

A Multi-Criteria Evaluation Framework for Performance, Sustainability, and Scalability of Moodle-Based Learning Management Systems: A Data-Driven Approach

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Received: April 2, 2026; Revised: June 18, 2026; Accepted: July 9, 2026; Published: August 8, 2026

Abstract: Learning management systems (LMS) have become an important part of the modern higher education industry, and Moodle is one of the most popular open-source systems, which have become popular on an international level. Despite its extensive application, the majority of the existing evaluation tools are inclined to examine either performance, sustainability, or scalability separately and, thus, cannot be useful in long-term institutional planning. The current study proposes an assessment model that is a rational model of a Moodle-based LMS, as all three dimensions are included in the assessment model. The framework incorporates system performance metrics, resource utilization and management indicators, a load-adaptive scalability metric, and an adaptable, algorithm-based assessment procedure suitable for various deployment environments. The framework applies Min–Max normalization and weighted aggregation to combine the three evaluation dimensions into a unified assessment score. To make the model more realistic, it was tested on publicly available data, for example, the Open University Learning Analytics Dataset (OULAD), which simulated actual interactions between LMS users and the utilization of cloud resource traces to analyze scalability and sustainability. Experimental evaluation using the OULAD and cloud resource datasets demonstrated approximately a 10% improvement in performance under medium workload conditions, an 18% reduction in sustainability due to increased resource utilization, and a 20% improvement in scalability as workload increased. These findings demonstrate that the proposed framework provides a systematic and data-driven approach for evaluating Moodle-based learning management systems and supports informed institutional decision-making.

Index Terms: Learning Management System, Moodle, Performance Evaluation, Sustainability, Scalability, Digital Education, Evaluation Framework, Higher Education

1. Introduction

The learning management system (LMS) has become a fundamental component in the world of higher education, considering the fast-growing sphere of digital education. An LMS can deliver content, assessments, communication, and many other academic tasks in an online and blended learning platform. Moodle is a prominent example, widely adopted in institutions of all sizes due to its open-source nature and high customizability [1-3].

Recent research demonstrates a correlation between LMS quality and student achievement. Studies indicate that system quality, information quality, and service quality significantly influence students' academic performance and satisfaction [4, 5]. It has also been discovered that Moodle-based applications can provide a positive contribution to learning engagement, attitudes, and academic performance provided they are well-designed and supported [1, 6, 7]. These results emphasize the importance of structured LMS environments that function as intended.

Despite the ubiquity of learning management systems, various evaluation efforts have been sporadic. There is an increasing acknowledgement of the importance of understanding usability, user perception, or technology acceptance for learning management systems. However, most existing user studies focus on isolated dimensions rather than providing an integrated system-level perspective with few attempts to integrate user studies. In particular, student-centered evaluations often employ perception- and adoption-based modelling, including the Unified Theory of Acceptance and Use of Technology (UTAUT) [8, 9], to characterize LMS usage behavior. While these models provide valuable insights into user satisfaction, they fail to address the long-term trade-offs between system performance and operational efficiency.

Recent research has focused on the role of artificial intelligence in enhancing the capabilities of LMS. The second trend supporting eLearning development is AI-based approaches, which assist algorithms in learning adaptively, provide personalization and intelligent tutoring services, and conduct in-depth learning analysis of eLearning platforms [10, 11, 12]. These innovations improve the effectiveness of learning but introduce new challenges related to the computability, sample efficiency, and scalability of systems. As LMS products mature, integrating technical performance with emerging trends into a balanced evaluation framework has become essential.

The sustainability of digital systems of education is another crucial and least studied aspect. The higher the number of LMSs, the greater the infrastructure, power, and maintenance requirements. However, a recent study has emphasized that the assessment of LMS should be aimed at sustainability and long-term functioning [13], with less attention to the pedagogical effectiveness and efficiency of LMS usage [14], which is generally preferred. Global policy documents also specify that sustainable digital education ecosystems require systematic and integrated evaluation measures with institutional governance and strategic planning [15, 16].

