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Editorial

Sustainability, scalability, intelligent networking, and user-centered digital experiences are increasingly shaping contemporary research agendas. The four papers discussed in this editorial reflect these priorities by addressing environmentally responsible material design, enterprise software modernization, advanced routing strategies for next-generation networks, and personalized learning in digital education systems. Although diverse in application, these studies share a common emphasis on optimization, adaptability, and practical implementation under real-world constraints.

The first paper responds to the global demand for sustainable mobility by examining bamboo as an alternative material for bicycle frame construction through finite element analysis and topology optimization. By developing a detailed three-dimensional FEA model and simulating multiple loading scenarios, the study evaluates the structural integrity, durability, and design efficiency of bamboo frames. Beyond mechanical performance, the research situates bamboo within a broader environmental context, comparing its ecological footprint to that of conventional materials such as steel and aluminum. The findings highlight bamboo's favorable strength-to-weight ratio, natural vibration damping, and renewability, reinforcing its viability as a sustainable engineering material for eco-friendly transportation [1].

The second contribution addresses a pressing challenge in enterprise software engineering: managing mixed Java versions during large-scale system upgrades. Focusing on the transition from legacy Java 8 to modern long-term support versions such as Java 17, the paper proposes a Jenkins-based CI/CD pipeline capable of handling multiple Java versions without reliance on containerization technologies. Through a Spring Boot enterprise application case study, the approach demonstrates improved automation, reduced regression risk, and enhanced developer productivity. By aligning with real organizational constraints, this work offers a reproducible and extensible solution for enterprises navigating complex software modernization efforts [2].

Advances in wireless communication and autonomous networking are explored in the third paper, which proposes a bio-inspired directional routing strategy for MANETs in a 6G context. The approach integrates an updated Tunicate Swarm Algorithm with cross-layer interaction to overcome issues such as local optima entrapment and routing overhead. By enabling information exchange between network layers and optimizing parameters at the medium access control level, the proposed method enhances routing efficiency in directional antenna-enabled networks. Simulation results confirm superior performance compared to existing routing schemes, demonstrating the potential of biologically inspired optimization combined with cross-layer design in next-generation ad hoc networks [3].

The fourth paper focuses on improving user experience and learning outcomes in E-learning systems through personalized content recommendation. By analyzing user interactions, preferences, and behavioral patterns, the proposed model aims to deliver tailored educational content that enhances student engagement and performance. Experimental results show substantial improvements in prediction accuracy after retraining, indicating the effectiveness of adaptive learning models. This work underscores the importance of personalization and user-centered design in building intelligent E-learning platforms capable of supporting diverse learner needs [4].

Together, these four studies illustrate how optimization-driven and adaptive approaches are being applied across engineering, computing, networking, and education. From sustainable material design and enterprise software pipelines to intelligent routing in future networks and personalized digital learning environments, each contribution addresses contemporary challenges with practical, data-informed solutions. Collectively, they highlight a broader shift toward systems that are not only technically efficient but also environmentally responsible, scalable, and responsive to user needs, providing valuable directions for future research and application.

References:

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Finite Element Analysis and Topology Optimization of Bamboo Bike Frame

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ABSTRACT: In response to the global imperative for sustainable solutions, this study investigates the finite element analysis (FEA) and optimization of bamboo as a material for bicycle frames. As eco-friendly transportation gains importance, bicycles are recognized as a key component of sustainable mobility. This research utilizes FEA to thoroughly examine the structural performance of bamboo frames, enabling design optimization to enhance their strength and durability. The objectives include creating a comprehensive 3D FEA model of the bamboo bike frame, simulating various loading scenarios, and using the FEA results for topology optimization. Special emphasis is placed on assessing bamboo's environmental impact in comparison to traditional materials like steel and aluminum. Bamboo's intrinsic properties, such as high tensile strength, lightweight nature, and natural vibration absorption, present it as a compelling alternative for bike frame construction. This study integrates FEA techniques, and topology optimization to establish the viability of bamboo as a material for bicycle frames, highlighting key factors influencing frame design, material properties, and optimization techniques.

KEYWORDS: Finite Element Analysis (FEA), Bicycle Frame, Bamboo Material, Topology Optimization, Material Properties

1. Introduction

In the face of unprecedented global challenges, sustainable solutions across various life aspects have become imperative. Transportation, a pivotal domain in this endeavor, is increasingly turning towards eco-friendly alternatives to mitigate its environmental footprint. Among these alternatives, bicycles have emerged as a sustainable and environmentally friendly mode of transport. The choice of materials for bicycle frame construction significantly influences their performance, sustainability, and cost-effectiveness. Traditional materials like aluminum, carbon fiber, and steel have long dominated the bicycle industry, but the introduction of sustainable materials such as bamboo has brought about a significant shift [1]. Bamboo bicycles present a promising alternative due to bamboo's inherent properties like high tensile strength, lightweight nature, and natural vibration-damping capabilities. These properties not only make bamboo an environmentally friendly choice but also offer unique riding experiences [1]. Bamboo has emerged as a promising alternative to conventional steel or composite frame bicycles due to its cost effectiveness, rapid growth rate, and ease of processing. Furthermore, bamboo exhibits favourable attributes such as lightweight properties, impressive stiffness, and remarkable strength of approximately 40 KN/cm^2 compared with steel, which can resist 37KN/cm^2 [2]. Bamboo is an excellent construction material due to its high bending strength and flexibility. Unlike other building materials, bamboo can grow up to 40 meters tall and withstand strong winds without breaking [3]. Bamboo has an average ultimate tensile strength of 300-350MPa and an average density of 0.4(g/cm^3). This strength is comparable to that of aluminium, a commonly used material to construct bicycles, which has an ultimate tensile strength of 310 MPa but an average density of 2.7 (g/cm^3) [4]. The advantage of bamboo bike designs lies in their use of easily accessible and renewable materials, offering an alternative to potentially costlier industrial products. Environmentally, this approach is more sustainable since the materials for the bicycle's production are not mined and processed but are instead harvested and replanted as needed, ensuring a continuous and endless supply of bamboo [5].

The growing interest in sustainable transportation and environmentally friendly materials underscores the significance of this study. Bamboo bike frames contribute to reducing carbon footprints and offer unique riding experiences due to their material characteristics. Despite the potential of bamboo as a sustainable alternative, there is a lack of comprehensive research on its structural performance and optimization for bicycle frames [6]. The advancements in both experimental and numerical insights into bamboo-based structural systems have been made recently. Furthermore, studies have explored dynamic tensile failure mechanisms of bamboo under strain-rate loading, this highlights the importance of validation beyond static Finite Element Analysis (FEA) [7]. Apart from this, the FEA-based stress analysis of composite bamboo bicycle frame (heat-treated) shows experimental and simulation integration which is useful for fatigue and joint optimization [8]. This gap in knowledge necessitates focused investigation to harness the full potential of bamboo in bicycle manufacturing.

This research aims to analyze the structural performance of bamboo as a material for bike frame construction using FEA and subsequently optimize the design for enhanced strength, durability, and sustainability. Through detailed FEA modelling, simulation, analysis, and Topology Optimization, this study seeks to provide valuable insights into bamboo's potential as a competitive alternative for bicycle frame construction, addressing the current gaps in standardization and predictability of bamboo as a material for bicycle frames.

2. Methodology

2.1. Static Analysis of Bike Fram

In the 1D static analysis, the bike frame was simplified into a one-dimensional model, focusing on key structural elements such as tubes and joints. This analysis was done in HyperMesh, and it was essential for understanding the behaviour of these elements under static loads, which are consistent and unchanging over time.

2.1.1. Modelling

The core structure of a bike is its frame, which consists of essential parts like the top tube, seat tube, head tube, chain stay, and seat stay. These components serve as the foundation to which the wheels and other bike parts are attached. The design of this bike frame has been tailored for individuals with a height ranging from 5 feet to 5 feet 11 inches, and the design parameters are shown in the table 1.

Table 1: Design parameter of bicycle frame

Parameter	Value
Top Tube	585 mm
Seat Tube	508 mm
Head Tube	104 mm
Chain Stay	450 mm
Seat Stay	590 mm
Seat Tube angle	73°

2.1.2. Assumptions

- Bamboo material is considered homogeneous throughout the frame.
- Variation in properties within the material are neglected for simplicity.
- Bamboo is treated as an isotropic material. Bamboo is naturally anisotropic due to its fibrous structure, but it was modelled isotropically in this study for simplicity and computational practicality. This assumption could affect accuracy, particularly when capturing directional stiffness and strength, and is regarded as a limitation.
- Consistent mechanical properties are assumed in all direction.
- Bamboo exhibits linear elastic behaviour under various loading conditions.
- The analysis focuses on static loading scenarios.
- Dynamic effects or dynamic loading conditions are disregarded.
- A consistent environmental context is assumed during the analysis, such as temperature and humidity.

2.1.3. Material Selection and Properties

The primary focus is on the finite element analysis (FEA) of bike frames using HyperMesh for steel, aluminum, and bamboo to evaluate their mechanical performance. The research aims to provide a comprehensive understanding of how bamboo, as a sustainable material, compares to traditional bike frame materials. In HyperMesh, the properties of each material are utilized to create precise models of bike frames constructed from Bamboo, steel, and aluminum. This software facilitates simulations under static loading conditions to evaluate how each material influences the overall performance and durability of the bike frame.

The boundary and loading conditions are chosen to represent genuine circumstances that occur during typical cycling operations. These are in accordance with regulatory norms (e.g., BNA, CPSC), which include frame stress testing through vertical and horizontal loading, pedal force and rear wheel braking applications.

Table 2: Mechanical properties of materials selected

Materials	Modulus of elasticity (Mpa)	Poisson's ratio	Density (kg/m³)
Bamboo	16170	0.3	600
Aluminum	72000	0.33	2700
Steel	205000	0.29	7800

2.1.4. Boundary Conditions

In the analysis of the bike frame, specific boundary conditions have been established to simulate realistic structural responses. The rear drop-outs and front head tube have been fixed to emulate the secure attachment of these components, reflecting real-world structural stability as shown in figure 1. The fixed constraints prevent translational movement at these critical points, ensuring an accurate representation of the frame's behaviour under various loads. These boundary conditions are crucial for a comprehensive finite element analysis, contributing to the assessment and optimization of the bike frame's strength and durability.

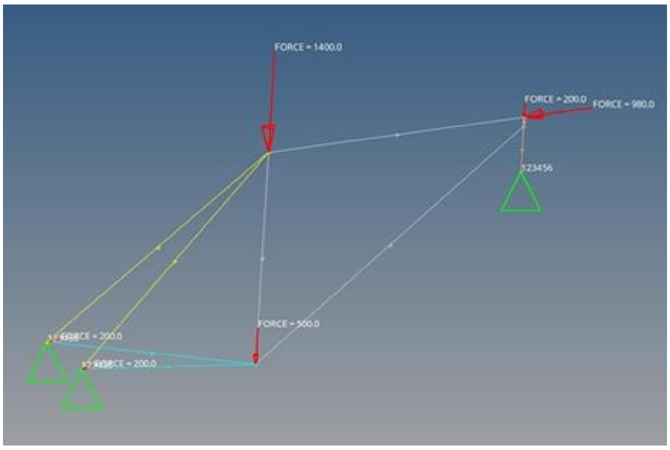

Figure 1: Loading and boundary conditions

2.1.5. Loading Conditions

Numerous studies have explored the analysis of bicycle frames using Finite Element Analysis (FEA) under various loading conditions. The investigation involved simulating recumbent and Schwinn upright bicycle frames, exposing them to different scenarios like vertical loads on the steering tube, vertical load at the center of the bottom bracket, vertical load on the seat [7]. Additionally, the simulations covered static situations, steady pedalling on different pavements, and hard acceleration on level ground and uphill. The research considers six loading conditions: static start-up, steady pedaling, standing up on bikes, vertical loading, horizontal loading, and rear wheel braking.

1st Condition: Static start-up

In this condition, we consider the bicycle to be at rest, and there's a rider on the saddle with a weight of 700 N (equivalent to 71.3 kg). We account for the gravitational force, which is 9.81 m/s². It's important to note that this analysis doesn't take into consideration the impact of air resistance.

2nd Condition: Steady-state pedalling

In this scenario, imagine a person riding a bicycle, weighing about 700N. They're pedaling steadily while applying a constant force of 200N to the pedal attached to the bike's bottom bracket.

3rd Condition: Standing up on the bikes

In cases where the rider stands up on the bike, forces of 300 N and 200 N are applied to the pedal and front head tube, respectively.

4th Condition: Vertical loading

This condition represents a vertical force equivalent to twice the weight of the driver, influenced by the G factor. The G factor is utilized as a simplification for the vibration effects of biking on uneven roads, holes, and rough terrain. The simulation introduces the "G factor" to account for the impact on the bicycle frame when encountering a deep road hole, assuming total energy transfer to the structure and it can be seen in figure 1.

5th Condition: Horizontal loading

A force of 980 N is applied horizontally to the front head tube of the bicycle, simulating conditions where the rear drop-out remains stationary. In the bicycle manufacturing industry, compliance with standards set by the Bureau of National Affairs (BNA) in 1976 and the Consumer Product Safety Commission is crucial [8]. Every bicycle design undergoes various physical tests to meet these standards. An example scenario is akin to a low-speed bicycle hitting a wall. During such tests, it is essential for the bike to withstand the force without developing significant cracks or deformations in order to pass the examination.

6th Condition: Rear wheel breaking

In this scenario, we assume a gradual application of hindrance specifically at the wheels, causing all loads to be concentrated only on the rear wheels. The load, equivalent to 200 N, is applied to the rear drop-outs, representing the braking force. This condition simulates a decrease in speed and is integrated into our analysis. The process involves the driver pedaling the bike until it reaches a steady speed and then applying brakes until the bike comes to a complete stop, as illustrated in Figure 1.

2.2. Mesh Convergence Study

In the finite element analysis (FEA) of the bamboo bike frame, the meshing process is a critical step [9]. The quality and size of these elements significantly influence the accuracy of the FEA results. For bamboo, precise meshing is crucial to capture its behavior accurately under load [10].

2.2.1. Conducting Mesh Convergence Tests to Ensure Accuracy

Mesh convergence tests were conducted to determine the optimal mesh size that balances computational efficiency with result accuracy. This process involved systematically changing the element size and observing the impact on key output parameters, such as Von Mises stress and displacement. The goal was to identify a mesh size where further refinement does not significantly alter the results, indicating that the solution has converged.

2.2.2. Selection of Optimal Mesh Size Based on Convergence Results

The table 3 and figures 2 and 3 show the mesh convergence test results for the bamboo bike frame.

Table 3: Element size vs von mises stress and displacement

Element Size (mm)	Von Mises Stress (Mpa)	Displacement (mm)
32	36.7	0.19
31	42.1	0.27
30	48.3	0.42
28	52.2	0.50
26	58.9	0.54
24	64.5	0.63
22	69	0.71
20	78.1	0.781
18	87.6	0.78
16	87.86	0.78
14	87.9	0.719

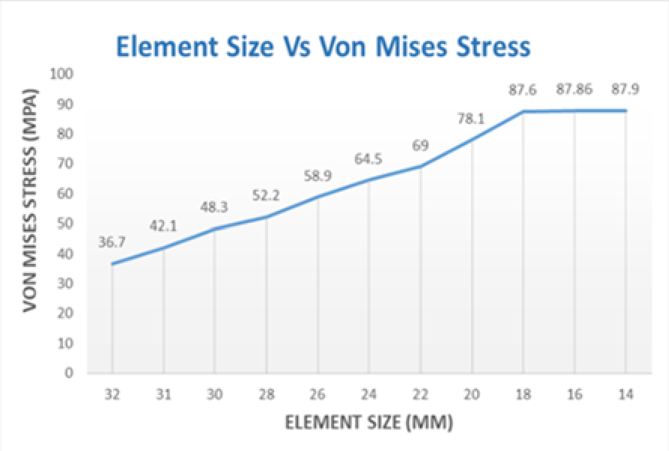

Figure 2: Graph between element size and von mises stress

Based on these results, a 16mm element size was selected as optimal. This decision was made considering the balance between computational efficiency and the accuracy of stress and displacement results. At 16mm, the Von Mises stress and displacement values showed sufficient stability, indicating that further refinement of the mesh would not significantly alter the results. This mesh size effectively captures the mechanical behavior of the bamboo material under static loading conditions, as required for the accurate simulation of the bike frame's performance.

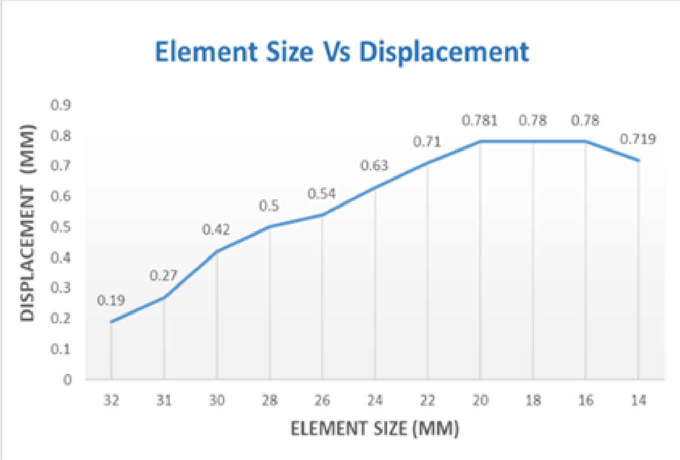

Figure 3: Graph between element size and displacement

2.3. 3D Static Analysis of Bamboo Bike Frame

The 3D static analysis begins with the detailed modelling of the bamboo bike frame. While the model does not replicate an exact bike frame, it closely represents the Design space of a typical bamboo frame as shown in figure 4. This model incorporates the unique characteristics of bamboo as a material. The 3D model is created using SolidWorks and it includes all critical components such as joints, and connections, ensuring a comprehensive representation of the frame's physical and mechanical properties.

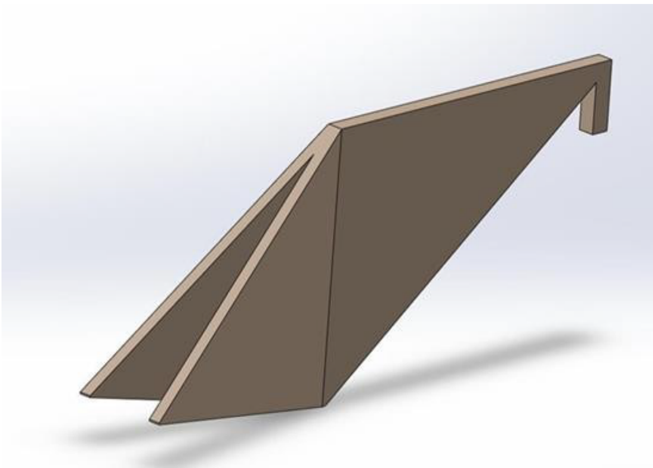

Figure 4: Design space for bamboo bike frame

2.3.1. Material Properties

Material – Bamboo with Modulus of elasticity value 16170MPa, Poisson's ratio 0.3, and Density 600kg/m^3 which is equal to 0.6e^{-9} ton/mm^3. As we used HyperMesh for this analysis so we have mentioned the value of density in ton/mm³ and all other dimensions in millimeter (mm) such as length, diameter, and thickness.

2.3.2. *Meshing*

The meshing used in this research is 3D mesh with tetrahedral elements types and the element size is 16mm as shown in Figure 5. This mesh size was strategically chosen to ensure a balance between computational efficiency and the accuracy of the simulation results. Tetrahedral elements, known for their flexibility in modelling complex geometries [11]. This element type is particularly suitable for capturing the intricate details of the bamboo bike frame.

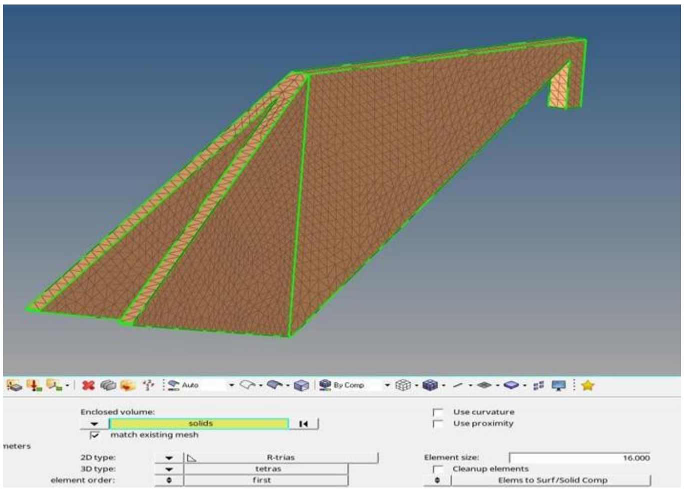

Figure 5: Meshing of bamboo frame

2.3.3. *Static Load and Boundary Conditions*

Static loads are applied to the 3D model to simulate real world conditions. These loads include the weight of the rider, gravitational forces, and any additional static forces that a bike frame might encounter during typical use. In this analysis, we provide different loading condition scenarios: static starts up, steady pedaling, standing up on bikes, vertical loading, horizontal loading, and rear wheel braking as shown in figures 6 and 7.

