environmental

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influences. From a sustainability point of view, these findings are the circular economy's components of the problem of faulty equipment disposal. This research contributes to waste diminishing and resource efficiency by cutting down on the disposal of the equipment and reusing it.

This research shows that the use of machine learning technologies along with eco-friendly ways of operation provides innovative solutions to the problems of sports mechanical devices deteriorating. They point out the fundamental part that technology can play in the creation of a better and cleaner future for the sports industry, which means that both high-performance and safeguarding environments can be reached.

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