Simultaneously, scalability has become an increasing need for Moodle LMS. The increase in the number of students accessing the system at the same time and the amount of digital content place an extra strain on the system. The learning experience could suffer from degraded performance and lack of scalability, unless one is careful to work around it. Although many studies have analyzed the performance of systems deployed on a large scale and the difficulties in deploying them [17], very little effort has been devoted to defining a comprehensive model that considers their performance, sustainability, and scalability.

In this study, we propose a systematic framework for a Moodle-based learning system through a thorough review of related research work. This study establishes a framework with three mutually dependent dimensions: system performance, sustainability, and scalability. Unlike existing approaches that evaluate these dimensions independently, this study introduces a comprehensive, data-driven model with a rigorous mathematical definition and an organized evaluation process. The real-world learning management system (LMS) interaction data and massive cloud workload traces support the framework as well and permit the application of the framework in digital learning environments of today. The main innovative feature of this work is the development of a reusable evaluation scheme to support the process of decision making with the help of data and evidence for implementing Moodle in a sustainable and scalable manner. Compared to literature focusing solely on performance, sustainability, or governance [4, 13, 18], this research provides an initial empirical foundation for integrated testing and implementation in higher education. Although the effectiveness, usability, and performance of LMSs have been explored, the predominant theme of most of the research is one of the three dimensions. However, no existing data-driven model comprehensively evaluates the functionality, sustainability, and scalability of Moodle-based LMSs simultaneously. The key findings of the research are as follows:

- (1) A unified evaluation framework integrating performance, sustainability, and scalability for Moodle-based LMSs.
- (2) Validation using real-world LMS interaction data (OULAD) and large-scale cloud resource utilization traces.
- (3) A mathematical and algorithmic model that enables systematic and flexible evaluations across different institutional contexts.
- (4) An analytical assessment of system behavior under varying workload conditions.

Unlike standard LMS evaluation methods that assess individual performance or perception, the proposed framework offers a coherent, data-driven strategy incorporating both system-level and user-level indicators into a single evaluative model. The novelty of this approach lies not only in combining multiple dimensions but also in operationalizing them using real-world datasets to support consistent evaluations across diverse institutional contexts. This is what differentiates the proposed framework from previous ones because it allows for operational evaluations instead of conceptual or perception-based evaluations.

This paper is organized as follows. Section 2 reviews the related work on learning management system evaluation. Section 3 presents the proposed holistic evaluation framework, including the mathematical formulation and algorithmic procedure. Section 4 discusses the implications of the proposed framework. Section 5 provides experimental results and analysis. Finally, Section 6 concludes the paper and outlines directions for future research.

2. Related Work

Over the last ten years, Learning Management Systems (LMSs) have been actively researched with reference to system success, end-user perception, learning performance, and technical effectiveness. Initial studies have provided reviews and research agendas focusing on the evolving nature of LMSs in online learning [18]. Although these pioneering writings have emphasized the importance of proper assessment systems, their focus on pedagogic and managerial aspects has tended to neglect technical problems that sustainability and scalability require.

A more recent academic study examined the effectiveness and results of LMS. According to descriptive studies, LMS quality aspects, such as system quality, information quality, and service quality, are significantly associated with students' academic performance and satisfaction [4, 5]. The impact of Moodle also reports some advantages for students, such as increased involvement, changed attitudes, and content comprehension, if the format supports this [1, 2], [7, 19]. Although these studies have confirmed the educational effect of LMS, most have relied on perception- or achievement-based evaluations.

The second main area of research concerns user perception and technology acceptance. Some studies measured the use of LMS through surveys of students, whereas others used behavior-based models. Perception-oriented assessments of LMS technologies typically focus on usability, ease of use, and perceived usefulness [8]. In higher education settings, models such as UTAUT have been utilized to characterize both LMS usage and usage intention [9]. Although all these methods provide a significant amount of user-level information, they do not capture the performance upper bounds of the system and how to operate it efficiently over a long period.