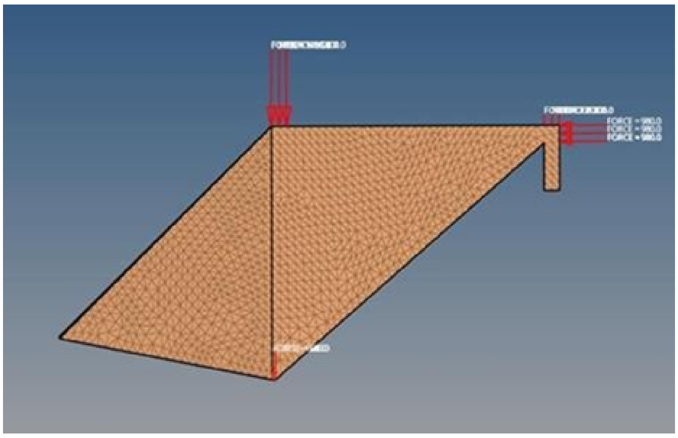

Figure 6: Loading conditions 1

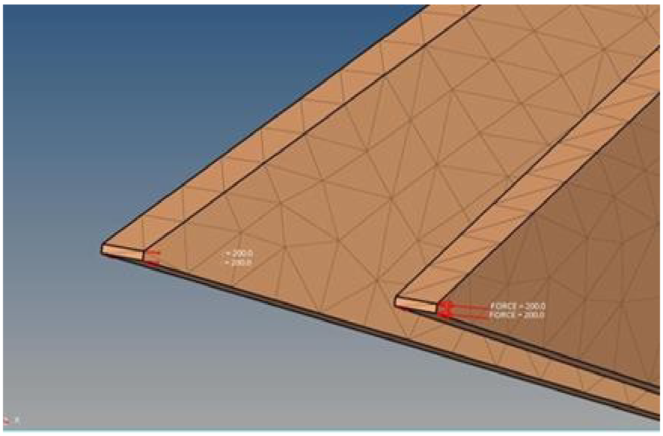

Figure 7: Loading conditions 2

Boundary conditions are set to replicate real-world constraints, such as fixed joints or points of contact with other parts of the bike. This step is crucial for accurately simulating how the frame will perform under load, taking into account the unique properties of bamboo. In this study, constraints were placed below the front head tube and in the rear dropout of the bike frame models, restricting both translational and rotational movements as shown in Figure 8 and 9.

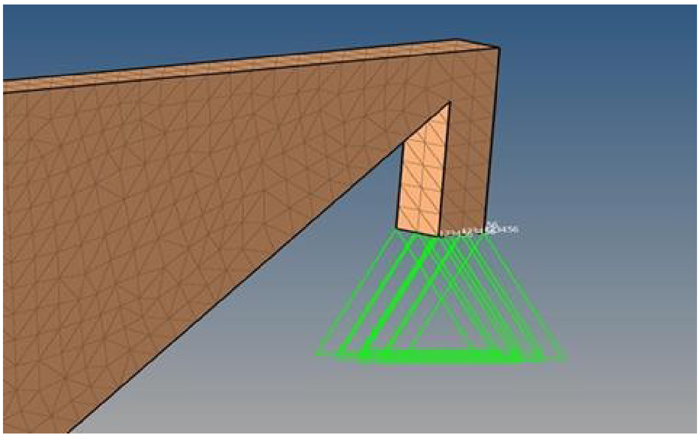

Figure 8: Boundary condition 1

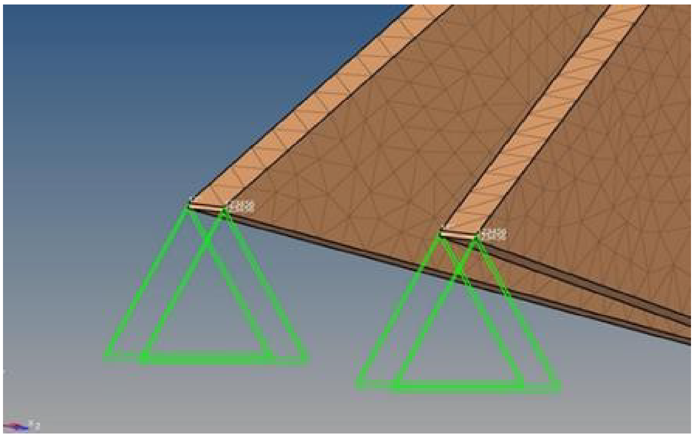

Figure 9: Boundary condition 2

2.4. *Topology Optimization*

Optimization methods will play a critical role in enhancing the frame's performance. The optimization process will likely involve the use of algorithms such as topology optimization techniques. These algorithms will iteratively adjust the design parameters of the bamboo frame, such as geometry and material distribution, based on FEA results and specific performance criteria as shown in figure 10. The goal will be to achieve an optimal design that maximizes structural integrity, minimizes weight, and ensures the frame meets the desired mechanical specifications. In the topology optimization process for the bamboo bike frame, the following steps were methodically executed:

2.4.1. *Design Variable/Space Establishment*

The optimization commenced with the creation of a finite element model representing the bamboo bike frame structure, which defined the design space. The model was processed and prepared for optimization using HyperMesh, a pre-processing tool. Within HyperMesh, the optimization feature in the analysis toolbar was accessed to establish the design parameters for the bamboo bike frame. This step included updating parameters and pattern grouping to align with the specific optimization objectives.

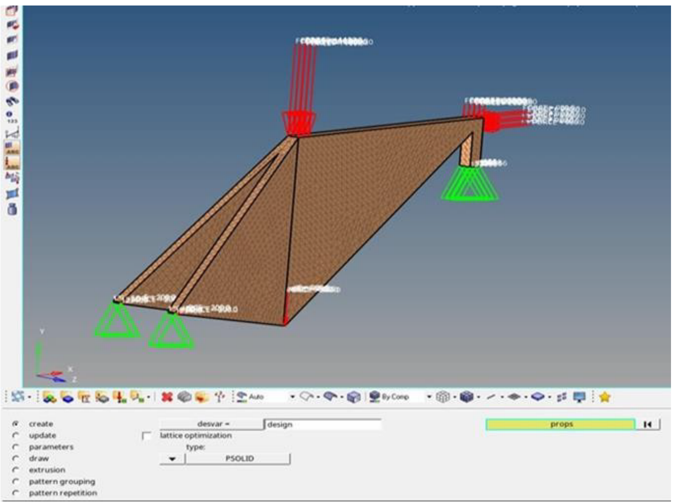

Figure 10: Establish design parameters.

2.4.2. *Setting Responses such as Volume Fraction and Weight*

Key responses, including the volume fraction and weight of the frame, were identified and set as targets for the optimization process. These responses served as critical indicators of the optimization's effectiveness, guiding the algorithm in material distribution and structural refinement as shown in figure 11.

2.4.3. *Constraints Implementation (Limiting Value Fraction)*

A crucial aspect of the optimization was the implementation of constraints, particularly concerning the volume fraction. An upper bound value of 0.3 was set as shown in figure 12, indicating that the solver should retain a minimum of 30% of the original volume in the optimization process. This constraint was essential to prevent the solver from utilizing an excessive volume, potentially reaching 100%. The establishment of this upper bound ensured a balanced approach to material reduction and structural integrity.

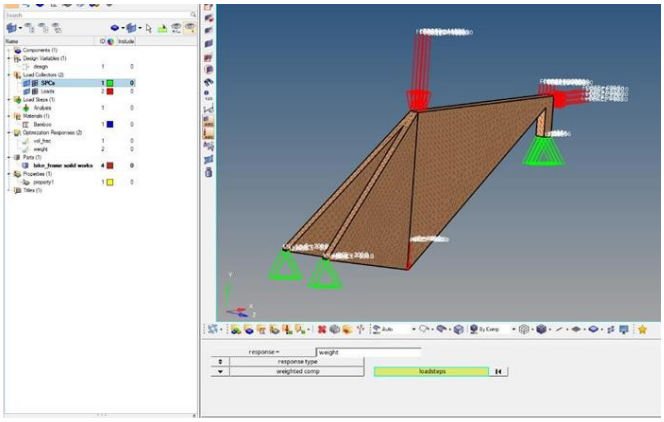

Figure 11: Setting responses for topology optimization.

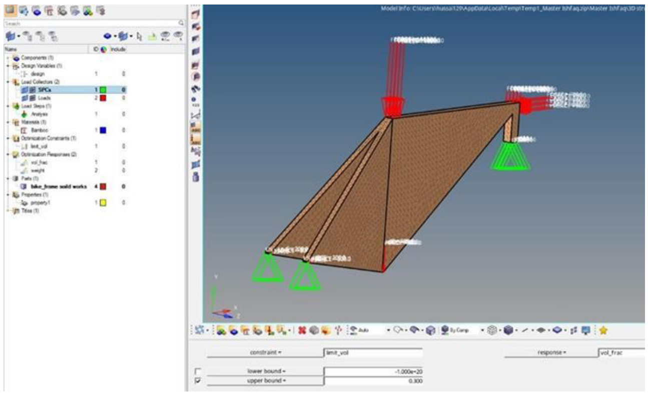

Figure 12: Constraint implementation for topology optimization.

2.4.4. *Setting Optimization Control Panel*

The optimization control panel is employed to define key control parameters, specifically setting the values of discreteness and checkerboard to 2 and 1, respectively as shown in Figure 13. The choice of a discreteness value of 2 significantly influences the tendency of solid elements in topology optimization to converge towards dominant structures, incorporating member size control while adhering to manufacturing constraints. This strategic configuration plays a vital role in guiding the optimization process, ensuring effective and controlled convergence to desired outcomes in the bamboo bike frame analysis.

2.4.5. *Objective Setting*

The objectives for the topology optimization of the bamboo bike frame included weight reduction and strength maximization. Weight reduction was targeted to enhance the bike's efficiency and maneuverability, while strength maximization was crucial for ensuring the safety and durability of the frame. These objectives were carefully balanced to achieve an optimal design that does not compromise on either aspect.

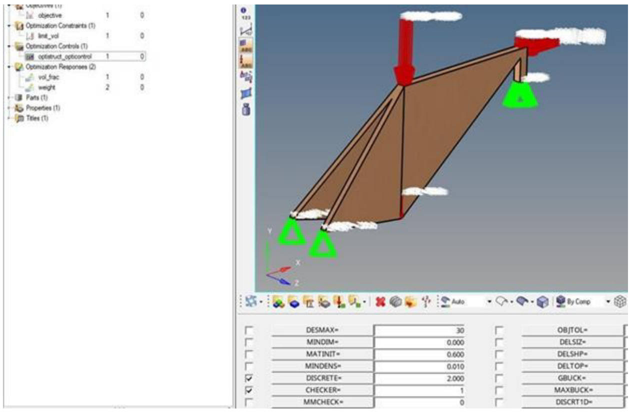

Figure 13: Setting opticontrol panel for optimization.

Finally, the optimization was executed using OptiStruct, a process that involved a systematic approach to refine the bamboo bike frame's design in alignment with the set objectives and constraints.

3. Results

3.1. 1D Results

In the 1D static analysis of the bike frame, three different materials, namely Bamboo, Aluminum, and Steel, were subjected to analysis using HyperMesh. The obtained results, as presented in the table below, showcase the displacement and Von Mises stresses for each material.

Table 4: 1D analysis results for different frame materials

Materials	Displacement (mm)	Von Mises Stresses (Mpa)
Bamboo	0.1371	1.099
Aluminum	0.0307	1.098
Steel	0.0108	1.099

The 1D static analysis revealed that the Bamboo bike frame exhibited a displacement of 0.1371 mm and Von Mises stresses of 1.099 MPa. The figure 14 and 15 visually represent the stress distribution and deformation patterns in the Bamboo frame. The larger displacement suggests more flexibility in the Bamboo frame compared to Aluminum and Steel.

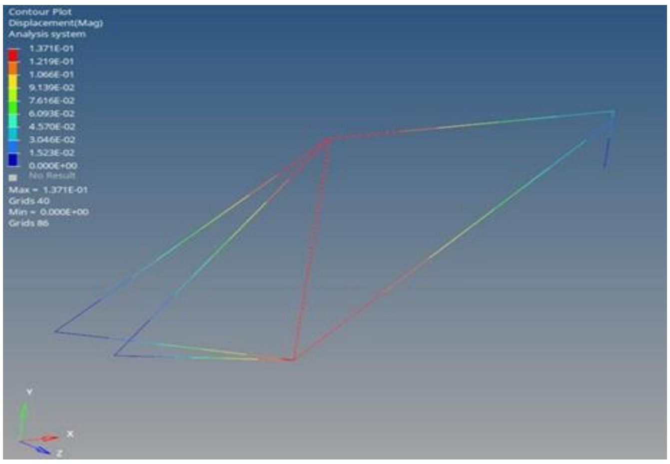

Figure 14: Total displacement of bamboo bike frame

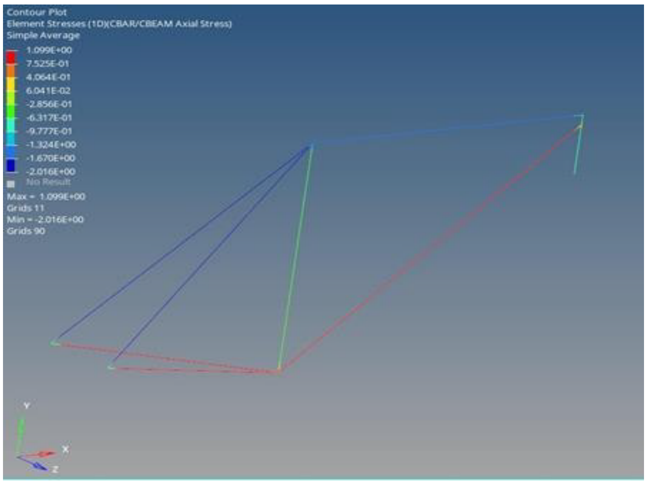

Figure 15: Von mises stress of bamboo bike frame

Comparing the three materials, it is evident that Bamboo provides higher displacement, indicating a more flexible structure. Aluminum showcases an intermediate level of displacement, while Steel demonstrates the least flexibility with minimal displacement. The Von Mises stresses across all materials are relatively close, suggesting comparable strength characteristics. These results contribute valuable insights into the material-specific responses, aiding in the subsequent stages of the finite element analysis and optimization process.

3.2. 3D Results

The 3D static analysis of the bamboo bike frame, representing the design space rather than an exact frame, yielded insightful results. The obtained values are summarized in the table 5, followed by a detailed discussion.

Table 5: 3D bamboo frame results

Parameter	Value
Total Displacement	0.6984 mm
Von Mises	87.86 MPa
Yield Strength	142 MPa
Ultimate Strength	265MPa

The total displacement of 0.6984mm in Figure 16 indicates the maximum deformation within the sitting area of the bike frame. Von Mises stress is a scalar value derived from stress components that is used for predicting yield in ductile materials. A material remains elastic if its Von Mises stress is less than the yield strength. This result suggests a degree of flexibility in the bamboo frame, allowing for some deformation under applied static loads.

3.3. Comparision with Material Strength

The yield strength of bamboo is determined as 142MPa, and the ultimate strength is 265MPa [12]. Comparing these values with the Von Mises stress, it is evident that the frame's stress level is well below the yield strength as shown in figure 17. This implies that, under the applied loads, the bamboo frame remains within its elastic deformation range, preventing any permanent structural damage.

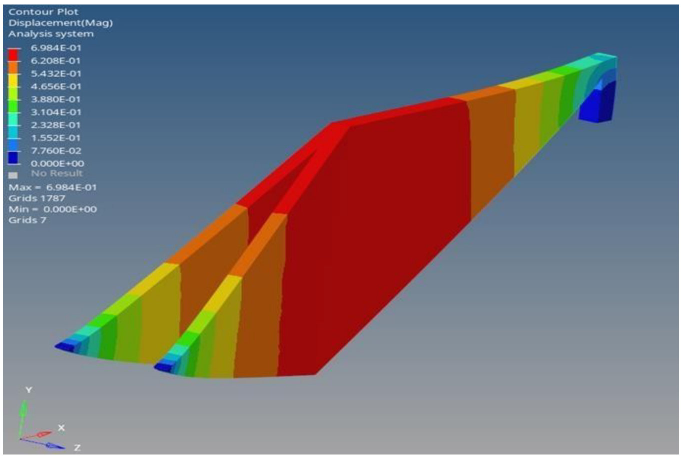

Figure 16: Maximum displacement

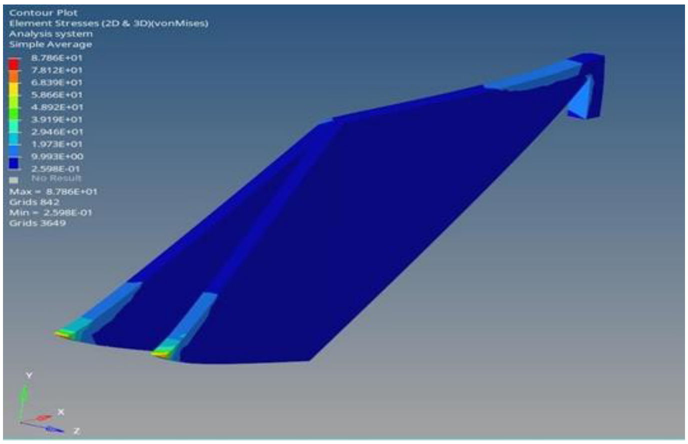

Figure 17: Von mises stress

3.4. Implications for Design

The observed total displacement and stress distribution provide valuable insights for the design considerations of the bamboo bike frame. The flexibility of the frame allows it to absorb and distribute stress, contributing to a comfortable riding experience. The stress levels well below the material's yield strength ensure that the frame maintains its integrity during standard operating conditions. The 3D static analysis results demonstrate the structural behavior of the bamboo bike frame. The observed deformation and stress distribution align with expectations for a material with inherent flexibility.

These findings contribute to the understanding of the bamboo frame's mechanical response, guiding further optimization and design enhancements.

3.5. Topology Optimization Results

The topology optimization process resulted in a refined and efficient design for the bamboo bike frame, as illustrated in Figure 18.

The optimized frame exhibits a strategic distribution of material, successfully achieving the set objectives of weight reduction and strength maximization. The utilization of HyperMesh for preprocessing proved instrumental in establishing the design variables and preparing the model for optimization. The implementation of constraints, particularly the upper bound on volume fraction, ensured a balanced approach to material reduction, preventing excessive utilization. The optimization control panel, configured with discreteness and checkerboard values, played a pivotal role in guiding the convergence process, leading to a design that aligns with dominant structures and manufacturing constraints as shown in Figure 18.

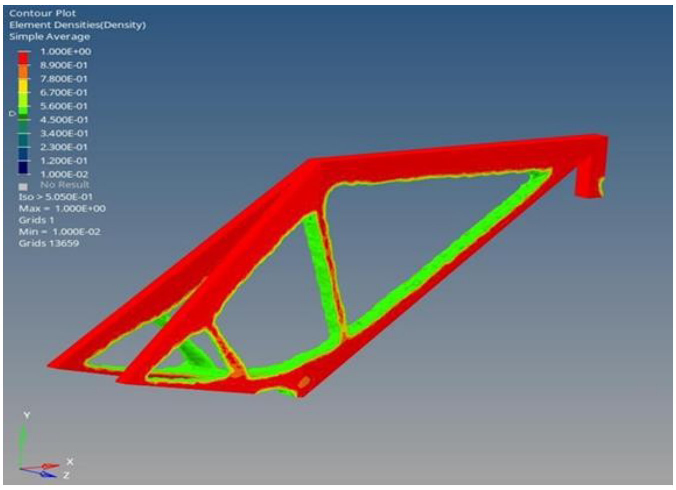

Figure 18: Optimized design of bamboo bike frame

In Figure 19, we present the optimized bamboo bike frame resulting from the topology optimization process. A careful examination reveals a refined and strategically modified structure. The optimization algorithm, guided by the predefined objectives and constraints, has effectively redistributed material to enhance the frame's performance. Key features include an reduction in weight, contributing to improved efficiency and manoeuvrability, and a maximization of strength, ensuring safety and durability. Overall, the topology optimization results demonstrate the efficacy of the approach in achieving a well-balanced and optimized bamboo bike frame design.

4. Validation through Stimulation

The finalized and optimized bamboo frame design was subjected to various simulated real-world scenarios and conditions to ensure that it meets the desired performance criteria and shown in figure 20.

4.1. 1D Analysis for Optimized Design

The validation phase began with a detailed 1D analysis of the optimized bamboo bike frame design. This analysis was primarily focused on assessing two key aspects: deformation and weight reduction. The objective was to ascertain the extent to which the optimization process had enhanced the frame's structural performance and reduced its overall weight.