Recent studies have analyzed the technical performance and deployment issues of LMS platforms. Performance analysis, conducted in natural operating environments, aims to characterize system responsiveness, reliability, and overhead [17]. Some studies have also focused on the organizational and technical challenges of adopting and scaling up LMS [20]. Another stream of research deals with performance alone and some practical issues regarding infrastructure and system operations. Cloud resource scheduling and energy-aware resource allocation have also been studied recently to enhance the efficiency and sustainability of cloud-based infrastructure. These optimizations dynamically allocate computational resources based on the characteristics of the workload, thereby minimizing the cost of operation and ensuring the quality of service. These studies can be useful in the deployment of an LMS on a virtualized cloud infrastructure [21], as the latter is becoming increasingly common in modern educational institutions that use Moodle.

Advanced technologies are being widely adopted, and researchers have explored Artificial Intelligence (AI) as a tool for LMSs. Self-learning solutions with the promise of transparency, personalization, and prediction [10, 11] have been developed with the help of AI. Such technologies enhance the quality of learning but at the cost of increased computational complexity; therefore, system efficiency and scalability have become important research aspects. However, the analysis of AI variables in the LMS assessment area is not a widely accepted approach.

Interest in the sustainability of digital education has recently grown. Several researchers have sought to assess LMSs resource utilization, efficiency, and sustainability [13]. Policy-based reports have argued that effective digital pedagogical systems should be grounded in evaluation/development models congruous with governance, which allow for institutionalization and scalability [15, 16]. While these advancements are steps in the right direction, sustainability is still separate from notions of duo performance and scalability.

Evaluating complex systems with multiple conflicting objectives often employs Multi-Criteria Decision-Making (MCDM) methods [22]. The Analytic Hierarchy Process (AHP), Entropy Weight Method (EWM), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are techniques that are used to systematically weight and combine heterogeneous evaluation criteria. Such methods have been effective in engineering and sustainability and are not widely used for integrated LMS evaluation, particularly for the simultaneous evaluation of performance, sustainability, and scalability at the same time.

Several studies have advanced the knowledge of LMS performance, user perceptions, sustainability, and AI-powered learning environments; however, most have considered them separately. While performance-based studies emphasize system efficiency, perception-based studies are based on user acceptance and satisfaction. Similarly, sustainability studies mainly focus on the use of resources without considering the scalability of the system or the overall performance during operation. Existing practices, therefore, only offer limited understanding of the effectiveness of LMS and demand an integrated multi-criteria evaluation framework that considers performance, sustainability, and scalability.

In summary, the contributions of the present literature allow us to gain a greater understanding of LMSs from the perspectives of effectiveness, usability, performance, and several specific emerging technologies. Nevertheless, most studies treat these dimensions in isolation from one another. We observed a distinct absence of integrated evaluation frameworks for assessing the performance, sustainability, and scalability of Moodle-based LMSs. This gap motivates the holistic framework proposed in this study, which provides a unified, data-driven model integrating these dimensions.

Table 1. Comparison of Related Work on LMS Evaluation

Ref.	Focus Area	Moodle-Specific	Performance	Sustainability	Scalability	Limitations
[4]	LMS success & academic performance	No	partially addressed	not addressed	not addressed	Focuses on quality–performance links only
[1]	Moodle implementation & learning outcomes	Yes	not addressed	not addressed	not addressed	Pedagogical focus
[2]	Moodle usability & design perception	Yes	not addressed	not addressed	not addressed	User perception based
[15]	LMS technical performance	No	explicitly addressed	not addressed	partially addressed	Performance evaluated in isolation
[8]	Student perception of LMS	No	not addressed	not addressed	not addressed	Survey-based evaluation
[9]	LMS adoption (UTAUT)	No	not addressed	not addressed	not addressed	Behavioural focus only
[10, 11]	AI in LMS	No	partially addressed	not addressed	partially addressed	No holistic evaluation
[12]	LMS sustainability & efficiency	No	partially addressed	explicitly addressed	not addressed	Limited scalability discussion
[13, 4]	Digital education governance	No	not addressed	explicitly addressed	explicitly addressed	Policy-level analysis

Table 1 illustrates that existing approaches address individual dimensions but fail to provide a comprehensive evaluation framework.