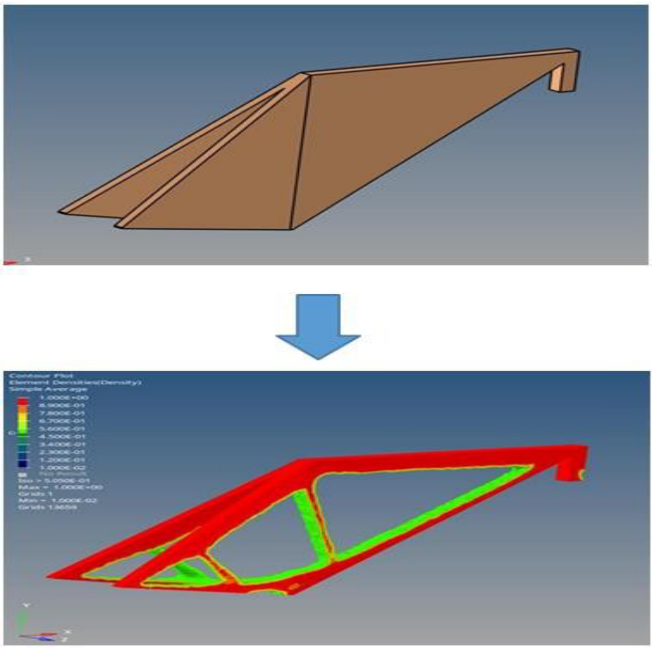

Figure 19: Initial to optimized design

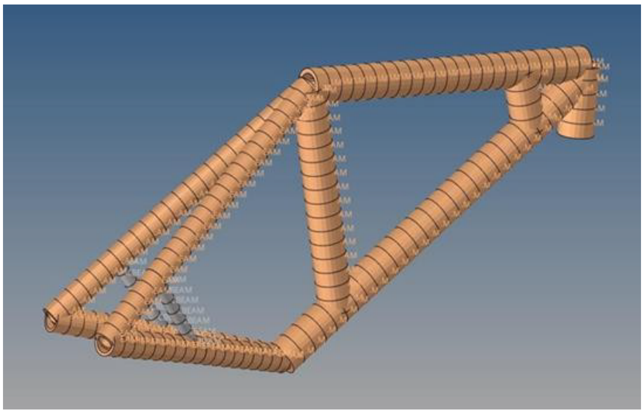

Figure 20: Optimized design model

The results of the 1D analysis for the optimized design of the bamboo bike frame are presented in Figure 21 and 22 respectively. Figure 21 illustrates the element stresses of the optimized model, indicating a value of 0.6077MPa. This stress value is crucial in assessing the structural integrity of the frame, revealing how the material responds to applied loads. A stress value within this range suggests that the bamboo bike frame is experiencing relatively low levels of stress, indicating a design that can effectively handle the expected mechanical forces.

Figure 22, on the other hand, shows the total displacement of the optimized model, which measures 0.09049mm. The total displacement is a key parameter in understanding the flexibility and deformation characteristics of the bamboo bike frame. A displacement value within this range indicates that the frame exhibits a controlled level of deformation under the applied loads. This controlled deformation is desirable as it ensures that the frame maintains its structural integrity and stability during operation.

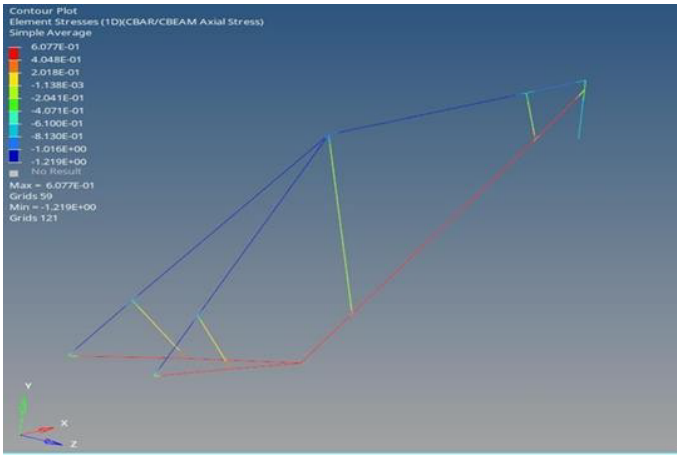

Figure 21: Element stresses of optimized model

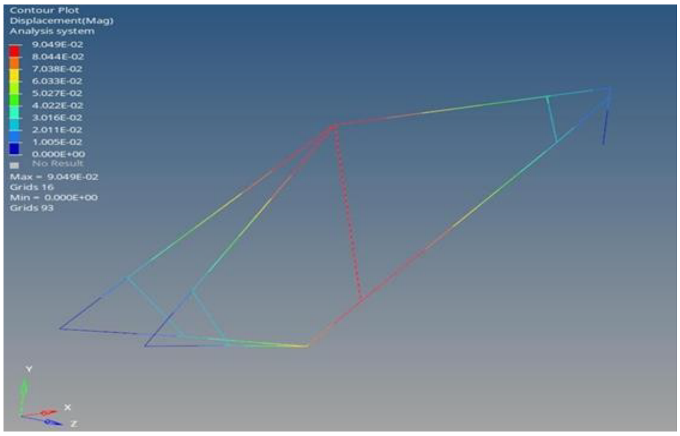

Figure 22: Total displacement of optimized model

4.2. Comparision with Initial Design

In the comparison of the results between the 1D analysis of the optimized design and the initial 3D analysis of the bamboo frame, notable differences were observed as shown in table 6. The 3D analysis indicated Von Mises Stress of 87.86 MPa and a Total Displacement of 0.6984 mm, while the subsequent 1D analysis on the optimized design revealed Von Mises stress of 0.6077 MPa and Total Displacement of 0.09049 mm. The variance in results can be attributed to the differing nature of the analyses. In the 3D analysis, loads were applied on the surfaces, providing a comprehensive representation of stress distribution and displacement throughout the three-dimensional structure. On the other hand, the 1D analysis, utilizing point loads, simplified the structure, potentially leading to discrepancies in stress and displacement values.

The contrast between 1D and 3D results is due to modelling complexity: 1D analysis utilises point loads and simplified geometry, whereas 3D analysis integrates genuine surface interactions and full structural stiffness. 3D results produce more realistic stress concentrations and are used in optimization.

Table 6: Comparison between 3D and 1D analysis results

Analysis Type	Von Mises Stresses (Mpa)	Total Displacement (mm)
3D Analysis	87.86	0.6984
1D Analysis	0.6077	0.09049
Yield Strength	142	-

Despite the variations, both analyses show that the Von Mises stress values are well below the yield strength of bamboo (142 MPa), indicating a favourable safety margin. This suggests that, even under different analysis methods, the bamboo bike frame remains within its structural limits, demonstrating resilience and suitability for practical applications.

4.3. Benchmarking against Steel and Aluminum Frames

To further validate the effectiveness of the optimized bamboo frame, its performance was benchmarked against frames made of steel and aluminium. This comparison extended to both deformation characteristics and weight. The objective was to evaluate if the optimized Bamboo frame's deformation and weight were comparable to or better than those of frames made from traditional materials like steel and aluminium. This benchmarking was crucial to establish the optimized bamboo frame's competitiveness in terms of both structural integrity and weight efficiency.

Table 7: Benchmaking of bamboo against aluminum and steel bike frame

Material	Initial 1D Deformation (mm)	Optimized 1D Deformation (mm)	Total Mass (ton)
Bamboo	0.1371	0.09049	2.448e-3 (2.22kg)
Aluminum	0.0307	-	3.553e-3 (3.2kg)
Steel	0.0108	-	5.241e-3 (5kg)

5. Final CAD Model

A detailed CAD model of the bamboo bike frame was created using SolidWorks, a widely-used and precise computer-aided design (CAD) software as shown in figure 23. The Final CAD model represents the optimized bamboo bike frame, incorporating findings from the thorough analysis and simulation phases. SolidWorks was employed to generate an accurate and visually clear model, allowing for a close examination of the design details. The use of SolidWorks in this phase highlights the importance of user-friendly CAD tools in translating theoretical insights into practical and refined designs. This Final CAD model signifies dedication of the research to achieve a well-balanced design in terms of structure, optimization, and visual appeal in bamboo bike frame construction.

Figure 23: Final CAD model

6. Conclusion

The study's limitations include the assumption of isotropic bamboo behaviour and a lack of experimental or dynamic validation. These factors influence accuracy and generalisability, which will be addressed in future study.

The study demonstrates a complete FEA analysis and topology optimisation of a bamboo bicycle frame. Key investigation reveal that bamboo provides equivalent strength, weight reduction, and sustainable manufacturing benefits to traditional materials. The optimised design reduced displacement by 34% and achieved 30% lower mass than aluminium, all while keeping stress within elastic limits.

7. Future work

7.1. Anisotropic Analysis of Bamboo Material

In the future phase of this research, there is a critical need to explore and integrate the anisotropic nature of bamboo into the analysis. This identified limitation underscores the significance of prioritizing this aspect in future research to enhance the overall understanding of bamboo's mechanical characteristics in bicycle frame applications.

7.2. Dynamic Analysis and Experimental Validation

Incorporating dynamic analysis would provide insights into the behaviour of the bamboo bike frame under varying loads and conditions. This could include time-domain simulations or modal analysis of real-world input data (e.g., road bumps, rider acceleration). Future studies should combine transient dynamic FEA and fatigue models to assess durability under cycling settings. Additionally, experimental validation is required to guarantee simulation accuracy. Mechanical lab testing of real bamboo bike prototypes (tensile, fatigue, and dynamic load testing) should be included in future work. Collaboration with material labs or bamboo bike manufacturers will help with this.

Conflict of Interest

The author declares no conflict of interest.

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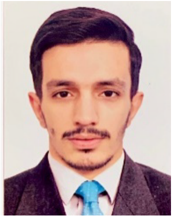

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Enterprise-Grade CI/CD Pipelines for Mixed Java Version Environments Using Jenkins in Non-Containerized Environments

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ABSTRACT: Enterprises with large Java codebases are increasingly facing challenges in maintaining different versions of Java, mainly during upgrade of legacy Java 8 to modern long-term support (LTS) versions like Java 17. These concerns are majorly identified in environments where several Java versions co-exist, such as during incremental migration or version restrictions based on dependencies. This paper proposes a model for designing and implementing enterprise-grade CI/CD pipelines that support mixed Java version development using Jenkins. The proposed solution manages build execution, automated testing, static code analysis, and deployment validation in different Java versions without depending on container tools like Docker or Kubernetes. A Spring Boot-based enterprise application case study demonstrates the effectiveness of the approach, showcasing improvements in automation, developer productivity, and avoiding regression. By following best practices and real-world constraints, this work contributes a reproducible and extensible solutions to organizations that are scaling their Java applications.

KEYWORDS: CI/CD pipeline, Java 8, Java 17, Jenkins, Spring Boot, Software modernization, multi-Java environment, Legacy system upgrade, Static code analysis, Enterprise DevOps

1. Introduction

Continuous integration and continuous delivery (CI/CD) pipelines that can handle complex, heterogeneous environments are essential for modern software development. Maintaining applications developed on different Java versions is a common problem for enterprises, especially when switching from Java 8—which is no longer receiving public updates—to more recent Long-Term Support (LTS) versions like Java 11 or Java 17 [1]. This situation frequently occurs in large Enterprises where microservices or modularized components coexist with legacy systems [2].

Significant enhancements over Java 8 are brought about by Java 17, an LTS release, which includes the Java Platform Module System (JPMS), improved garbage collectors (such as G1GC and ZGC), and expressive language features like records, sealed classes, and pattern matching [3]. Enterprise application migrations to Java 17 are rarely straightforward and not simple. Teams may need to support multi-Java environments both during and after migration because crucial dependencies, like Spring Framework components, third-party libraries, or even build tools, may still depend on Java 8 compatibility [4].

CI/CD pipelines are crucial for facilitating safe and scalable modernization in these kinds of situations. Jenkins is a popular open-source automation server that offers the ability to plan builds, tests, and deployments in a variety of Java environments. When properly set up, it can assist with backward compatibility validation, run unit tests across various Java runtimes, and enforce security and quality standards with SonarQube, SpotBugs, and Checkstyle [5].

Although CI/CD is widely used in DevOps culture, little scholarly research has been done on how pipelines should be built to accommodate different Java versions in business settings, especially in non-containerized settings that do not use Docker and Kubernetes. By offering a structured Jenkins-based pipeline architecture that supports applications that have been compiled, tested, and validated for both Java 8 and Java 17, this paper seeks to close that gap without adding needless complexity or infrastructure overhead.

2. Background and Related Work

Modernizing legacy systems is essential for maintainability, security, and performance as enterprise Java applications get bigger and more complex. Because it introduced lambda expressions and the Stream API, Java 8, which was released in 2014, gained a lot of traction. However, it lacks the performance optimizations and contemporary language features of more recent Long-Term Support (LTS) releases, such as Java 11 and Java 17 [6]. Organizations are facing mounting pressure to upgrade their applications to more recent versions that provide vendor and community support as Java 8's public updates come to an end [7].

2.1. Java Version Evolution and Migration Challenges

The language and runtime of Java underwent significant modifications in later iterations. The Java Platform Module System (JPMS), which was introduced in Java 9, changed the way applications are loaded and structured and enforced strict encapsulation [8]. Java 14–17 greatly increased the expressiveness of the language by introducing sealed classes, records, pattern matching, and improved switch expressions [9]. For large-scale applications, more recent garbage collectors such as G1GC and ZGC provide better memory management and shorter pause times [10].

Despite these advantages, switching from Java 8 presents serious compatibility issues, particularly in business settings. Applications need to be checked for build system updates, incompatible third-party libraries, and deprecated or removed APIs. For instance, to support newer language features, tools such as Maven and Gradle need plugin and configuration updates. Java version dependencies in frameworks like Spring and Jersey need to be properly handled [11]. Transitive dependency updates may unintentionally cause regressions, particularly when third-party libraries stop supporting older Java versions, according to the authors [12].

2.2. CI/CD in Enterprise Java

Pipelines for continuous delivery (CD) and continuous integration (CI) are essential for reducing the risks associated with migration. Jenkins' adaptability, plugin extensibility, and robust community support help it maintain its position as a leading CI/CD solution. Using tools like SonarQube and Checkstyle, it can integrate quality gates, run automated tests, and coordinate builds across various Java versions [13]. Because of this, Jenkins is especially well-suited to handling transitional states during modernization when applications depend on a variety of Java versions.

Not all enterprise contexts are prepared for containers, even though many companies use containerization tools like Docker and Kubernetes to separate and scale Java environments. Widespread adoption of containers may be impeded by resource limitations, security policies, or legacy system constraints. Although they require more setup work, Jenkins pipelines set up on virtual machines or bare-metal servers provide a good substitute in these situations [14].

2.3. CI/CD for Mixed Java Environments

There aren't many studies that specifically address CI/CD design for projects with mixed Java versions. In [15] the authors talk about the difficulties of replacing and deprecating APIs in enterprise codebases, while In [16] the authors investigate the modularization issues that arise when integrating JPMS into legacy Java systems. Nevertheless, rather than build automation, the focus of both studies is code-level migration.

Whitepapers and community discussions frequently suggest utilizing Jenkins agents set up with toolchains for Java 8 and Java 17 to isolate build jobs based on Java version. Teams can concurrently compile, test, and analyze applications in both environments thanks to these agents. Nevertheless, peer-reviewed literature hardly ever formalizes or documents this practice.

2.4. Gaps in Existing Research

Most of the literature currently in publication concentrates on either CI/CD automation or Java migration separately. Research that methodically examines CI/CD design patterns that support multiple Java versions is conspicuously lacking, especially in non-containerized enterprise settings. Furthermore, practical limitations like Jenkins integration with SAP-oriented libraries, legacy dependencies, or backward-compatible test automation are not considered in the current work.

To fill these gaps, this paper suggests a CI/CD pipeline architecture based on Jenkins that allows for mixed Java versions throughout the migration process. Without the need for container orchestration tools, the pipeline is made to manage a variety of build scenarios, execute parallel tests in various environments, and enforce quality and security standards.

3. Methodology

A thorough methodology for implementing enterprise-grade CI/CD pipelines for Java applications moving from Java 8 to Java 17 is presented in this section. The method is tailored for use in enterprise settings, especially those that are limited by legacy environments that do not support containerization. System audit and dependency mapping, environment setup, pipeline architecture design, testing validation, and iterative refinement are the five main stages of the methodology.

3.1. System Audit and Dependency Mapping

A comprehensive audit of the current Java application is the first stage in the modernization process. The following sub-activities are included in this:

- **Source Code Audit**: Review the codebase for instances of internal or proprietary Java API usage, look for deprecated or removed APIs, and evaluate modularity and test coverage. Java 8-specific constructs can be found with the help of tools like Java Migration Toolkit, jdeps, and jdeprscan.
- **Third-Party Library Assessment**: Many enterprise Java applications depend on third-party libraries, such as Hibernate, Jersey, ActiveMQ, OpenSAML, and Apache CXF. Maven Dependency Tree and OWASP Dependency-Check [17] are two tools that assist in determining compatibility with Java 17 and identifying outdated dependencies.

Components are classified as high, medium, or low risk according to their effect on enterprise reliability and Java 17 compatibility, as shown in Figure 1 and Table 1. Targeted planning and early mitigation of significant obstacles are made possible by this risk-based perspective.

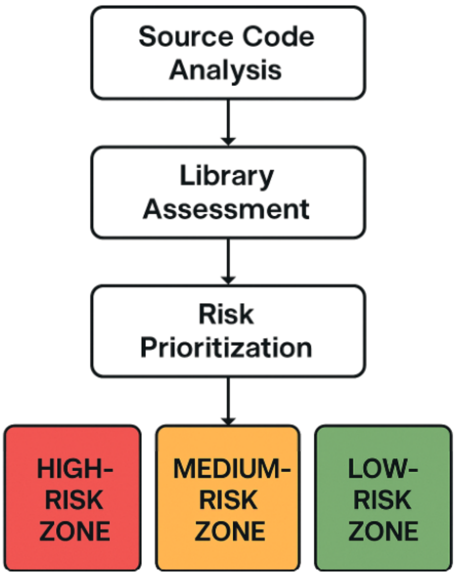

Figure 1: Dependency and Risk Classification Flow

Table 1: Risk Classification of Modernization Components

Component	Example Tools	Risk Level	Justification
Source Code Audit	jdeprscan,jdeps, Java Migration Toolkit	High	Deprecated APIs can break at runtime or compilation; internal APIs may be removed
	Internal Api's	High	These are unsupported and may no longer exist in Java 17
	Manual, Static analysis tools	Medium	Impacts ability to adopt JPMS and confidence in migration regression
Third-Party Libraries	OWASP Dependency-Check, Maven Dependency Tree	High	Namespace migration and unsupported Java EE APIs
	Manual, CVE database	High	Security-critical; old versions may not support Java 17
	OWASP Dependency-Check	Medium	May require log framework upgrades but core features work
	jdeps, Revapi	Medium	Works with Java 17 but requires tuning or module opens
	Maven Plugin, Dependency Tree	High	Transitive incompatibility can break builds silently

3.2. Environment Setup with Mixed Java Versions

Support for both Java 8 and Java 17 within the CI/CD pipeline becomes essential because full migration is usually not possible in a single step. Jenkins is a popular automation server that offers mechanisms for managing multiple JDKs and configuring toolchains.

- **Toolchain Configuration**: Multiple JDKs can be set up via Jenkins' global tools configuration. Java versions are mapped to various modules using Maven's toolchains.xml file.
- **Agent Isolation**: Jenkins agents are set up to classify builds by Java version, whether they are running on bare metal or virtual machines. This guarantees reproducibility and prevents environmental contamination.
- **Fallback Environment**: Virtual machines are used as a backup configuration in environments where containerization is not feasible because of security regulations or infrastructure constraints. Version-specific configurations and OS-level isolation are used to maintain these virtual machines.
- **Fallback Strategy:** In the event of breakdowns or incompatibilities, the pipeline has a fallback plan in place to guarantee continuation. Jenkins falls back to VM-based builds if Docker or Kubernetes are unavailable. With pinned dependency versions, these

virtual machines run separate Java 8 and Java 17 environments. This configuration lessens the effect of ecosystem shifts and maintains reproducible builds. Modules can continue to build and test on Java 8 when libraries or JDK features block migration, while others go on to Java 17. This enables incremental modernization and prevents release delays. In order avoid deployment conflicts and maintain traceability, all fallback builds are tagged by version.

This architecture supports gradual refactoring while maintaining legacy components by enabling dual version builds using isolated Jenkins agents and JDK toolchains, as shown in Figure 2.

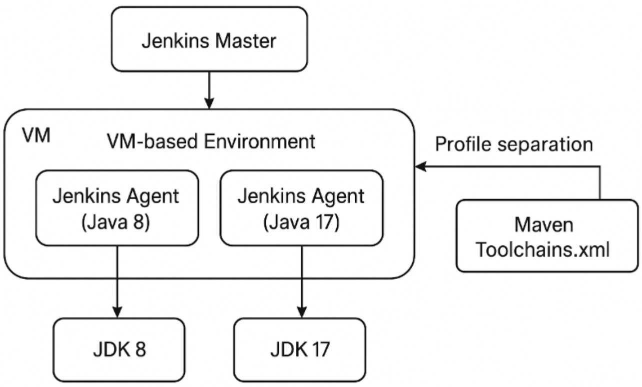

Figure 2: Jenkins Agent and JDK Isolation Architecture

3.3. Pipeline Architecture Design

Conditional branching and per-version customization are supported by the pipeline's modular design. The crucial pipeline phases are:

- **Build Stage**: Compatibility metadata determines which JDK is used to compile modules. Version-specific compilation flags are handled by Maven or Gradle profiles.
- **Test Stage**: Unit tests are executed using the appropriate JUnit versions: JUnit 5 for Java 17 code and JUnit 4 for legacy modules. Parallel job execution and tagging are used to achieve test segregation.
- **Static Code Analysis Stage**: There is integration of tools such as SonarQube, Checkstyle, and PMD [18]. Jenkins pipelines specify quality gates that enforce style compliance and coverage thresholds.
- **Security Scan Stage**: Each pipeline iteration is set up to run vulnerability scanners, OWASP Dependency-Check and enhanced SpotBugs [17]. Dashboards are updated with the scan reports so that developers can take appropriate action.

For traceability, each of these phases supports customized logging and result archiving. To ensure the consistency across jobs, Jenkins Shared Libraries are utilized. The overall Jenkins-based CI/CD pipeline, illustrating dual-version builds, parallel testing and integrated quality/security checks, is presented in Figure 3.

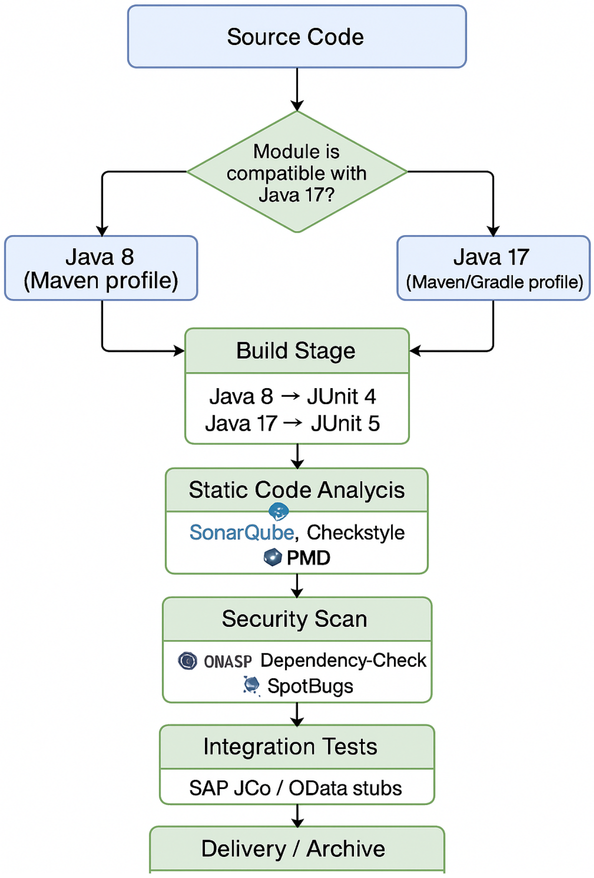

Figure 3: Jenkins CI/CD Pipeline Flow

3.4. Regression Testing and Validation

To make sure that modernization efforts don't introduce functional discrepancies, validation includes thorough regression testing:

- **Functional Tests**: To Verify feature parity run builds on both Java 8 and Java 17. Backward compatibility for end-user functions is guaranteed by regression testing.
- **Locale-Sensitive Validation**: Java 9+ replaces the Compact format with CLDR (Common Locale Data Repository). Locale-mocked test scenarios are used to validate locale-sensitive modules, such as financial reporting, sorting, and date formatting [19].
- **Performance Benchmarking**: Performance metrics like throughput, memory usage, and GC behavior are monitored and compared across Java versions using Java Microbenchmark Harness (JMH). Configurations of ZGC and G1GC are assessed under load.
- **Quality Gates**: If test coverage decreases or if new critical vulnerabilities are discovered, pipelines are set up to fail.

The JUnit plugin and SonarQube dashboards are used to publish test results to Jenkins so that all teams can see them.

3.5. Iterative Refinement and Risk Tracking

A feedback loop is essential to the pipeline design because dependencies, language features, and runtime behavior are always changing:

- **Build Feedback Analysis**: To find patterns and reoccurring problems, build failures are examined. Reports that are automatically generated assist in prioritizing issues pertaining to specific Java versions.
- **Change Logs and Tickets**: Every library upgrade or refactor has a Jira change ticket attached to it. Accordingly, risk scores are updated.
- **Monitoring Tooling Evolution**: Testing tools, JDKs, and Maven plugins are evolving continuously. Jenkins refers to plugin compatibility matrices and performs periodic updates [20].
- **Developer Feedback**: Developers and testers provide feedback during weekly retrospectives, which is then used for improvement of documentation, add validation scripts, and increase test coverage.

Enterprises can modernize Java applications with the least amount of risk and the most automation possible by using this flexible and traceable approach. Using Jenkins-based pipelines, the methodology guarantees that even non-containerized systems can safely migrate to Java 17.

3.6. Limitations of the Methodology

The suggested methodology has certain drawbacks even though it offers a structured and efficient way to manage Java version transitions in enterprise settings using Jenkins-based CI/CD pipelines:

- **Limited Scalability for Complex Polyglot Architectures:** Only Java-based systems are the focus of this methodology. This methodology does not address the additional tooling and coordination mechanisms needed by enterprises with polyglot environments (such as those involving Node.js, Python, or.NET components).
- **Manual Overhead in Risk Classification:** Manual evaluation, domain knowledge, and tool output interpretation are necessary for classifying components into high, medium, or low risk (as shown in Table 1). This procedure can be challenging and subjective, especially when dealing with large legacy codebases that lack adequate documentation.
- **No Support for Containerization:** Because of organizational limitations, the solution is designed for non-containerized environments. The advantages of container-based orchestration, isolation, and reproducibility through Docker/Kubernetes are thus not utilized. Future portability and cloud-native readiness may be limited by this.
- **Dependency Volatility and Ecosystem Lag:** The approach assumes that third-party libraries will eventually become compatible with Java 17. But some essential libraries (like outdated JAXB, OpenSAML, or proprietary SDKs) might not keep up, which could cause pipeline bottlenecks or require temporary forks and patches.
- **Initial Setup Complexity and Learning Curve:** Jenkins internals, Maven profiles, and CI orchestration must be understood to configure multi-version toolchains, Jenkins agents, shared libraries, and conditional pipelines. The initial time and resource commitment may be too much for smaller teams to handle.
- **Restricted Capability to Generalize Beyond Jenkins:** Despite its widespread use, the methodology takes Jenkins to be the CI/CD engine. It would be necessary to re-architect pipelines and modify plugin configurations to port the solution to GitLab CI, Azure DevOps, or GitHub Actions.

4. Results and Evaluation

An internal enterprise-grade Java application was chosen as a representative case study in order to validate the suggested methodology. Using the dual-version Jenkins pipeline outlined in Section 3, the system was gradually moved to Java 17 after being initially developed on Java 8 with Spring Boot 2.x and deployed on Apache Tomcat.

4.1. Performance Gains

The Java Microbenchmark Harness (JMH) was used to simulate production-like load conditions and gather performance benchmarks both before and after the migration. Table 2 provides a summary of the findings.

Table 2: Performance Metrics – Java 8 vs Java 17

Metric	Java 8	Java 17	Improvement
Application Startup Time	5.1 sec	3.5 sec	31% faster
Heap Memory Usage (avg)	480 MB	390 MB	19% less
GC Pause Time (99th perc.)	160 ms	44 ms	72.5% lower
API Throughput (req/sec)	920	1090	18.5% more

4.1.1. Key Observations

- **Application Startup Time**: Java 17's improvements in class data sharing, more effective classloading, and tiered compilation optimizations are largely responsible for the 31% decrease in startup latency. This is essential for microservices and CI/CD environments, where services are regularly restarted during builds or deployment.

- **Heap Memory Usage**: The average heap memory usage decreased by about 19% in Java 17. JIT compilation optimizations, enhanced object layout, and improved string deduplication are responsible for the smaller memory footprint. Additionally, modules that switched to Java 17 made use of features like records, which naturally lower memory usage by avoiding boilerplate code.
- **GC Pause Time**: A notable 72.5% decrease in GC pause time at the 99th percentile was observed when Java 17 switched from Parallel GC (default in Java 8) to G1GC and optional ZGC. This improvement enhances system responsiveness and user experience, particularly during periods of high load.
- **API Throughput**: Through faster method inlining, better garbage collection scheduling, and a decrease in blocking I/O latencies, REST API throughput increased by 18.5%. Profiling reports showed that Java 17 had less thread contention and fewer full-GC invocations.

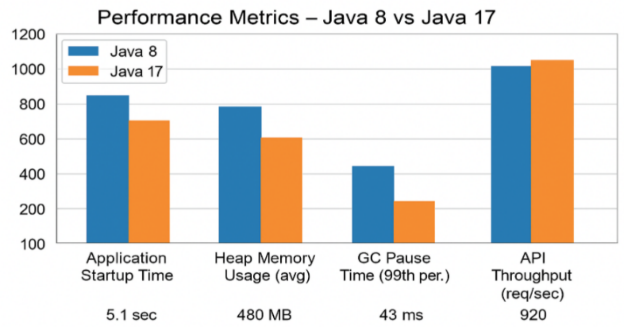

Figure 3: Comparative Performance Benchmark – Java 8 vs Java 17

Figure 3, which contrasts the performance of Java 8 and Java 17 across important metrics, provides a visual summary of these numerical gains.

4.2. Functional Stability

When modernizing enterprise applications, functional stability is a crucial component of success, especially for systems that incorporate internationalization features and are integrated with SAP backends. A thorough regression testing cycle was carried out following the migration from Java 8 to Java 17 to verify compliance, prevent feature regressions, and guarantee backward compatibility.

Jenkins-driven test suites were used to run more than 2,000 automated tests in both environments. The core modules that were tested included:

- **REST API response validation**: Ensuring that identical requests executed with the Java 8 and Java 17 runtimes yield consistent endpoint outputs.
- **Locale-sensitive UI components**: Verifying that dates, currencies, and sorting are rendered correctly across various locale configurations.

The move to CLDR (Common Locale Data Repository) in Java 9+, which was made the default source for locale data in Java 17, presented a significant validation challenge. Dates, currencies, and casing were handled differently because of this modification, especially in UI validation tests. To address these problems and guarantee alignment with user expectations and business requirements, test normalization scripts were added to account for locale-sensitive output variations.

Table 3: Regression Test Summary

Category	Java 8 Pass Rate	Java 17 Pass Rate	Observations
Unit Tests	100%	100%	Fully compatible; no syntax or logic regressions
Integration Tests	98.3%	98.5%	Stable JCo and OData behavior maintained
UI Validation	97.1%	96.8%	Minor locale-related discrepancies resolved

4.2.1. Key Observations

- **Unit Tests**: In both environments, complete compatibility was achieved without any issues. Better test hygiene resulted from the enhanced compiler diagnostics in Java 17.
- **Integration Tests**: Java 17 observed minor enhancements because of improved thread management and quicker request processing.
- **UI Validation**: A closer look showed that the slightly lower initial pass rate in Java 17 was caused by locale format mismatches (e.g., differences in currency symbols, date separators). The behavior was in line with Java 8 outputs after normalization layers were applied. Rendering and frontend logic were found to be flawless.

These findings show that a smooth upgrade to Java 17 without sacrificing functional reliability is possible with a carefully thought-out CI/CD pipeline that includes isolated environments and automated regression validation.

4.3. Code Quality and Security

The switch to Java 17 offered an opportunity to enhance the security posture and overall code quality in addition to updating the runtime environment. As part of the CI/CD pipeline, automated static analysis and focused dependency remediation were used to achieve this.

SonarQube, SpotBugs, Checkstyle, and OWASP Dependency-Check were among the tools used for performing static analysis. To guarantee that each build was assessed against to an extensive collection of quality and security metrics, these tools were directly incorporated into the Jenkins pipeline.

4.3.1. Key Focus Areas

- Identification and removal of excessively complicated structures and code smells.
- Evaluation of test coverage patterns as new features and modules were added during modernization.
- Libraries with known CVEs (Common Vulnerabilities and Exposures) can be identified through dependency risk scanning.
- Refactoring of outdated or deprecated APIs and removal of error-prone legacy patterns.

Table 4: Code Quality Comparison

Metric	Java 8	Java 17	Change
Code Smells	137	44	-67.8%
Critical CVEs	4	0	-100%
Test Coverage	89.6%	93.2%	+3.6%

4.3.2. Key Observations

- **Code Smells**: After switching to Java 17, a 67.8% decrease in code smells was noted. The introduction of modern language features like records, sealed classes, and switch expressions, which decreased boilerplate and enhanced code clarity, is primarily responsible for this. For example, concise record declarations were used in place of data-carrying POJOs, improving readability and maintainability.
- **Critical CVEs**: Four unfixed CVEs were present in the codebase prior to the migration, two of which were associated with Log4j 1.x and two of which were caused by earlier iterations of OpenSAML. These vulnerable libraries were either patched or swapped out for maintained alternatives as part of the upgrade process. All critical CVEs were fixed by utilizing libraries compatible with Java 17 and conducting transitive dependency audits with OWASP Dependency-Check.
- **Test Coverage**: Test coverage increased by 3.6% as a result of the modernization process. To ensure compatibility, new unit tests were developed for refactored modules, particularly those updated to use modern APIs. Furthermore, parameterized and dynamic tests were made possible by the adoption of JUnit 5, which increased testing depth and decreased redundancy.

4.4. Developer Experience

In addition to technical metrics, developer experience—which is crucial for long-term maintainability and productivity in enterprise environments—was used to evaluate the migration process and the updated CI/CD pipeline.

Twelve developers who actively took part in the modernization effort were surveyed to gather information on this dimension. The survey covered topics like collaboration efficiency, language and tooling preferences, and pipeline usability.

Table 5: Survey Highlights

Question	Agreement (%)
The CI/CD pipeline was easy to use and clearly separated Java versions.	83%
Java 17 features improved code readability and developer productivity.	91%
Shared Jenkins libraries reduced duplication and improved maintainability.	100%

4.4.1. Key Observations

- **Intuitive and Version-Isolated Pipeline**: The modular Jenkins pipeline, which distinguished between Java 8 and Java 17 build/test lanes, was well-received by developers. Teams were able to work on modernization gradually without interfering with legacy behavior due to this version isolation, which also guaranteed confidence during refactoring.
- **Java 17 Developer Ergonomics**: Because of its improved language features—like records, sealed classes, pattern matching, and better switch expressions—Java 17 was strongly preferred. Developers identified improved IDE code assistance (particularly in IntelliJ IDEA ≥ 2021.2), less boilerplate, and cleaner business logic as critical elements. Records made it easier to create domain models and DTOs, which reduced cognitive load and saved time.
- **Impact of Shared Libraries in Jenkins**: Pipeline maintenance effort was significantly reduced as a result of the implementation of Jenkins Shared Libraries. Several modules shared common stages (build, test, scan, and report) that were codified once. Developers observed fewer configuration bugs, consistent error handling, and quicker onboarding of new team members. Additionally, this method made

pipeline-as-code governance possible, guaranteeing adherence to enterprise build guidelines.

5. Discussion

Even in environments without Docker/Kubernetes, the migration strategy confirmed that enterprise Java version transitions could be managed with CI/CD. Important observations are covered below.

5.1. Risk-Driven Planning

As previously mentioned in Table 1, the implementation of risk-based classification was a key component of the migration's success. Each component of the modernization process was evaluated for potential impact, complexity, and criticality to production workflows rather than being treated as a single, homogenous task. Phased, parallelized workstreams and better resource allocation were made possible by this detailed assessment. The following were the main results of the risk-driven planning approach:

- **Early Mitigation of Critical Issues**: OpenSAML and other high-risk elements were handled up front. Because the XML parsing logic was closely linked with Java 8 internals and older versions of OpenSAML had CVEs that made them incompatible with more recent JDKs, there were both technical and security issues. The team reduced downstream disruptions and increased trust in the upgraded security stack by separating and upgrading these early.
- **Parallel Execution of Lower-Risk Tasks**: Parallel updates were made to components that were considered medium or low risk, including Hibernate, logging frameworks, and certain utility libraries. As a result, the team was able to advance steadily without delaying important migration milestones. Hibernate modules frequently only needed small configuration adjustments to function with Java 17, freeing up developers to focus on high-impact projects.
- **Reduced Integration Failures**: Because of unanticipated interdependencies and untested scenarios, traditional "big bang" upgrades frequently result in integration bottlenecks. On the other hand, developers were able to test integrations iteratively, especially around API gateways, by tackling the riskiest components first. This prevented last-minute regressions.
- **Effective Communication and Planning**: Project managers and QA teams, among other stakeholders, could easily understand the scope and difficulties of the migration because of risk classification. Prioritizing testing and planning concentrated sprints around high-severity modules were done using the classification.
- **Improved Developer Morale and Confidence**: When changes were divided into smaller, risk-bounded increments, developers expressed greater confidence. Because there was significantly less perceived uncertainty surrounding migration, there were fewer rollbacks and an increase in sprint velocity.

5.2. Dual-Version Pipelines Are Sustainable

Implementing a dual-version Jenkins pipeline that supported both Java 8 and Java 17 environments simultaneously was one of the most significant architectural decisions made during the modernization. This method allowed for progressive migration, lowering risk and guaranteeing business continuity, as opposed to imposing a full and instantaneous upgrade, which is rarely possible in highly integrated enterprise systems.

5.3. Key Benefits and Observations:

- **Concurrent Support for Legacy and Modern Code**: Maven toolchains.xml enabled the build system to choose the proper Java version for each module, and Jenkins agents were set up with separate JDK installations. This allowed teams to gradually introduce Java 17 features in new or refactored code while maintaining and improving existing Java 8 modules. Crucially, this dual support made maintenance easier by eliminating the need for distinct repositories and branching techniques.
- **Non-Disruptive Deprecation of Java 8 Components**: Older components could be safely and gradually deprecated with backward-compatible tests and build logic. Until their Java 17 counterparts were thoroughly examined and verified, legacy modules continued to be used in production. The "all-or-nothing" upgrade constraint that can paralyze development teams—particularly in high-risk enterprise environments like those integrating with SAML-based identity systems—was avoided as a result.
- **Shared Library Reusability and Maintainability**: Jenkins Shared Libraries were essential for enforcing pipeline consistency and cutting down on redundancy. Reusability across Java 8 and Java 17 jobs was made possible by the abstraction of stages like static code analysis, security scanning, and artifact archiving into shared functions. Repetitive edits across dozens of pipelines were eliminated when logic updates (such as moving from Checkstyle 8 to 10 or improving OWASP rules) were distributed centrally.
- **Sustainability Over Multiple Release Cycles**: Over six production release cycles (about nine months) with the dual-version setup in place, the team saw no regressions caused by the pipeline or build failures because of version conflicts. Indicating that the

architecture was not only stable but also able to accommodate gradual enhancements over time, test coverage and code quality metrics also showed consistent improvement during this time.

- **Enhanced Developer Experience**: Without changing the environment, developers could build and test in the Java version of their choice. While backward compatibility made sure legacy teams continued to be productive, tooling support (such as IntelliJ IDEA's Java 17 features and static analyzers) promoted early adoption. Teams working on modernization and legacy maintenance were able to collaborate more easily thanks to this flexibility.

6. Conclusion and Future Work

6.1. Conclusion

Enterprise Java applications moving from Java 8 to Java 17 using Jenkins-based CI/CD pipelines in environments without container orchestration platforms like Docker or Kubernetes can be supported by the risk-driven, automation-centric framework this study presented. Maintainability, incremental risk mitigation, and developer empowerment were given top priority in this methodology because it acknowledged that many enterprise systems—operate under stringent infrastructure constraints.

System audit, pipeline architecture design, dual-environment setup, regression and performance validation, and iterative refinement were the five main stages of the suggested methodology. Production stability was maintained while a gradual migration was made possible by this methodical approach.

6.2. Key conclusions drawn from the implementation include

- Technically and operationally, dual-version pipelines are feasible. Java 8 and Java 17 components could be supported simultaneously because of the Jenkins configuration with toolchain isolation. This made it possible to test and develop in parallel, easing the burden on development teams and preventing disruptive, all-at-once upgrades.
- Targeted static analysis tools and compatibility testing were used to successfully upgrade high-risk components, especially OpenSAML and transitive dependencies with known vulnerabilities. Reducing last-minute failures was greatly aided by early risk classification (Table 1, Figure 1).
- Java 17 offered tangible technical benefits, including:
  - 31% faster application startup
  - The average memory footprint is reduced by 19%.
  - Reduced GC pause times by 72.5%
  - An increase in API throughput of about 18.5%, JVM enhancements, modern language features, and better memory management techniques included in newer Java releases (e.g., G1GC, ZGC) enabled these improvements.
- Developer satisfaction and productivity increased significantly. When asked why they preferred Java 17, developers pointed to improved IDE support, the expressive potential of new features like records and pattern matching, and less boilerplate. Additionally, Jenkins Shared Libraries enhanced maintainability across several repositories and reduced duplication.
- Improved security posture: After migration, all known critical CVEs (such as legacy Log4j vulnerabilities) were fixed, and code smells were decreased by almost 70%. Test coverage increased from 89.6% to 93.2%, indicating that modernization is crucial for maintainability and risk mitigation in addition to performance.