3. Proposed Holistic Evaluation Framework

In this section, we strengthen the mathematical and logical foundations of the operation of the proposed holistic framework. We aim for a clear, interpretable, and data-adaptable design.

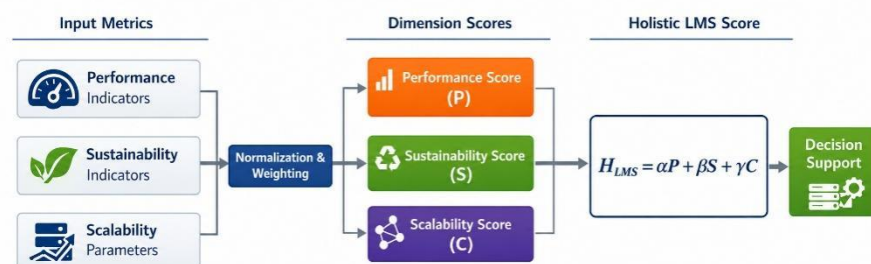


Fig. 1 illustrates the overall architecture of the proposed holistic evaluation framework for Moodle-based learning management systems.

Figure 1 shows the high-level architecture of the proposed approach, which provides a holistic evaluation framework for Moodle-based learning management systems. The framework divides the input metrics into three categories: performance indicators, sustainability indicators, and scalability parameters. We first normalized and weighted these inputs to ensure that they were comparable across heterogeneous metrics. The normalized values were then used to compute three separate scores for each dimension: performance (P), sustainability (S), and scalability (C) scores. Finally, we aggregated these scores using a weighted formula to obtain the overall LMS evaluation score, which we used as a decision support indicator to understand the trouble spots and plan for system optimization and sustainability of LMS deployment. The components shown in Fig. 1 correspond directly to the mathematical formulations presented in Eqs. (1)–(9) and are implemented through Algorithm 1.

3.1. Conceptual Basis of the Framework

The proposed model is composed of three connected dimensions to assess LMS driven by Moodle: performance, sustainability, and scalability. These dimensions are related to short-term system operation, long-term sustainability of resource management, and the capability to grow. Considering all these dimensions will help maintain balanced judgments and prevent biased claims/tasks based on one (or a single) metric evaluation.

3.2. Evaluation Metrics and Dimensions

A systematic description of the following characteristics of the proposed framework should be included: clarity, transparency, and flexibility. The proposed framework uses generic and system-independent performance, sustainability, and scalability metrics to be applicable to different institutional environments without the need for proprietary datasets.

The efficiency and reliability of the LMS were evaluated using the performance dimension. These measures represent how often LMS is used in curricular tasks (instructional use, learner assessment, communication). When the system is overloaded, it impacts the user experience and continuity of online learning activities. The sustainability component assesses the performance of the corporation in the long term and how online resources are used reasonably. As the LMS expands, additional infrastructure and computational resources are required, resulting in increased operating expenses. The adoption of sustainability indicators results in resource efficiency and the viability of LMS deployments measured over time. Scalability denotes the power of the LMS to manage growing numbers of users, content, and concurrent requests. The need for scalable systems is evident in Moodle deployments in large-scale institutions and MOOCs. To assess the metrics, the framework categorizes the metrics into three types, as summarized in Table 2.