The study concludes by offering enterprises a scalable, risk-aware roadmap for updating modern Java versions while navigating difficulties of mixed-version dependencies and legacy infrastructure. It demonstrates how modern CI/CD techniques can speed up digital modernization without compromising system integrity, even in traditional environments.

6.3. Future Work

Although this study offers a solid basis, there are still a number of directions for further investigation:

- **Enhancements to Tooling Automation:** Including AI-powered recommendation engines (like OpenRewrite and Revapi analyzers) to automatically identify or refactor code that is incompatible while conducting audits.
- **Multi-Language Integration**: Expanding the pipeline to handle hybrid applications that combine Java with Kotlin, Scala, or Groovy and determining compatibility under Java 17
- **Legacy API Adaptation Layer**: Designing reusable shims or compatibility wrappers for deprecated or removed APIs, particularly for organizations that cannot yet eliminate legacy modules.
- **Performance Monitoring in Production**: Utilizing tools like Java Flight Recorder (JFR), Prometheus, or Dynatrace to extend benchmarking beyond JMH-based lab tests to continuous profiling in production environments.
- **Longitudinal Migration Studies**: Measuring long-term cost savings, technical debt reduction, and velocity improvements by collecting migration metrics across several release cycles or departments.

- **Container Readiness Roadmap**: A future extension might specify a phased plan to advance such CI/CD pipelines toward container-based deployments using Docker, Kubernetes, or SAP BTP, even though this study focused on non-containerized systems.

Organizations can further optimize their modernization journeys, lower operational risk, and prepare for future Java LTS releases by focusing on these future directions.

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Blending Bio Inspired Algorithm and Cross Layering for Optimal Route in MANETS; 6G Scenario

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ABSTRACT: In order to find the best path in 6G scenario, this paper suggests a directional routing approach for Mobile Ad hoc NETworks (MANETs) that investigates clubbing of updated Tunicate Swarm Algorithm (TSA), an updated intensification technique inspired by biology and Cross Layer Interaction (CLI). To address its previous shortcoming of trapping into local optima, updated TSA, which replicates the jet impulse and swarm actions of tunicates, has been modified. Through the use of CLI, the network density parameter is transferred between layers. In the the medium access protocol of directional antenna enabled MANETs, it is suggested that the directional monitoring time, optional handshake, and data fragment length be changed to lessen load on the routing protocol. Simulation results demonstrate that, when compared to competing proposals, Bio inspired algorithm and Cross layering blending-based routing approaches in MANETs yield better results.

KEYWORDS: MANET, Routing, PSO, ACO, Cross Layer, MAC.

1. Introduction

An ad hoc network is a kind of wireless network that is portable, allows for unrestricted mobility, and links devices of the same status on the network. In addition to functioning as relays and being in charge of effectively managing and structuring the network, the nodes are permitted to chain neighboring nodes as long as they are within their range. Numerous vision-based applications across numerous industries have been spawned by the advantages of ad hoc networks, including their mobility, adjustability, robustness, and in-coherence. Based on their intended use, wireless ad hoc networks are divided into three clubs: Vehicular Ad hoc NETworks (VANETs), which uses operating vehicles to build a network; Wireless Sensor Networks (WSNs), which uses separate sensors to control environmental parameters; and Mobile Ad-hoc NETworks (MANETs), which primarily consists of personal digital assistances [1].

This probe improves non-linear artificial problems using a modified Tunicate Swarm Algorithm (TSA), a metahiuristic algorithm that takes inspiration from nature. The swarm behavior of tunicates, which live in the deep ocean, served as the model. TSA provides an incentive to find solutions for MANET concerns. The following are some of the exceptional social nature of MANETs that can be effectively resolved by employing a metaheuristic approach. The existence of multiple node linking options, the establishment of node collaboration, A backup method for broken links, the self-association nature of the network and Spontaneous and healthy variation to address topology and traffic disturbances.

This probe has the following noteworthy additions:

- Network Density (ND) is measured from the network layer.
- Stable routes are established through enhanced bio-inspired TSA.
- To ensure flexibility or adaptation, Cross Layer Interaction (CLI) is used to pass the Network Density (ND) parameter.

As described below, this paper is standardized as follows. In the second section, we introduce basics of directional communication, CLI, other bio-inspired algorithms and TSA. Directional Monitoring concept used in Directional Medium Access Control (DMAC) and method to calculate ND are also summed in second section. Third section advocates the proposed routing protocol approach. The last section describes the simulation environment and highlights results followed by conclusion and possible future work.

2. Directional Communication, Concepts of Cross Layering, Bio-inspired algorithm and Adaptive Directional Monitoring

For the communication between nodes on a MANET, the Medium Access Control (MAC) layer of the MANETs previously preferred omni-directional antennas due to cost constraints and relies on a best-effort approach for the delivery of data packets. However, when Smart Antenna (SA) technology providing directional transmit or communication is used in MANETs in contrast to the traditional omni-directional antennas, the use of wireless media is greatly improved at the expense of problems such as directional hidden terminals caused by the lack of information on the channel status during antenna orientation of the node. An appropriate, agile MAC protocol is necessary to exploit the advantages of directional antenna.

Once DATA-frame fragmentations and short busy advertisement signals are able to communicate the communication situation to the directional hidden nodes of MANETs, the MAC protocol for MANETs with agile directional antennas will be able to overcome the directional hidden-node problem. By choosing the right fragment number and adaptively adjusting the data-fragment length, it can therefore decrease the frame collisions caused by the directional hidden nodes and boost the network throughput in comparison to the traditional protocol. To address the hidden terminal issues, directional beams are sent with the data fragments and Acknowledgments (ACK) to be sent. This allows for directional node monitoring. There won't be a directional hidden node issue because directional monitoring allows every node to be aware of the receiver condition during the Directional Monitoring Period (DMP). Additionally, the DMP period can be adjusted to improve the routing protocol's overall performance.

Layered design is assumed by a significant portion of the suggested routing protocols in MANETs. Because each layer-specific protocol designs only takes into account interaction with its neighboring layers, this design approach is extremely rigid and non-adaptive. Setting up meaningful interactions between different layers using the Cross Layering approach is important in recent protocol design approaches for MANETs in order to improve performance. Cross layer interaction between the physical, MAC, and routing layers is commonly used in cross-layering-based new protocols for MANETs in order to reduce protocol overhead and prevent collisions during data transmission. When social water particles are used to find and maintain high connectivity paths in unstable MANETs, routing protocols with lower end-to-end delay and route discovery latency are created. Concept of collective behavior in the updated Tunicate algorithm, where each person acts independently but nevertheless produces intended output.

In MANETs, CLI and biological process-based routing protocols show promise as against traditional methods for determining the globally optimal path. Theoretically and practically substitutes, these routes are also found to be Quality of Service (QoS) aware and fault tolerant [2]. The detailed abbreviations and definitions used in the paper are listed in Table 1.

Table 1: Abbreviations and their definitions

Acronym	Definition	Acronym	Definition
ACO	Ant Colony Optimization	CLI	Cross Layer Interaction
CBR	Constant Bit Rate	DMAC	Directional Medium Access Control
DMP	Directional Monitoring Period	MAC	Medium Access Control
MANETs	Mobile Ad-hoc NETworks	ND	Network Density
PSO	Particle Swarm Optimization	SA	Smart Antenna
QoS	Quality of Service	TCDMAC	TSA and CLI enabled Directional MAC Protocol
TCDRP	TSA and CLI enabled Directional Routing Protocol	VANETs	Vehicular Ad hoc NETworks
TSA	Tunicate Swarm Algorithm	WSNs	Wireless Sensor Networks

2.1. Cross Layering

In many MANET applications, the CLI design approach which emphasizes communication between multiple layers has proven to be a workable solution. It enables dynamic adaptation and fine tuning of protocol constraints during the blueprint phase, ideally allocating important data during run-time. The benefits of a CLI enabled MANET include planning conventions that adapt network conditions and supporting applications with constant, universal access to resources and control requirements. Dynamic network structure brought on by node movement raises the possibility of severing a connection with a neighbor, but neighbor, but it also raises the possibility of finding a quicker route to the target node in the event of group mobility [3]. In order to create adaptive protocols, the status of network's current information will now be stored in the network stack across various layers. Data streams between different layers of the protocol stack are needed for connections between them. The CLI approach in MANETs is motivated by [4]:

1. Protocol overhead, security, topology control, and QoS are among the issues in MANETs that require the active participation of multiple layers.
2. MANETs can be used for more applications if multiple protocol stack layers are aware of the channel status, congestion level and traffic density.
3. The protocols ought to be flexible and adaptable to the needs of MANET applications.
4. Adjusting the protocol's parameters in proportion to the current network state improves the network protocol's agile property.

2.2. Bio-inspired algorithms

Swarm intelligence, which comes from a computational intelligence approach, is used to solve a number of complex optimization problems. Researchers are especially fond of algorithms that draw inspiration from biology and recommend few parameter changes in these algorithms. Two well-liked algorithms in this field for global optimization problems are Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) [5]. These algorithms are made to mimic the collective behavior of ant colony and fish schools or flocks of birds, where each particle roams around a designated search area and updates its current state in relation to the global value until a satisfactory solution is found [6]. The behavior of MANETs, which results from the redundant local collaboration of individual specialists with peers as well as their environmental factors, has been extensively studied using population-based methods or techniques such as ACO and PSO.

When artificial ants in ACO mimic the foraging behavior of real ants, complex combinatorial streamlining problems are resolved to a higher fulfillment level. During their search, real ants leave pheromones on the ground, and these pheromones cause abnormal correspondences between ants. Pheromone path update and pheromone path vanishing rate are the administrators used in ACO. By accurately simulating the scrounging behavior, MANETs plan the computations using these administrators and the ACO control boundaries.

If ACO ant agents are used, routing in MANETs is designed with a lower end-to-end delay and a lower route discovery delay. If ACO-based algorithms are used in routing, energy awareness, route discovery, and maintenance of high connectivity paths are developed, which extends the MANETs lifespan. Additionally, MANET routing protocols based on the ACO algorithm can achieve higher performance at low routing overhead with fluctuating node counts, data volumes, and node movement.

AntNet [7], Hybrid ACO [8], AntHocNet [9], ACO-enabled routing in MANETs [10], On-demand distance vector ACO algorithm [11], ACO-based routing [12], ACO with QoS [13-14], a new version of the self-organized algorithm (EARA) [15], Enhanced with QoS [16], BeeAdHoc [17], an energy-efficient routing protocol, and energy-aware AOMDV (EA-AOMDV) [18] are a few examples of bio-inspired routing protocols that have been documented in the literature.

The social interaction of water particles is the focus of the efficiency adaptation technique known as PSO. Using this method, the initial number of particles is distributed throughout the solution space S. Each particle in S moves at a different speed. The gross population and each fragment (specific ideal) converge at the best price (overall ideal). After each cycle, the fragment modifies its level in accordance with the overall and specific ideal ratings.

There is always the question of whether more optimization algorithms are needed given the vast array of optimization techniques available. Its solution is the No Free Lunch (NFL) theorem, which states that due to the complexity and unique nature of each problem, a single intensification technique is insufficient for all of them [19]. Researchers are motivated by the NFL hypothesis to develop novel optimization strategies that can tackle a variety of problems.

2.2.1. Bio- Tunicate Swarm Intelligence

Tunicates are able to locate food sources within the ocean. The optimal food source is chosen in this work based on two tunicate traits. Two examples of these characteristics are jet momentum and swarm intellect. To mathematically express jet propulsion habits, tunicates must meet three requirements; avoid collisions with other search agents, move in the direction of the ideal location, and remain near the ideal search agents. Other search agents will stay informed about the best possible solution thanks to the swarm nature.

The ideal initial solutions will be replicated and other search agent's positions will be improved to match the ideal search agents' locations in order to mathematically simulate tunicate's swarm actions. The swarm intellect of tunicate is interpreted using the formula below.

$$Pp\,(x^{\rightarrow}+1) = [Pp^{\rightarrow}(x) + Pp(x^{\rightarrow}+1)]/(2 + C1) \quad (1)$$

where variable C1, *is* random number and the vector $Pp^{\rightarrow}(x)$ represents the location of tunicate.

The proposed modified TSA algorithm is as follows and flowchart is depicted as in figure 1.

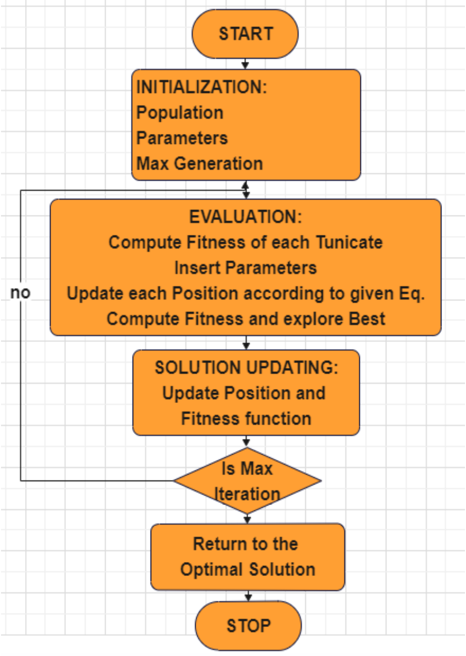

Figure 1: Proposed ETSA flowchart.

Algorithm 1: Modified TSA algorithm
Result: Optimal route
Step 1: Phase of Pre-requisite: The crowd of tunicates in a particular search area is started at random. Additionally, the algorithm's initial values, population size, and generation threshold limit (t) are assigned. **Step 2**: Phase of Estimation: According to the specified fitness function, each tunicate is estimated. **Step 3**: Phase of Refinement: Every location in the search formula relates to an active step; if it yields better results than the previous one, it is ideal. In this case, the searching space's limiting boundaries are dynamically altered. **Step 4**: Phase of Re-condition: Eq. (1) is used to update the tunicate crowd. To carry out the exploration capability, every area of the search space is taken into consideration. To fine tune the optimal solution, the fitness function of each tunicate is computed. **Step 5**: Iterations: Second step to fourth step repeated till the condition of termination is reached.

The maximum area of the search region is taken into account when executing exploration ability using (1). The suggested algorithm can increase exploitation capability by taking advantage of missing regions using (2) [20]. In order to prevent local optima trapping, a balance between exploration and exploitation is thus achieved.

$$\text{P pop}(t+1) = \text{P pop}(t) \pm \text{rand}^{t} \times (\propto |2) \quad (2)$$

where α is a dynamic step that shrinks as the optimization process continues to focus local searching.

2.3. Adaptive Directional Monitoring

The well-known hidden node problem is avoided by the method of directionally checking the receiver's condition prior to data transmission from the sender node [21]. The directional hidden terminal issue is largely resolved when DMP is integrated into the medium access strategy. RTS/CTS transmission followed by DATA/ACK transmission is the process used in DMP-enabled MAC to to establish mutual consent between source and destination. However, some problems still occur when using the MAC approach with a fixed DMP value. While hidden terminal issues cannot be prevented for smaller or marginal DMP values, the protocol incurs additional overhead for very large DMP values. As a result, DMP becomes adaptive; its value corresponds to the size of the packets that need to be sent. The initial value for DMP is decided after a number of test flows in different types of topologies are completed.

Therefore, adaptation of DMP value is as follows:

1. For transmission of shorter routing packet at Sender node, DMP will be decreased using λ, Now: New DMP = DMP - λ
2. For transmission of longer routing packet at Sender node, DMP will be enhanced using δ, Now: New DMP= DMP+ δ

2.4. Calculating Network Density

To determine the calculation of ND, solutions to network problems utilizing physics concepts are examined. To compute the ND, the following equation is suggested [22];

$$\mu = \frac{(N\pi R^2)}{A} \quad (3)$$

In this case, N stands for the number of nodes in locality A, and R. represents the transmission range. A more accurate formula defines the ND as follows [23];

$$d(r) = \lim_{|A|\rightarrow 0} \frac{N(A)}{|A|} \quad (4)$$

Here: Nodes per m^2 is the unit to describe node density.

The ND calculation makes the assumption that it is a particular quantity that is limited to a certain area and depends on the transmission range. Other factors (like mobility, obstacles, etc.) are not included in the ND calculation and could affect the calculation of connected nodes.

3. Proposed Routing and Medium Access Approaches

Flexible planning rules that adjust to shifting network conditions and give applications reliable control over important resources and their administration are advantageous to CLI-enabled MANETs. The proposed method is based on a modified searching technique that replicates jet impulse and swarm conduct in order to improve TSA's exploration and exploitation issues.

A new directional routing technique, the Tunicate swarm algorithm and Cross layer integration enabled Directional Routing Protocol (TCDRP), is proposed with the help of enabling 6G technologies. To determine its benefits, TCDRP is contrasted with benchmark and the most recent directional routing approach-based protocols. TCDRP is designed to take full advantage of blending updated Tunicate swarm algorithm and Cross layer interaction enabled Directional Medium Access Protocol [TCDMAC]. Figure 2 displays a block diagram of the TSA and Cross layering-based routing approach.

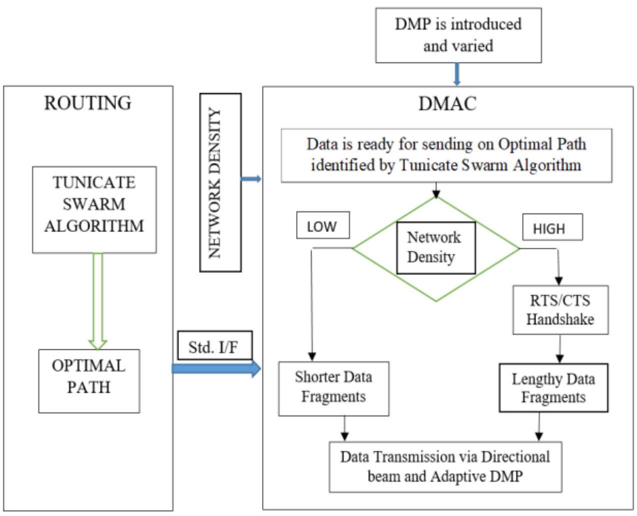

Figure 2: Block diagram of TSA and Cross layer-based routing approach

Actions taken in TC and TCDRP are as below:

3.1. Steps in TCDRP Approach

Step 1 Examine every possible route from the sender to the destination in the input set.

Step 2. As tunicate particles, chart these identified paths.

Step 3. Modified TSA is used to determine the best route.

Step 4. The source node sends the desired data to target node via the TCDMAC protocol using the nodes found on the optimal path.

3.2. Steps in TCDMAC Approach

Step 1. TCDRP first determines which path offers the best route for data transmission.

Step 2. To determine the network's condition, estimate the parameter ND.

Step 3. Verify that the value of ND has reached its threshold

Once the data is ready to be sent;

if (YES) send data with RTS/CTS handshake; Send lengthy data fragments

else send data without RTS/CTS handshake; Send shorter data fragments (to reduce overhead)

Step 4. Data packets are converted into data fragments. The length of the data fragment is proportional to the estimated ND. Use IFDS to transmit continuously.

Step 5. Directional antennas are used to transmit data fragments.

Step 6. It makes use of adaptive DMP.

Step 7. Retransmit the data if there is transmission error.

4. Simulation Results and Discussion

Network Simulator (NS2) is recommended to validate the suggested method [24]. Nodes are permitted to move within a designated simulation area of 1.3 kilo sq m for a time period of 50 seconds. Each node with simulation traffic of Constant Bit Rate (CBR) has a 250-meter transmission capability. Table 2 shows the specifics of the simulation environment along with a few important parameters. Iterative simulations are conducted, and performance matrices are plotted using average values.

Table 2: Specifications of the simulation environment.

Nodes in simulation setup	In steps of 20 from 20 to 100
Applied simulation area	1.300 X 1.300 square KMs
Medium Access protocol	IEEE 802.11
Transmission distance	250m
Time period of simulation	50 sec
Origin of Traffic	CBR
Identified size of packet	512
Packet transfer rate	In steps of 50 (50 to250kbps)
Architectures of Network	Non-Linear
Propagation scheme	Two Ray Ground
Antenna mode	Omni/Dir Antenna
Count of directions	4
Modulation	BPSK

4.1. Performance Metrics

To judge the total performance gain, the suggested TCDRP approach is contrasted with the fundamental directional routing approach DRP [25]. In order to observe improvements over the most recent routing protocol, CEELBRP, non-linear network topology is used, which varies the number of nodes and traffic rates as well as execution metrics [26]. The following metrics are considered in the suggested method's performance.

The number of packets that did not reach their intended destination during their journey from source to destination nodes is indicated by the packet delivery ratio. It is computed by dividing the number of packets sent by the sender by the number of packets received at the recipient.

- Packet Drop: Described in terms of average packet drops, this is a sign of either poor service or erratic network connectivity.
- Throughput: Throughput is the rate at which information is sent over the network being tested.
- Delay: This summative term takes into account four distinct elements and measures how long it takes for nodes to send the allocated data packets.

4.2. Based on number of nodes

The TCDRP approach improves performance by using a modified TSA to determine the best path and a Cross layer enabled and ND-aware TCDMAC protocol to transmit data. The packet delivery ratio for TCDRP, CEELBRP, and DRP in relation to non-linear topology with node addition is shown in Figure 3. Comparative Summary of Nodes Vs. delivery ratio when nodes are added to the system in Figure 4. The delivery ratio in all three protocols drops linearly. The TCDMAC technique, which operates at the medium access layer beneath TCDRP, makes use of the ND information that is accessible across the network stack to provide flexibility in the route initiation procedure. The medium access mechanism also modifies frame length to accomplish adaptation (a collection of bits is bundled into frames of varying length with respect to ND). To attain a comparatively higher packet delivery ratio, adaptive DMP is utilized in conjunction with directional beam data transmission. As a result, in terms of delivery ratio, the TCDRP performs better than the DRP and has slight advantages over the CEELBRP.

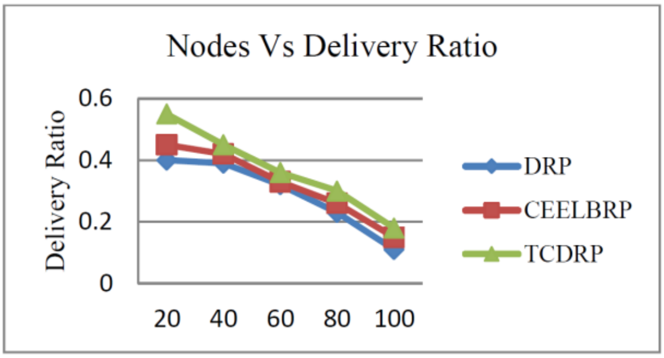

Figure 3: Graph of changing nodes and corresponding delivery ratio

The throughput achieved in the TCDRP, CEELBRP, and DRP for the non-linear topology when numbers of nodes in the simulations are changed is displayed in Figures 5 and 6. As the number of nodes in the system increases, all three protocols exhibit a trend towards decreased throughput. The TCDR's average throughput is 21% higher than the CEELBRP's and 48% higher than the DRP's.

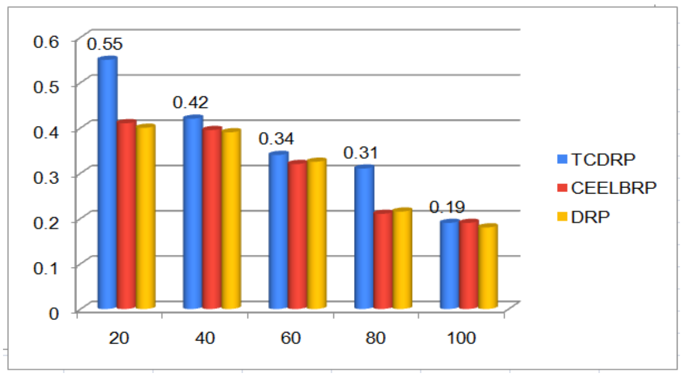

Figure 4: Bar chart of changing nodes and corresponding delivery ratio

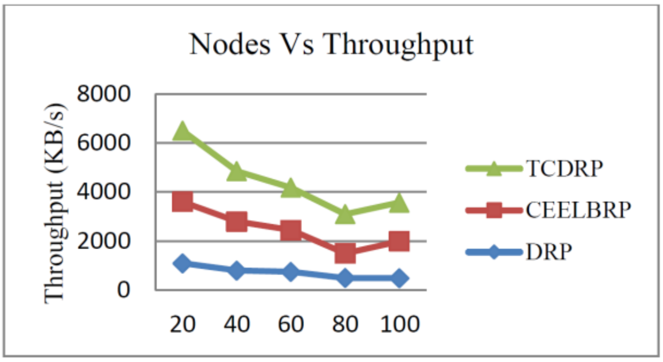

Figure 5: Graph of changing nodes and corresponding throughput

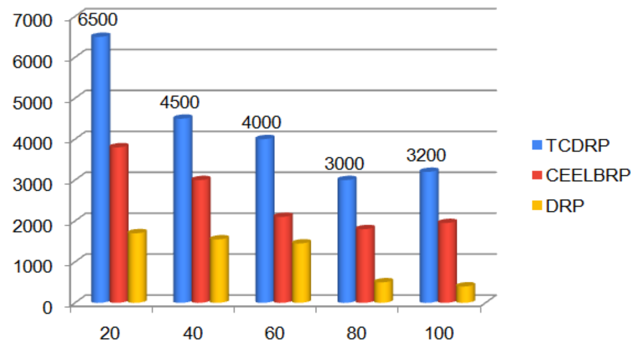

Figure 6: Bar chart of changing nodes and corresponding throughput

4.3. Based on Traffic Rates

The performance of suggested method is checked at various traffic rates, traffic flow is set as 50, 100, 150, 200 and 250 Kbps for allotted 100 nodes in the non-linear topology.

The delivery ratio of packets in the TCDRP, CEELBRP, and DRP for the non-linear topology where the traffic rate is altered is as shown in Figures 7 and 8. Delivery ratios for all tested protocols show a linear decline with increasing traffic rates. The TCDRP's average delivery ratio value is 12% higher than the CEELBRP's and 18% higher than the DRP's.

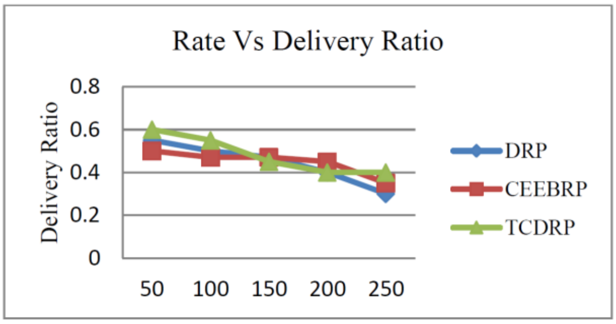

Figure 7: Graph of changing transmission rate and corresponding delivery ratio

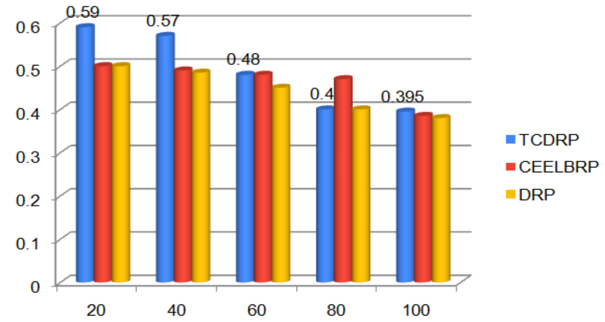

Figure 8: Bar chart changing transmission rate and corresponding delivery ratio

The throughput of the TCDRP, CEELBRP, and DRP for different traffic rates is displayed in Figures 9 and 10. In order to increase throughput, the TCDRP's joint optimization of traffic in route establishment relies on minimum loss of routes rather than longer hops. The TCDRP has a throughput that is 25% higher than the CEELBRP and 44% higher than the DRP.

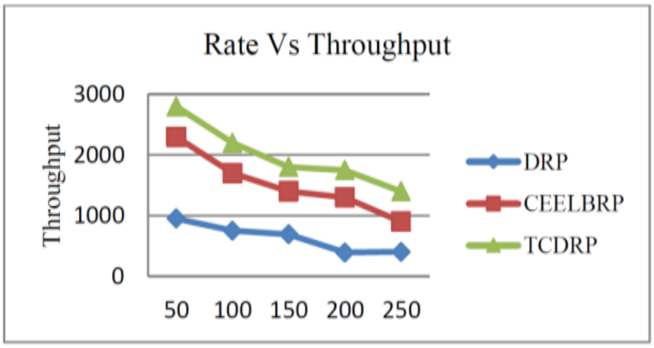

Figure 9: Graph of changing transmission rate and corresponding throughput

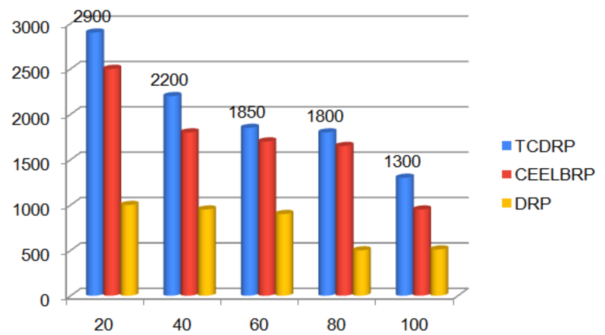

Figure 10: Bar chart of changing transmission rate and corresponding throughput

5. Conclusion

The MANET conundrum, in which ineffective path identification leads to a shorter network lifetime, is partially resolved by the development of diverse routing forms in recent years. In this study, the routing path is optimized using the bio-inspired modified tunicate swarm method. NS2 is used to simulate TCRDP, which is then examined in a range of scenarios and evaluated for packet delivery success and throughput metrics. The experimental results of the TCRDP technique demonstrate that a notably different approach to CLI in MANETs enables more precise adjustments to the state of the network. The evaluation results demonstrate that the suggested configuration performed better than both the most basic and routing protocols.

6. Future works

This research project entails the analysis of basic performance matrices and the development of a basic structure based on TSA and CLI concepts. Other performance metrics, such as protocol overhead and energy consumption, will be calculated and analyzed in subsequent work.

Conflict of Interest

The authors declare no conflict of interest.

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Content Recommendation E-learning System for Personalized Learners to Enhance User Experience using SCORM

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ABSTRACT: E-learning is a main field used to improve learners' learning environment. It would be more useful if the E-learning systems were improved by getting interactions and focusing on user experience. This research suggests increasing the user experience of students towards E-learning environments by recommending content according to their preferences. This research aims to make personalized content recommendations by identifying user interactions, trends, and patterns. Finally, this research provides a model that could help to create an intelligent E-learning system. Then the student engagement towards E-learning and user performance level can be enhanced using this research. After developing the model, there is a 73.99% accuracy in initial training and 63.16% accuracy in initial testing. After retraining and retesting, there was 85.58% accuracy for retraining and 78.90% accuracy for retesting.

KEYWORDS: E-learning, Personalized Content Recommendation, User Experience, SCORM

1. Introduction

1.1. What is E-learning?

E-learning is a method that is used to provide education. E-learning is the use of the Internet and other digital technologies to facilitate learning outside of the traditional classroom setting. The key components and features of E-learning can be mentioned as content delivery in digitally formats, learning management systems (LMS), online courses and MOOCs, Interactive and Multimedia Tools, Synchronous and Asynchronous Learning, Assessments and Feedback, and Collaborative Learning Tools. The central point of E-learning is learning management systems (LMS). Learners can create, manage, and deliver courses using E-learning because LMSs provide a structured environment. E-learning has some challenges that can be addressed to replace traditional educational methods.

1.2. E-learning Systems

E-learning systems are becoming more common among people which can be used to gravitate toward beyond traditional learning methods. Typically, E-learning systems consist of courses and activities such as quizzes and distribute them among students, post notifications, review assessments, and exams, and accept or reject student enrollment.

1.3. Educational Data Mining

Data mining is used to uncover patterns, correlations, relationships, and anomalies within extensive sets of data to predict future results and trends. Educational data applies to data mining for research needs such as enhancing the educational procedure, leading students to learn, or having a better knowledge of educational phenomena.

Educational Data Mining is a contributing discipline that plays a key role in improving educational outcomes. By mining data types from educational settings and applying data mining techniques, students can gain a deeper understanding and the environments in which they learn. With the usage of the educational system raised, high amounts of data become available.

Educational Data Mining offers valuable insights into the necessary information and presents a clear profile for learners. Then data mining is used to solve educational-related issues. There are some educational data mining techniques like clustering, prediction, and discovery with models and relationship mining. Then, it can identify novels, interesting, and useful information from educational data.

1.4. Content Recommendation

The content recommendation method can be used to increase user interaction in most E-learning systems. The types of content suitable for different levels should be properly mentioned in a content recommendation system.

1.5. Research Problem

With the increase in popularity in the remote teaching field, more people have a desire to share their knowledge. However, the presentation of knowledge is directly proportional to how efficiently knowledge can be passed on. Everyone has a different capability for learning and the general content delivery system is not very successful. There are some prior research works which are using data mining techniques, can be used to predict performance of students'. Several research works were done on personalized lesson recommendations based on the probabilistic model and agent-based models. However, no significant research has been observed on recommending content based on the subject's interest from the student in current E-learning systems.

1.6. Research Objectives

This proposed system has two main objectives which are mining data from user interactions identifying user needs and delivering targeted lessons to enhance user interest in relation to lesson content.

1. Identify user needs and user interactions through mining data

2. To enhance user interest and interaction, develop lessons based on user needs

1.7. Research Questions

Students' interactions are very crucial to understand user engagement and enhance the learning experience. The students' interactions can be identified by focusing their activities on the system. Collecting data through surveys and assessments can provide a better understanding of user experiences and preferences. Students' interactions with the content are required to be evaluated. There are some metrics like the frequency and duration of content access, completion rates of assignments or quizzes, and any interactions or discussions within the system to evaluate. These metrics are useful to enhance the level of student engagement. Personalized learning approaches are necessary to deliver targeted content to increase students' interactions. Collecting data, such as interactions, performance, preferences, and interests will be useful in creating content for specific needs. Multiple content formats such as texts, audio, or images are useful to engage their preferences and learning styles.

1. How to identify student interactions and attractions towards the contents of the E-learning?

2. How to evaluate user interest for the E-learning content?

3. How to deliver targeted content to each individual student to interact with students?

4. How to translate content through different media according to the user's interests such as when given content is in text format and the targeted audience requires the content in audio format to be interested?

1.8. Research Scope

This project intends to cover the extraction of student behaviors related to interests in the content from E-learning systems of Sri Lanka, developing a simulation of an E-learning system, and testing different content recommendation techniques that can be used to deliver targeted content to the Sri Lankan undergraduate students based on extracted data and user interest levels.

1.9. Research Significance

The proposed research will help to enhance the interest students have in the content through targeted delivery of content. By analyzing and understanding individual student preferences, learning styles of students, and students' relationships, the E-learning system can deliver content by aligning with their essential requirements and interests. This personalized method enhances the preferences of students to be motivated and engaged with the relevant materials. Somehow, if one student has shown preference for audio-based content, then the system can provide audio-based text-based content, that can be accessed and appealed to that student. The research targets to provide a more personalized and engaging learning experience by adjusting the material delivery to the interests of the individual.

1.10. Research Outline

Section 1 provides a comprehensive introduction to the entire research, setting the foundation and context for the study. Following this, Section 2 delves into the related literature, where it reviews previous research efforts relevant to the proposed study. This section not only summarizes earlier work but also critically highlights the limitations and drawbacks that have been identified, thereby establishing the need for current research. The methodology of the study is detailed in Section 3, which emphasizes the novel approach and procedures that define this research. This section carefully explains the specific methods employed, underscoring the innovations introduced to address the gaps found in prior studies. Upon implementing the methodology, the research progresses to Section 4, which presents the results obtained from the experimental or analytical processes. This section also includes an in-depth discussion that interprets the findings, considering both the current results and the shortcomings noted in previous work, thus providing a clear comparison and justification for the research' contributions. Finally, the study concludes with a meaningful conclusion section that synthesizes the key outcomes, addressing the initial research questions, problems, and objectives. This concluding part not only summarizes the study's achievements but also reflects on its significance, implications, and potential directions for future research.

Figure 1 shows the outline throughout the research flow.

2. Related Works

The following sections state the similar works that were done on the existing works for the proposed research system, the topics of Student behavior extraction, content formatting, and SCORM. Finally, research remarks have been clarified according to the whole literature review.

2.1. Existing Research Works

Many studies have discussed intelligent E-learning management systems to enhance user experience. In [1] and [2], both focus on personalized recommender systems, with [1] emphasizing the role of these systems in overcoming information overload and [2] proposing an intelligent profiling system to recommend courses based on user preferences. The management of learning information [3] was discussed in E-learning systems, emphasizing the need for interoperability and proposing an Open Education Service Architecture.

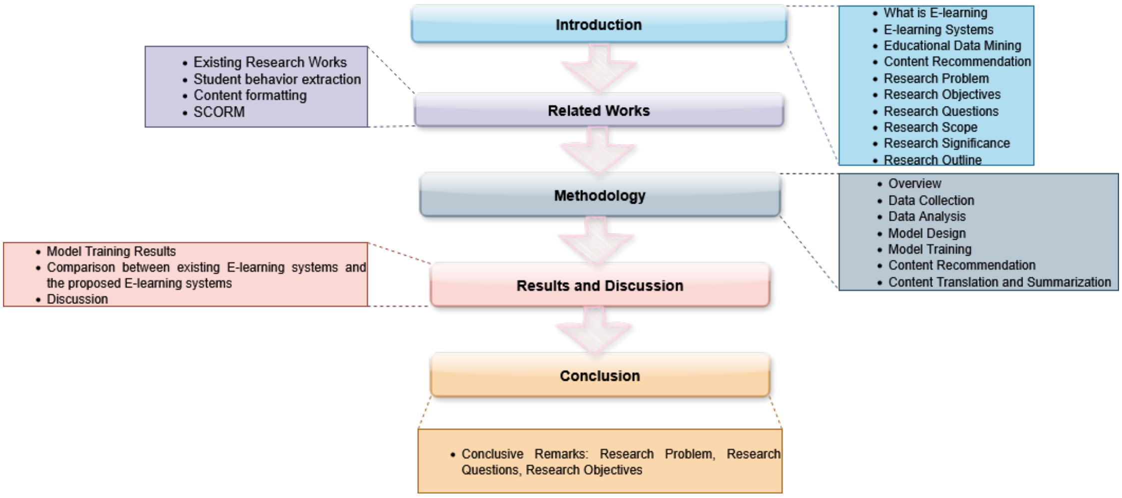

Figure 1: Research Outline

2.1.1. Intelligent E-learning Management Systems

An intelligent adaptive E-learning model [4] has been proposed to classify learners and to provide adaptive content. Another intelligent E-learning Management system [5] has been introduced to enhance multi-agents that can be used to organize content resources and provide personalized access.

2.1.2. E-learning Management Systems for enhanced user experience

A range of studies have been done regarding the usage and experience of users for various E-learning management systems. An improved E-learning system [6] was designed with features such as online material upload, one-on-one interaction, and real-time communication with lecturers. An E-learning management system [7] was proposed using web services, focusing on features like content and learning management, delivery management, and access control. These studies collectively highlighted the requirement of user experience in E-learning management systems and the potential for improvement through enhanced features and usability.

2.1.3. Existing Research Improvements

Table 1 shows how improvements should be focused on.

By considering the above research works improvements, the proposed research project has been focused on considering those improvements which have to be focused on existing research works. A methodology has been decided on what we can do to build the research project. According to that methodology, the following research works have been highlighted.

2.2. Student behavior extraction

E-learning had allowed students to engage in course content and develop their learning behaviors. There were several key categories that highlight E-learning behaviors [8, 9]. Learning preparation meant activities like accessing the course homepage, navigating to course pages, and reviewing supplementary materials that prepare students for learning. Knowledge acquisition behavior means behaviors focused on actively acquiring knowledge, such as accessing course content, watching videos, and participating in discussions.

Table 1: Existing Research Improvements

Research work	Improvement that should be focused
[1]	Personalized learning content formats and content versions of users
[2]	Content-based and collaborative filtering recommendation techniques are combined
[10]	How to arrange contents according to user requirements
[3]	The advancement of the E-learning systems which must be spread and that should be implemented to gain user interest in E-learning systems
[4]	With a minimum amount of data during the classification has been done. Only KNN algorithm has been used with lack of parameters
[11]	A model and a system based on Student-Centered based E-learning Environments
[6]	An improvement in making this research considering videos, and automatic course selection according to students registered level

Studies have been done on individual learning styles and approaches impact E-learning behaviors and performance [9, 12]. There are some factors that can be reasoned to influence their E-learning behaviors and intentions [9].

The E-learning engagement levels of students could be examined with the extracted behavior from the contents. There are several research to highlight features [13, 14, 15] on behavioral extraction of students. Emotions [16, 17] and moods [18, 19] of students can be extracted from student engagements using online lecture videos.

2.2.1. Data Gathering

The data were gathered from the E-learning system before any information. This could be done using two ways such as active and passive information gathering. Active information gathering would be done by observing user interactions surveys, quizzes, tutorials, assignments [15], lab practicals, and exams. Passive information gathering could be done by observing user interactions using the E-learning systems.

2.2.2. Pattern Recognition

Several data are not in order, because of that they should be processed and sorted to extract meaningful information.

Unsupervised clustering algorithms [20, 21] or supervised machine learning algorithms [14, 21, 22] were used to identify patterns from a large collection of data.