Table 2. Evaluation Metrics and Dimensions for Moodle-Based LMS

Dimension	Metric	Description	Relevance to LMS Evaluation
Performance	Response Time	Time taken by the LMS to respond to user requests	Affects user experience and learning continuity
Performance	System Availability	Percentage of time the LMS remains operational	Ensures uninterrupted access to learning resources
Performance	Throughput	Number of concurrent users or requests handled efficiently	Indicates system capacity and efficiency
Performance	Error Rate	Frequency of system failures or request errors	Reflects system reliability
Sustainability	Resource Utilization Efficiency	Efficient use of server and computing resources	Reduces operational waste
Sustainability	Operational Cost Awareness	Cost associated with LMS maintenance and infrastructure	Supports long-term affordability
Sustainability	Digital Resource Optimization	Efficient delivery and storage of learning content	Improves sustainability of digital services
Scalability	User Growth Capacity	Ability to support increasing numbers of learners	Critical for expanding institutions
Scalability	Content Expansion Handling	Ability to manage growing volumes of digital content	Supports curriculum scalability
Scalability	Resource Elasticity	Ability to scale resources with demand	Indicates efficiency of system growth

Table 2 presents the key indicators for each evaluation dimension. The selected metrics are operational and relevant to system sustainability. Performance measures align with short-term system responsiveness and reliability; sustainability measures align with the efficient utilization of digital resources; and scalability measures align with preparedness for future growth. The measures are conceptually determined in a controlled manner to ensure that the institutions can implement them with the aid of the indicators that are available on the locality and yet conform to the evaluation model. The mathematical formulations discussed in the subsections that follow are expressed using these metrics, which are presented in this section.

3.3. Performance Evaluation Model

Performance is the effectiveness of the Moodle infrastructure (the architecture) in accommodating standard learning functions, namely content delivery, sharing, and information assessment. Response time, availability, throughput, and reliability are performance measures that may be considered.

Normalization is attributed to non-identical scales used as performance indicators.

$$\hat{p}_i = \frac{p_i - \min(p)}{\max(p) - \min(p)} \quad (1)$$

This transformation maps all metrics to a normalized range $[0, 1]$, confirming comparability.

The overall performance score P is then computed using a weighted aggregation:

$$P = \sum_{i=1}^n w_i \cdot \hat{p}_i \quad (2)$$

where w_i represents the importance of the i -th performance metric and satisfies:

$$\sum_{i=1}^n w_i = 1 \quad (3)$$

Institutions can focus on indicators relevant to their mission.

This provides scalability and flexibility for evaluation in various LMS environments.

3.4. Sustainability Evaluation Model

The overall efficiency of using resources and doing it well in Moodle-based systems is called sustainability. It could be derived from either infrastructure utilization efficiency, cost control in operational processes, or digital resource exploitation.

The normalization of each sustainability indicator s_j is performed by dividing them:

$$\hat{s}_j = \frac{s_j - \min(s)}{\max(s) - \min(s)} \quad (4)$$

The sustainability score S is calculated as:

$$S = \sum_{j=1}^m v_j \cdot \hat{s}_j \quad (5)$$

where v_j represents sustainability weights and satisfies:

$$\sum_{j=1}^m v_j = 1 \quad (6)$$

This approach allows for flexibility while maintaining a consistent evaluation structure.

3.5. Scalability Evaluation Model

Scalability refers to the ability of a system to maintain its performance as its load size increases; the more the load increases, the more the resource requirements increase in the platform, and the greater the chances of losing some functionality. It is a measure of growth efficiency, not a capacity for growth.

Scalability is used as:

$$C = \frac{\Delta U}{\Delta R} \quad (7)$$

where:

- ΔU represents the increase in supported users or workload, and
- ΔR represents the corresponding increase in computational or infrastructure resources.

The higher the value of C , the more efficient the scalability. If the scalability value is close to or equal to 1, it means that resources are allocated in line with the growth of workloads; if the scalability value is significantly lower, it means that the scalability of the resources is reduced, which may cause resource bottlenecks.

3.6. Holistic LMS Evaluation Score

The overall LMS score incorporates the three dimensions as one score:

$$H_{LMS} = \alpha P + \beta S + \gamma C \quad (8)$$

subject to the constraint:

$$\alpha + \beta + \gamma = 1 \quad (9)$$

where α , β , and γ are the institutional priorities of performance, sustainability, and scalability, respectively.

To prevent institutional bias, equal weights ($\alpha = \beta = \gamma = 1/3$) were used for the three evaluation dimensions unless otherwise stated. It also allows institutions to set their own priorities to determine the weights.