2.2.3. Clustering Algorithms

Clustering algorithms, particularly K-means, are widely applied in E-learning for grouping similar learning behaviors and enhancing personalization. They support adaptive systems, identify struggling students, and improve content delivery [23, 15, 24]. Techniques also predict learning styles using log files [25], categorize students by behavior [26], and analyze learning preferences via weblog mining [27]. These methods enhance academic performance and optimize resource delivery [28].

2.2.4. Pattern recognition with Supervised Machine Learning

Supervised learning techniques like neural networks and decision trees have been used to analyze student learning behaviors and tailor teaching strategies [29, 14]. E-learning systems have also leveraged data mining and big data for pattern recognition and predictive analytics [30], while challenges and credentials were explored using process mining methods [31].

2.2.5. Interest Recognition

Interest Recognition involved analyzing user interactions with content, including factors like duration and click frequency, as well as feedback on interactive features. Several earlier studies were conducted [32] with respect to this issue, among which had been used to identify factors affecting student acceptance for E-learning and their intension to usage of E-learning. Several patterns [33] were identified in the behavior of students while learning several things in different incidents. Data collection and the center of interest construction [34] were done by two modes.

2.2.6. Scoring User interactions in the systems

User engagement can be assessed by scoring interactions based on their relevance to the user's content interests. Studies have examined such systems [35] analyzed engagement and interactivity using scoring methods, while [36] evaluated interaction through usage metrics and system usability scores.

2.3. Content formatting

Personalized content recommendations should be implemented upon determining user interest levels and behaviors. There were various methods for achieving this, including organizing content with templates, dynamically arranging content using templates, translating content across different media types, and summarizing content.

2.3.1. Content arrangements with templates

A content customization strategy can involve templating for different skill levels—novices benefit from visual aids and simplified language, while experts prefer dense, detailed texts [37]. Prior efforts emphasized aligning content with E-learning standards and interactive digital formats [38].

2.3.2. Dynamic Content arrangements

A system can dynamically organize content based on user preferences to enhance engagement. Prior work applied such adaptive content arrangement to address variations in learner behavior, goals, styles, and knowledge levels [39].

2.3.3. Content translation across media

Content creators on an E-learning system were often experts in their field but may lack the expertise, resources, or time to create engaging multimedia content. Using machine learning models and existing content enabled the generation of created multimedia content for specific users. Research had demonstrated that combining machine translation systems and translation technologies, could enhance performance of students and translation quality in educational settings [40].

2.3.4. Content Summarization

Advanced users who already had knowledge of the given domain, but they required the core content of the given lesson, or a blog presented in a condensed manner. The content summarization had been used [41] to aid both individual and collective learning endeavors. Content summarization [41] had been employed to support learning activities, understand user proficiency and annotations, and generate multiple summaries of the same document created to different skill levels.

2.3.5. Personalized content recommendation

Previous E-learning research has explored personalized learning using mathematical models [42], sentiment-aware recommendations [43], and solutions for integrity issues in learning platforms [44]. Recommendation system architectures leveraging ontologies and rule-based reasoning were proposed [45], along with broad reviews of personalized recommendation techniques [46]. Further enhancements included content matrices, logistic regression, deep learning, and flexible frameworks for adaptive course design.

Finally, in [47, 48], emphasis was placed on employing machine learning-based methods which allow for personalized learning experiences by selecting suitable relevant shaping activities. For course selection recommendations to E-learners and instructors, they utilized Natural Language Processing methods as well as semantic analysis approaches [49].

These personal recommendations, such as those based on the search history [50] of users, are highly relevant to individual users. An E-learning system had been specially designed to improve student learning by creating recommendations that embed latent skill based on historical interactions [51] between students, lessons, and assessments. This probabilistic framework for students and educational material could suggest customized lesson sequences to assist students in getting ready for evaluations.

2.4. SCORM

2.4.1. Overview

The article [52] described the main features, technical books, history, and support of Sharable Content Object Reference Model (SCORM), standards and specifications collections that enable interoperability of learning content across different systems and tools. The paper [53] presented a SCORM digital teaching resource management model, comprising of four parts: content aggregation model, run-time environment, sorting and navigation, and collaborative filtering engine. It also included the design and implementation of SCORM related digital teaching resource library system. That system is based on collaborative filtering technology with performance evaluation using a data set of movie ratings. The results showed that the system can improve the learning efficiency and satisfaction of the learners. The article [54] explained that SCORM combines three specifications: content packaging, run-time environment, sequencing and navigation. It also lists the benefits of SCORM, such as compatibility, reusability, personalization, and tracking. It integrates contributions from organizations like IMS Global Learning Consortium, AICC, and ARIADNE, enabling multimedia presentations for distance learning across platforms [55]. Versions like SCORM 1.0 and 2004 (also known as 1.3) focus on packaging, delivery, and tracking of learning objects [55].

2.4.2. Core components

SCORM comprises three main components: Content Aggregation Model (CAM), Run-Time Environment (RTE), and Sequencing and Navigation (SN).

1. Content Aggregation Model (CAM) This specification defines how learning content is structured and packaged. The CAM establishes the framework for Sharable Content Objects (SCOs) and Assets, which serve as the fundamental building blocks of SCORM-compliant content. SCOs are standalone, reusable learning modules that can communicate with the Learning Management System (LMS), while Assets are static content collections that do not require LMS communication. [55, 56].

2. Run-Time Environment (RTE) The RTE specification governs the communication protocols between learning content and the LMS during execution. It implements a standardized JavaScript API that enables content to exchange data with the hosting system, facilitating learner tracking, progress monitoring, and content state management [55].

3. Sequencing and Navigation (SN) Available in SCORM 2004, this component provides sophisticated content flow control mechanisms. It enables the creation of adaptive learning paths based on learner performance, prerequisites, and pedagogical rules defined by instructional designers [57].

SCORM represents a foundational achievement in e-learning standardization, providing technical specifications that have enabled widespread interoperability and content reusability. While the standard faces contemporary challenges related to mobile compatibility, content flexibility, and integration with emerging technologies, ongoing academic research continues to address these limitations through innovative architectural approaches, middleware solutions, and enhanced metadata models.

The technical depth of SCORM's specifications, from its JavaScript API implementation to its sophisticated sequencing mechanisms, demonstrates the standard's robust engineering foundation. However, the emergence of newer standards like xAPI and the evolving demands of modern e-learning environments suggest that SCORM's future lies in architectural evolution rather than incremental enhancement.

2.5. Research Remarks

A comprehensive literature review using many research works has been conducted in the areas of students' behavior extraction and content recommendation. The field of student behavior extraction covers several key areas including data gathering, pattern recognition, clustering algorithms, interest recognition, and scoring user interactions in the systems. On the other hand, in the realm of content recommendations, significant focus is placed on content arrangements with templates, dynamic content arrangements, content translation across media, content summarization, and personalized content recommendation as discussed in the literature review that was conducted. Additionally, further research findings related to other works have also been highlighted.

From the related works done so far, we can conclude that many research works have been done in this domain. Existing research findings are inadequate in enhancing user interest in E-learning content. From the research findings, it can be seen that there is room for improvement. In content recommendation systems, that target user interests. Thus, in the proposed system research will be done in the direction of user interest enhancement to extract data by personalized content recommendation

3. Methodology

The prevalence of online learning is steadily increasing, contributing to the establishment of a knowledgeable world. In Sri Lanka, there is a notable trend wherein students predominantly utilize E-learning systems for their educational needs. The E-learning interface plays a crucial role in facilitating student interaction and exploration of diverse topics or subjects of interest. In this context, when a user expresses interest in a particular topic, the E-learning interface promptly retrieves relevant details and presents them to the user. As a result, it will be generating valuable data that serves as the foundational basis for the improvement of the user experience. This academic behavior highlights the significance of E-learning systems in Sri Lanka, that focusing their role in providing students with interactive learning contents in variety of subjects. The information gathering and data collection support the enhancement of the E-learning experience for users.

This E-learning system can adapt content based on learning styles. For example, the learners can get advantages from multimedia content, while some others can get advantages from simulations. The recommendations can be adjusted based on monitoring learner behavior. If a learner struggles with a particular type of content, the system can suggest alternative formats or additional resources. The insights into learner preferences can be measured and learner recommendations can be refined based on time spent on tasks and interaction frequency.

The completed research project will flow as presented in Figure 2. A comprehensive database was created by collecting data and integrating survey responses during the training phase. This dataset was processed and used to train the model, focusing it to understand build relationships between user interactions, requested content, and user preferences. After this training, the model [58, 59, 60] was developed to identify patterns and conditions governing the recommendation of useful content types based on learners past interactions in the E-learning system. At the completion of the training phase, when users access the content of the E-learning interface, the E-learning system interacts with the trained model, instead of directly requesting the content from the system. The model prompts the learning conditions and patterns to identify the most appropriate type of content according to the user's specific requirements and preferences.

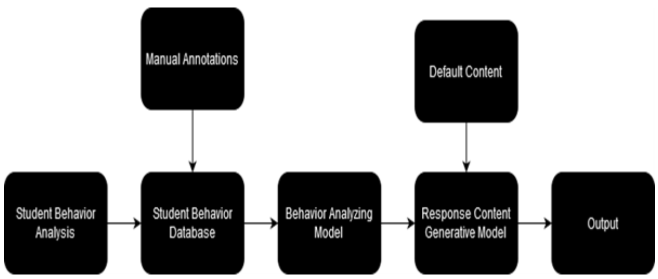

Figure 2: Model Architecture

To meet user preferences, a content translation algorithm adapts material into the desired format or learning style—such as converting text to audio for users who prefer auditory content.

Figure 3 [60] presents a graphical representation of the complete model throughout the research.

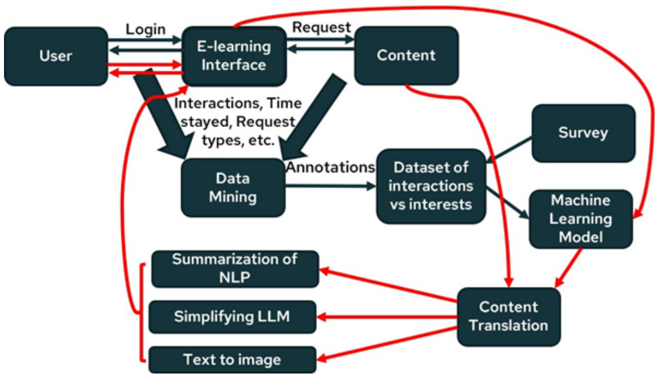

Figure 3: Model Flow Diagram

3.1. Data Collection

In the data collection procedure, data were collected in different ways, by surveying to gather user responses towards E-learning, a survey to analyze students' interactions towards the contents of E-learning, and from the Moodle log data.

3.1.1. Survey to analyze student's interactions towards the contents on E-learning

In the pursuit of understanding students' preferences for learning content, the data were collected using a survey on various aspects of academic performance. Approximately 1000 users actively participated in this survey, providing valuable insights into their preferences. The survey focused on three key dimensions: the preferred format for learning content, the preferred content version, and the preferred content presentation style.

Preferred Format for Learning Content: students have stated their preferences according to the learning content format that is collected according to their academic performance rate. This can be used to identify the medium that delivers educational materials.

Preferred Content Version: students expressed their preferences concerning their most favorable content version. This includes their preferences in summarized content and content presented more in-depth.

Preferred Content Presentation Style: students' preferences on the content were also gathered using the survey. They implied their responses on content to be conveyed in a story format or presented more straightforwardly.

The survey results contribute valuable insights for educators and instructional designers seeking to optimize content delivery in line with student preferences. From around 1000 users, Table 2 shows how many users preferred various learning contents. Table 3 shows how many users are preferred for various learning contents according to user performance rating.

From around 1000 users, Table 4 shows how many users preferred content that is summarized or explained. Table 5 shows how many users preferred content that is summarized or explained according to user performance rating.

From around 1000 users, Table 6 shows how many users preferred content that is the straightforward manner or story format. Table 7 shows how many users preferred content that is straightforward manner or story format according to user performance rating.

3.1.2. LMS log data

In the context of analyzing user behavior within an E-learning module, a sample dataset was required to understand user attraction and involvement in specific tasks. For this purpose, log data was collected from the Moodle platform in Sri Lanka.

The gathered log data encompassed approximately 47,647 events recorded by users interacting with the module.

Each event was associated with a specific status, reflecting the nature of the user's action. The statuses were identified within the module. Those statuses are added, assigned, created, deleted, downloaded, enrolled, graded, joined, posted, removed, restored, searched, started, submitted, subscribed, unassigned, updated, uploaded, and viewed which are done by the users. This academic categorization provides a structured overview of log data, enabling a systematic analysis of user interactions and behaviors within the E-learning module. The user's reaction according to each status has been shown in Table 8.

Table 2: No of users preferred for various learning contents

The preferred format for learning content	No of Users
Image-based	203
Audio-based	123
Video-based	492
Text-based	182

Table 3: No of users preferred for various learning contents according to user performance rating

Preferred content format	No of Users				
	Rating 1	*Rating 2*	*Rating 3*	*Rating 4*	*Rating 5*
Image-based	6	109	68	13	7
Audio-based	3	18	29	40	33
Video-based	69	143	174	64	42
Text-based	15	26	35	43	63

Table 4: No of users preferred content that is summarized or explained

Preferred content version	No of Users
Summarized content	604
Explained content	396

Table 5: No of users preferred for various learning content versions according to user performance rating

Preferred content version	No of Users				
	Rating 1	*Rating 2*	*Rating 3*	*Rating 4*	*Rating 5*
Summarized content	52	83	104	169	196
Explained content	138	101	62	53	42

Table 6: No of users preferred content that is straightforward manner or story format

Preferred content format	No of Users
Straightforward manner	431
Story format	569

Table 7: No of users preferred content that is straightforward manner or story format according to user performance rating

Preferred content format	No of Users				
	Rating 1	*Rating 2*	*Rating 3*	*Rating 4*	*Rating 5*
Straightforward manner	52	65	74	109	131
Straightforward manner	179	144	92	83	71

Table 8: No. of responses on statuses

Status	No of Users
Added	116
Assigned	61
Created	2272
Deleted	768
Downloaded	4
Enrolled	61
Graded	122
Has	87
Joined	752
Posted	2975
Removed	2
Restored	3
Searched	17
Started	69
Submitted	76
Subscribed	341
Unassigned	2
Unsubscribed	13
Updated	2878
Uploaded	23
Viewed	37023

In the realm of educational events, various attributes can be systematically categorized to facilitate a comprehensive understanding and analysis within the system. This academic categorization establishes distinct types, each serving a specific purpose. The identified categories encompass courses, discussion, comment, tag, user, role, grade item, override, page, group, module, post, attempt, submission or meeting.

This section shows a systematic framework that enhances the organization and interpretation of data related to educational events. It backbones to a more structured approach to manage and analyze various aspects of user interactions and behaviors within the educational context.

3.2. Data Analysis

As part of our initiative to analyze user engagement in E-learning, we used a Kaggle dataset of student activity logs to test and refine our code before applying it to the original data. This preliminary analysis as shown in Figure 4 helped identify key patterns and variables influencing user interactions. Using the Kaggle dataset allowed us to fine-tune model parameters, improving both the accuracy and reliability of our training process.

Figure 5 represents a correlation matrix for online classroom data. The trained dataset is given as a correlation matrix in figure 6.

In an online classroom setting, the dynamics of interactions among participants can be diverse. Various factors contribute to this variability, such as the nature of the posts generated during these interactions. One key aspect is the propensity of participants to initiate creative discussions. Analyzing the dataset reveals a distinction between posts categorized as either good or bad, shedding light on the overall quality of the contributions.

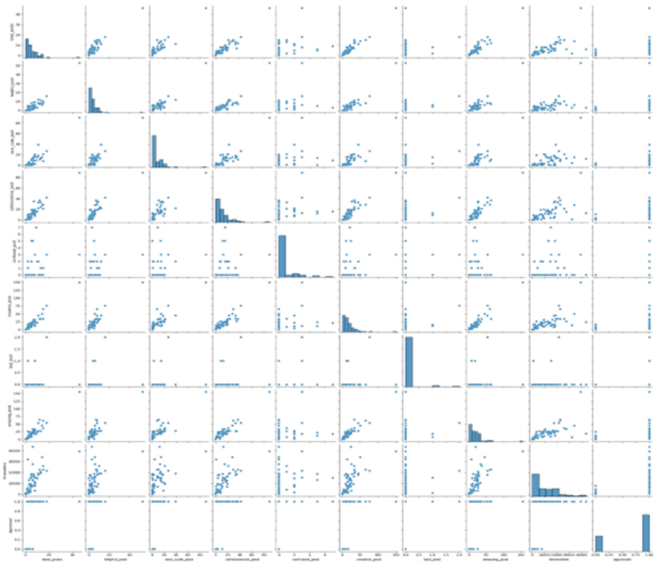

Figure 4: Kaggle Dataset Analysis

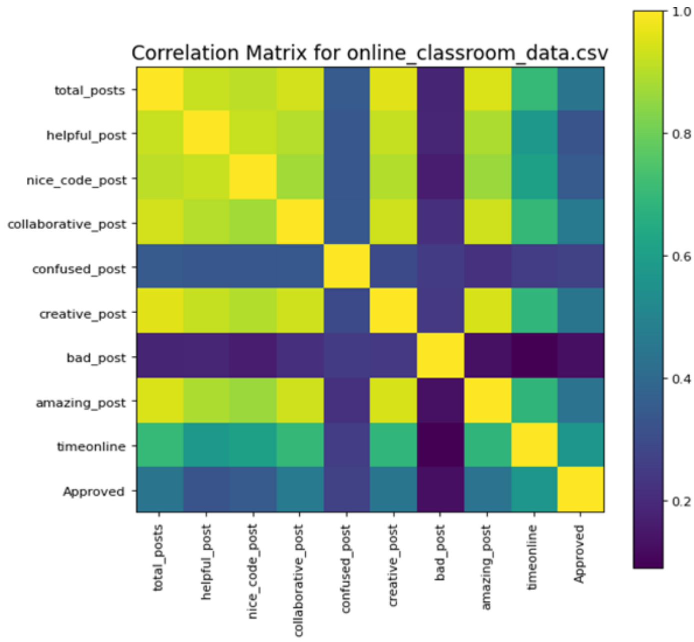

Figure 5: Correlation Matrix for online classroom

	precision	recall	f1-score	support
0	0.40	1.00	0.57	2
1	1.00	0.77	0.87	13
accuracy			0.80	15
macro avg	0.70	0.88	0.72	15
weighted avg	0.92	0.80	0.83	15

Figure 6: Training Dataset

Upon examining the entirety of posts, it becomes apparent that the number of posts deemed helpful is notably scarce. Curiously, there is a lack of posts categorized as bad when compared to the volume of helpful posts. This imbalance suggests a generally positive and constructive atmosphere within the online classroom, where participants are more inclined to assist rather than engage in detrimental interactions.

The online time duration is high when considering the dataset in addition to the total number of posts. This highlights a high level of engagement among participants that reflects an active online learning community.

It is observed that the frequency of creative posts is noteworthy. The dataset also highlights a high occurrence of categorized posts also. This is a reason to suggest the online classroom system that can be used to foster creativity and positive engagement with useful information and content.

This initial training was using the XGBoost algorithm that has been conducted on this dataset. The resultant model provides valuable points into the classification of posts. This training process obtained specific parameters and classification values. This stage offered a quantitative condition within the online classroom that gives a foundation for further analysis and refinement of the learning model.

Initially, the XGBoost algorithm was used for model training, but due to unsatisfactory accuracy, it was replaced with the Random Forest algorithm, which provided improved predictive performance. After initial training, data cleaning was conducted to remove unnecessary log columns like system and mentor logs, streamlining the dataset.

Survey insights guided the assignment of weights to user preferences across various content types (videos, audio, animations, text) and formats (summarized or detailed, straightforward or story-driven). Manual data annotation further enhanced the training dataset, and the Random Forest model achieved an 80/20 train-test split, effectively validating its performance.

In-depth analysis of this refined dataset, organized in a CSV file, revealed patterns and relationships, allowing accurate weight assignments based on user preferences. This structured framework supports a robust content recommendation system, enabling more precise and personalized content delivery based on user-specific features and preferences.

3.3. Model Design

It was required to calculate the weight to recommend the content. Then, an equation was created to calculate the weight. The following factors were considered when creating the equation 1.

$$Ur - Cr = Ar \tag{1}$$

- Ur- User rating
- Cr- Content rating
- Ar- Aggregate response value

3.3.1. User rating

The user rating weights are generated using the module's log data. Initially, weights were assigned arbitrarily based on user responses. These responses were collected from the relevant Learning Management System (LMS) platform and recorded by the users themselves. The obtained weights are mentioned according to the dataset. It is shown in Table 9.

Table 9: No of weights on statuses

Responses	Weights
Created	5
Posted	5
Updated	5
Joined	4
Subscribed	3
Added	3
Submitted	3
Uploaded	3
Assigned	2
Graded	2
Created	2
Deleted	1
Downloaded	1
Enrolled	1
Removed	1
Restored	1
Searched	1
Started	1
Submitted	1
Unassigned	1
Unsubscribed	1
Viewed	1

Table 10 presents the responses and their corresponding weights. Specifies the weights for each component of the Learning Management System (LMS) based on the data set. The random weights assigned to these components are shown in Table 10.

Table 10: No of components on weights

Components	Weights
Assignment	4
File	3
File submission	3
Folder	2
Forum	3
Page	2
Quiz	5
System	1
URL	2
Wiki	2
Zoom meeting	2

Initial values were arbitrarily assigned based on heuristic criteria, which considered the impacts of data collection and analysis during selection. Subsequently, a recurrent learning approach was implemented to fine-tune these values using the collected responses. Finally, the user rating values are generated. Table 11 displays the user ratings according to the defined event user rating values.

Table 11: User rating value on events

Events	User rating value
A file has been uploaded	3
A submission has been submitted	3
Clicked joining meeting button	2
Comment created	2
Course activity completion updated	2
Course module updated	1
Course module viewed	1
Discussion created	2
Discussion viewed	2
Feedback viewed	1
Group member added	1
Post created	2
Post updated	2
Question updated	2
Question viewed	2
Quiz attempt reviewed	1
Quiz attempt started	4
Quiz attempt submitted	5
Quiz attempt summary viewed	2
Submission updated	2
Wiki page viewed	1

3.3.2. Content rating

The Content Rating (Cr) value is assigned randomly through an analysis of the data gathered on various learning content formats. This assignment considers factors such as the performance rating (which evaluates how well the content performs in terms of user engagement or effectiveness) and the preferred content version (which reflects users' favored formats or styles of the material).

Table 12 illustrates how the preferred content versions and their associated weights vary, based on the insights from the "Data Collection" section. This table provides a detailed breakdown to show the relationships and variations in these elements.

Table 12: preferred content version and weights

Preferred Content Version	Weights
Image based	2
Video based	3
Audio based	4
Text based	5

If the user performance rating is nearly 4, and 5 summarized content will be given. If the user performance rating is nearly 1, 2, and 3 explained content will be given.

3.3.3. Aggregate Response Value

The aggregate response values are generated using a random forest algorithm, which is a machine learning ensemble method that builds multiple decision trees and combines their outputs for more accurate predictions. This step creates initial values based on the available data.

Subsequently, a recurrent learning approach—such as recurrent neural networks (RNNs) or similar iterative optimization techniques applied to fine-tune these values, incorporating insights from the specific content formats (e.g., videos, texts, quizzes, or interactive modules) to improve accuracy and relevance.

The resulting aggregate response value serves as a metric to represent pairwise relationships, capturing interactions and compatibility between different types of users (e.g., based on their preferences, engagement levels, or roles) and various content types within the system.

Table 13 displays these aggregate response values, organized according to the predefined content formats, providing a visual summary of how these relationships are quantified.

Table 13: Aggregate Response Values

Aggregate Content Format	Aggregate Response Value
Image based + Summarized	-3
Image based + Explained	-2
Video based + Summarized	-1
Video based + Explained	0
Audio based + Summarized	1
Audio based + Explained	2
Text based + Summarized	3
Text based + Explained	4

3.4. Model Training

A comprehensive comparative evaluation of XGBoost and Random Forest algorithms was conducted using critical performance metrics including precision, recall, F1 score, and accuracy. This systematic analysis revealed that Random Forest emerged as the superior model, demonstrating greater reliability and robustness compared to XGBoost. Random Forest's ensemble approach, which combines multiple decision trees through bootstrap aggregating, contributed significantly to its enhanced performance by naturally reducing variance and providing better generalization to unseen data. The algorithm's ability to handle high-dimensional data without extensive feature engineering, combined with its inherent robustness to noise and outliers, made it particularly suitable for complex datasets while providing valuable feature importance scoring capabilities

While XGBoost showed competitive performance through its gradient boosting methodology, it ultimately required more extensive hyperparameter tuning and computational resources compared to Random Forest's simpler configuration requirements. XGBoost's sequential tree-building approach, where each tree corrects errors from previous ones, provides excellent predictive capability but demands careful optimization to prevent overfitting. Random Forest's parallel tree construction enables efficient scaling and demonstrates lower sensitivity to hyperparameter settings, making it more accessible for practitioners while offering superior interpretability through feature importance scores and individual tree visualization capabilities.

Following initial model deployment, comprehensive user feedback was systematically collected through multiple channels including direct surveys, usage analytics, and performance monitoring systems to evaluate real-world performance beyond traditional statistical metrics. Based on this feedback, the model underwent strategic retraining to address identified performance gaps and enhancement opportunities, exemplifying modern machine learning best practices where continuous improvement drives sustained effectiveness. This iterative refinement process incorporated both quantitative performance metrics and qualitative user insights, ensuring that model improvements addressed both statistical accuracy and practical utility while maintaining alignment with user expectations and business requirements.

The successful integration of user feedback into model improvement processes highlights the importance of establishing robust feedback loops in production machine learning systems. Systematic feedback loops with automated triggers for retraining based on performance degradation thresholds enable proactive model maintenance and sustained relevance over time. This evaluation demonstrates that algorithm selection must be guided by specific use case requirements rather than general performance benchmarks, considering factors such as data characteristics, performance requirements, interpretability needs, and operational constraints. The comprehensive approach of combining rigorous comparative evaluation with continuous user feedback integration represents best practices in modern machine learning deployment and maintenance, ensuring sustained model effectiveness through iterative alignment with real-world usage patterns.

3.5. Content Recommendation

According to the aggregate response value, the content was recommended. The random forest algorithm was tested in this context. The aggregate response value is given according to the user rating and the content rating. That has been shown in Table 14.

3.6. Content Translation and Summarization

The process described involves a comprehensive approach to multimedia content analysis and summarization, focusing various tools and methodologies. The workflow encompasses translation, segmentation, image processing, deep learning, and natural language processing techniques.

Initially, content translation is executed based on the resultant weight. Videos are transcribed into text format according to user preferences. A summarization process is applied to distill key information for high performing individuals, while low performing individuals receive a more detailed explanation, accompanied by generated images to enhance understanding.

MoviePy (Python) is used to segment audio and video data, converting video frames into images for training with Deep Image Prior (DIP) to extract keywords and identify objects. A large language model then generates transcriptions, removes redundancies, and produces a consolidated image. BART (Google) summarizes content, while OpenAI's API aids in segment explanation. Vision API handles image generation, and a speech-to-text tool processes audio separately. Outputs—including explanations, summaries, and images—are delivered via SCORM for standardized, educational use.

In essence, the described process integrates various tools and methodologies to deliver a sophisticated multimedia analysis and summarization system, catering to diverse user preferences and levels of expertise.

4. Results and Discussion

The model was designed using the user rating value, content rating value, and aggregate response value. The user rating weights were generated by training the log data using recurrent learning. The content rating weights were gen-

Table 14: Content recommendation according to the aggregated response value

Content Type	Content Rating	User Rating	Aggregated Value	Recommended Output
Text based	5	1	4	Text based + Explained
Text based	5	2	3	Text based + Summarized
Text based	5	3	2	Audio based + Explained
Text based	5	4	1	Audio based + Summarized
Text based	5	5	0	Video based + Explained
Audio based	4	1	3	Text based + Summarized
Audio based	4	2	2	Audio based + Explained
Audio based	4	3	1	Audio based + Summarized
Audio based	4	4	0	Video based + Explained
Audio based	4	5	-1	Video based + Summarized
Video based	3	1	2	Audio based + Explained
Video based	3	2	1	Audio based + Summarized
Video based	3	3	0	Video based + Explained
Video based	3	4	-1	Video based + Summarized
Video based	3	5	-2	Image based + Explained
Video based	3	5	-2	Image based + Explained
Image based	2	1	1	Audio based + Summarized
Image based	2	2	0	Video based + Explained
Image based	2	3	-1	Video based + Summarized
Image based	2	4	-2	Image based + Explained
Image based	2	5	-3	Image based + Summarized

erated by analyzing the data gathering of learning content formats. Finally, aggregate response values were generated based on a random forest algorithm. Those values were created to fine-tune those values from the content format using recurrent learning. Using the XG-Boost algorithm and Random Forest algorithm, the model was trained. The content was recommended according to the aggregated response value. Then this model was used to build the E-learning system by assigning the SCORM standard.

To do the implementation of the system, it shows how the results were generated, the following sections consist of model training results, user-interface results, and the E-learning system with SCORM standard, and a comparison between the current E-learning system & the proposed E-learning system.

4.1. Model Training Results

Initially, the model was trained from the data annotated and processed from the log file dump of Moodle for student behavior analysis. The annotations were done with the results from various surveys and heuristic rules. Following is the loss graph for the training and testing curves of the model which was trained using the random forest algorithm. Figure 7 is the initial graph that trained and tested the existing data.

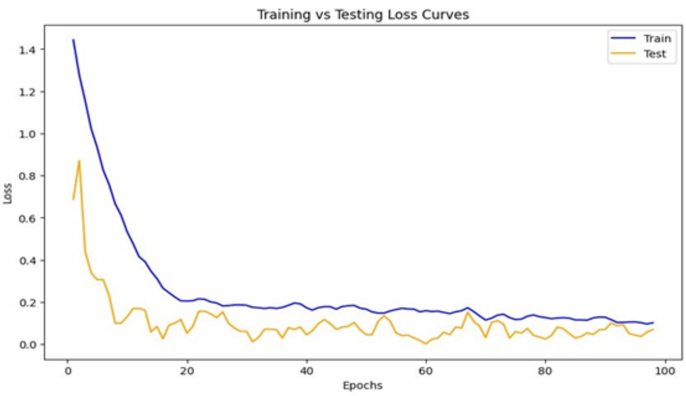

Figure 7: Initial Training and testing curves

After training and testing, there was a 73.9964% train accuracy value and a 63.1636% test accuracy value. The following graphs of Figure 8 represent that.

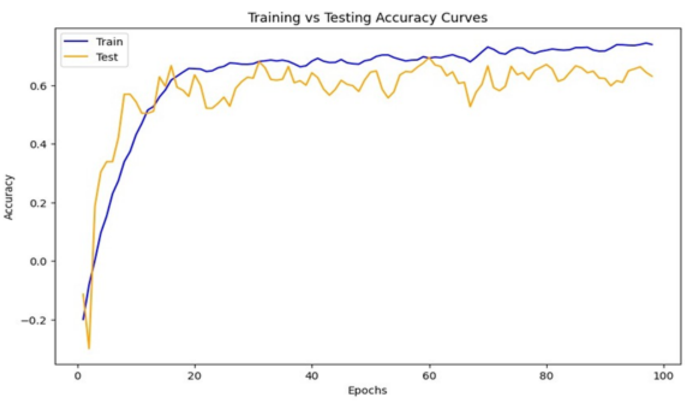

Figure 8: Initial training and testing accuracy curves

The simulated dataset was given to users, their feedback data were collected. Those data were retrained again. The retrained loss graph is shown in Figure 9.

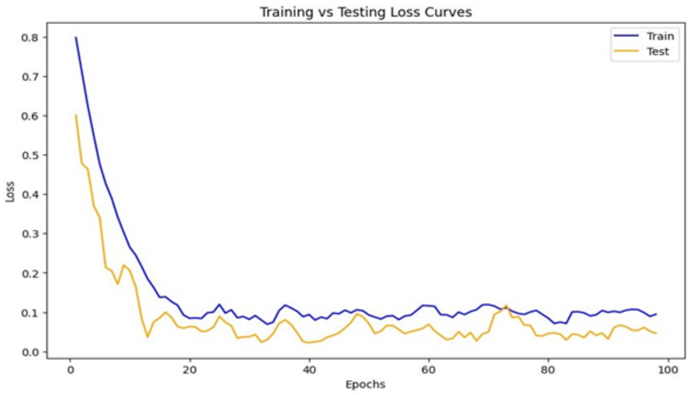

Figure 9: Retrained training and testing curves

After retraining and testing, there was an 85.5848% retraining accuracy value and a 78.9071% test accuracy value. The following Figure 10 graphs represent that.

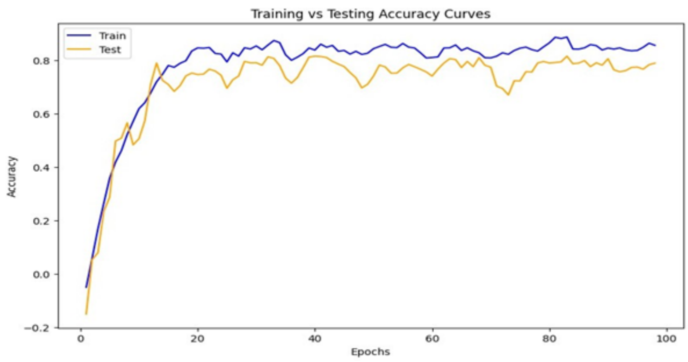

Figure 10: Retrained and tested accuracy curves

4.2. Comparison between existing E-learning systems and the proposed E-learning systems

Table 15 shows the comparisons between existing and proposed e-learning systems.

4.3. Discussion

4.3.1. Multi-Dimensional Data Integration and Model Performance Analysis

The research demonstrates a comprehensive approach to data collection and analysis by integrating multiple data sources to understand user behavior and preferences in e-learning environments. Survey data collection revealed critical insights into user content preferences, with findings showing that a significant proportion of users prefer video-based learning content over other formats, and users consistently favor summarized content rather than detailed explanations. Furthermore, survey responses indicated a strong preference for story-formatted content delivery rather than straightforward presentation methods, highlighting the importance of narrative-driven learning approaches.

Log data integration complemented survey findings by providing objective behavioral analytics that tracked user interactions, session duration, content engagement patterns,

Table 15: Comparison between existing E-learning systems & proposed E-learning systems

Existing E-learning Systems	Proposed E-learning System
Personalized learning environments were not considered	Personalized learning content formats and content versions of users were used
Content recommendation was not considered based on user interactions	A combination of content-based and collaborative-based recommendation filtering techniques were used
User requirements were not considered	How to arrange contents according to user requirements was considered
User learning interests were not considered	This system was implemented to gain user interest in E-learning systems
A high amount of data was not collected and trained	A maximum amount of data during the classification has been done. XGBoost and random forest algorithms were used
Student-centered E-learning Environments have been not concerned	A model and a system based on Student-centered E-learning Environments have been built
Multiple learning content versions have not been concerned	An improvement has been considered in making this research considering videos, and automatic course selection according to students registered level

and learning path navigation. This multi-source data approach enabled the researchers to capture both subjective preferences through surveys and objective behavioral patterns through system logs, creating a more comprehensive understanding of learner behavior than traditional single-source methodologies. The integration of these diverse data streams allowed the calculation of performance ratings and content ratings, which served as foundational input for the recommendation algorithm.

4.3.2. SCORM Standards Implementation and Content Transformation

The novelty of this research extends to its SCORM-compliant content delivery system, which enables standardized tracking and reporting across different learning management systems. SCORM (Sharable Content Object Reference Model) integration ensures that the recommended content maintains interoperability while providing comprehensive tracking capabilities including completion status, quiz results, time spent on modules, and detailed learner interaction data. The system's innovative content transformation capabilities allow dynamic conversion between multiple content modalities based on user preferences: text content can be converted to audio format, different text formats can be transformed into summarized or explained versions, and video content can be adapted to audio-only formats with transcription capabilities. This multimodal content adaptation, delivered through SCORM standards, represents a significant advance over traditional recommendation systems that typically focus on single content types.

4.3.3. SCORM Standards Implementation and Content Transformation

The reported accuracies (73.99% → 78.90%) show improvement after retraining, but baseline comparisons are missing. How does the model compare with standard/popular recommendation baselines (e.g., collaborative filtering, matrix factorization, deep learning-based recommenders)? The research achieved notable performance improvements through iterative model refinement, with training accuracy increasing from 73.99% to 85.58% and testing accuracy improving from 63.16% to 78.90% after retraining. However, the evaluation methodology presents significant limitations in its comprehensiveness. The results only include accuracy metrics, and it would be beneficial to have other types of metrics as well, like precision, recall, and F1 score. Standard recommendation system evaluation typically employs precision, recall and F1 metrics to assess the quality and coverage of recommendations, with precision measuring the fraction of recommended items that are relevant and recall measuring the fraction of all relevant items successfully retrieved. The absence of these metrics limits the ability to fully assess the system's performance compared to established baselines such as collaborative filtering approaches, matrix factorization techniques like SVD and SVD++, or advanced deep learning models including autoencoders, neural collaborative filtering, and hybrid deep learning architectures.

4.3.4. Enhanced User Engagement and System Effectiveness

Despite the evaluation limitations, the research demonstrates better user engagement compared to current e-learning systems, with the proposed content recommendation approach generating significantly more user interactions with recommended content. The integration of behavioral analysis, multimodal content delivery, and SCORM-compliant tracking creates a comprehensive ecosystem that addresses the multifaceted challenges of modern e-learning environments. This holistic approach contributes meaningfully to the advancement of intelligent tutoring systems by providing a framework that can adapt to individual learning styles while maintaining standardized tracking and reporting capabilities across various educational platforms.

5. Conclusion

This research presents a novel multimodal content recommendation model that significantly addresses current limitations in e-learning systems by integrating student behavior analysis, learning styles, and content personalization to enhance user engagement and learning outcomes. Despite substantial research in e-learning recommendation systems, existing approaches have shown limitations in effectively capturing user interests and providing personalized content that aligns with individual learning preferences. The novelty of this research lies in its comprehensive integration of both content rating and user rating mechanisms within a unified framework that supports multiple content modalities—text-based, audio-based, image-based, and video-based formats—all delivered through SCORM-compliant standards. The proposed model demonstrates significant performance improvements through iterative refinement, achieving 85.58% training accuracy and 78.90% testing accuracy after retraining, compared to initial results of 73.99% and 63.16% respectively. This substantial accuracy enhancement reflects the model's sophisticated approach to learning behavior analysis using machine learning techniques that automatically detect learning styles based on behavioral patterns rather than traditional questionnaire-based methods. The research contributes a unique multimodal approach that leverages advanced content-based and collaborative filtering techniques, addressing critical challenges such as data sparsity and cold-start problems commonly encountered in recommendation systems. By incorporating SCORM standards, the model ensures interoperability across different learning management systems while enabling comprehensive tracking of learner progress, engagement metrics, and content interaction patterns. The findings demonstrate how this integrated approach to content recommendation can promote growth in e-learning systems by providing academic and e-learning providers with enhanced tools for creating, designing, and delivering more personalized and effective learning experiences that adapt to individual user preferences and learning behaviors.

5.1. *Conclusive Remarks*

5.1.1. *Research Problem*

Everyone has a different capability for learning, and the general content delivery system is not very successful. There is no significant research found on recommending content based on the interest of the subject from the student in current E-learning systems in universities.

The research problem was solved by recommending the content based on user rating and user interest. Table 14 shows how content was recommended based on aggregated value, content rating, and user rating.

5.1.2. *Research Questions*

1. How to identify student interactions and attractions towards the contents of the E-learning?

   This research question was solved by using log data and those log data were used to gather student interactions towards the contents of the E-learning. Those logs were collected using undergraduate students of Moodle in Sri Lanka. Most of the students are interested in using E-learning systems. There is a high number of students who have user engagement towards the overall E-learning content.

2. How to evaluate user interest for the E-learning content?

   This research question was solved by doing surveys. A huge number of log data were gathered from Moodle and those log data were used to evaluate user interest in the content. The interactions of students with the E-learning systems have been shown. The greatest number of users preferred video-based learning content, the greatest number of users preferred content version summarized content, and the highest number of users preferred content format story format content.

3. How to deliver targeted content to each individual student to interact with students?

   This research question was solved according to the user performance and content rating; the targeted content was recommended. It can be shown that recommended output can be given according to user rating and content rating values.

4. How to translate content through different media according to the user's interests such as when given content is in text format and the targeted audience requires the content in audio format to be interested?

   This research question was solved according to the user performance rating, lengthy, unclear texts can be converted to summarized texts and explained texts. When the target audience needs the content in audio format, the videos can be converted to audio format and the audio can be transcribed.

5.1.3. *Research Objectives*

1. How to identify user needs and user interactions through mining data

   This objective was achieved by analyzing the data obtained from surveys, and user interactions, such as logins, course accesses, content views, and assignment completions, valuable insights that can be obtained regarding user behavior and preferences. This data mining process helped to uncover patterns and correlations, allowing the proposed model to achieve a deeper understanding of individual users and their specific learning requirements.

2. How to develop lessons based on user needs to enhance user interest and interact

   By analyzing user data—such as preferences, performance, and interactions, the system dynamically created content recommendations to meet each user's unique needs and interests. This alignment with individual learning styles, performance levels, and goals made the content more relevant and engaging, focusing on the learning process and boosting user interest. By delivering recommended content, the proposed system aims to create a highly engaging learning experience that motivates users to actively participate and explore the content, leading to enhanced user interest and ultimately an improved user experience.

6. Recommendations

In the surveys that were done during the research, most users preferred video-based learning content were found out. Most of the users preferred summarized content rather than explained content and most of the users preferred content story format content rather than straightforward manner content.

7. Future Works

The accuracy of the model can be enhanced by increasing the dataset size and increasing the iterations used to train the model. The system can be further implemented using common cartridge standards. The system can be further implemented as Artificial intelligence-based auto-generation content.

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