This is important for the interpretability and adaptability of this formulation to various institutions.

The three dimensions of evaluation are not assessed separately and do not provide an overall evaluation score. The operation of the system is a recursive process of interrelatedness of performance, sustainability, and scalability. For instance, with workload scaling up in size, it can boost the system throughput but consume more resources, thereby

impacting system sustainability and scalability. The dimensions cannot be assessed individually; weighted aggregation allows for an integrated assessment.

3.7. Algorithmic Evaluation Procedure

The following algorithm was used to operationalize the mathematical models. The algorithmic process of the proposed framework is summarized below.:

Algorithm 1: Holistic Evaluation Algorithm for Moodle-Based LMS

Input:

Performance metrics $\{p_i\}$, sustainability indicators $\{s_j\}$, scalability parameters $\Delta U, \Delta R$

Output:

Holistic LMS evaluation score H_{LMS}

Procedure:

1. Collect performance, sustainability, and scalability indicators.
2. Normalize performance metrics using Eq. (1).
3. Normalize sustainability indicators using Eq. (4).
4. Compute performance score P using Eq. (2).
5. Compute sustainability score S using Eq. (5).
6. Compute scalability score C using Eq. (7).
7. Compute holistic score H_{LMS} using Eq. (8).

3.8. Interpretation and Use

The scores were not designed to judge individual parts of an institutional LMS but rather to evaluate the institutional LMS. The framework provides administrators with a way to consider the balancing of the trade-offs in the system and prioritize enhancements in the future. Finally, the modularity of the framework enables the future extension of other evaluation metrics, visualization methods, and further experimental validation.

3.9. Conceptual Use-Case Scenario for Moodle-Based LMS Evaluation

Purpose of the Scenario

In this section, a hypothetical use case is introduced to demonstrate the application of the proposed framework. We are not claiming anything empirical, but we want to provide a systematic approach to the use of higher education institutions for identifying Moodle-based Learning Management Systems (LMSs).

Use-Case Context

Imagine an average-sized higher education institution with Moodle as its key learning management system. The HEI has several academic programs that increasingly use online resources so that a larger student population can be catered to, digital content creation can be facilitated, and peak time concurrent system utilization can take place during testing. The institution plans to assess the use of Moodle for information server infrastructure planning and long-term sustainability decisions. Perception-based measures cannot be used for long-range planning. The institution implemented a common assessment approach to address this issue.

Step 1: Identification of Evaluation Metrics

The institution adopts the metrics outlined in Section 3.2 and then first decides which indicators are relevant for the three evaluation dimensions:

- User experience is measured by performance indicators, including system response time, system availability, and reliability.
- Sustainability indicators (resource efficiency and awareness of operational costs) show long-term viability.
- Scalability indicators (user growth capacity, content expansion handling, and resource elasticity) evaluate the system's ability to accommodate increasing demand.

These indicators are identified and linked with system monitoring data available locally and do not need to be translated into specific numbers.

Step 2: Metric Normalization and Aggregation

Once the indicators were identified, they were normalized according to the procedures mentioned in Eqs. (1) and Eq. (4). This procedure enabled the comparison of all the different metrics. Eq. (2) and Eq. (5). Institutional values are represented by the selection of weights. For instance, an institution that wants to ensure the continuity of operations may prioritize system availability and therefore may weigh it more heavily than other indicators, while an institution that wants to focus on efficiency may emphasize sustainability-related indicators more.

Step 3: Scalability Assessment

Scalability was analyzed by conceptualizing Eq. (7), which corresponds to dependence-induced system demand and resource increase. Instead of using accurate numbers, the organization is investigating whether our scaling strategy can scale to the anticipated growth without having to scale the computer resources. This qualitative assessment of scalability provides business analysts with the ability to assess future growth capacity based on varying levels of scale.

Step 4: Holistic Evaluation and Interpretation

The combination of the performance, sustainability, and scalability scores is based on the holistic evaluation model, as shown in Equations (8) and (9). The score obtained as a holistic score is not a certain ranking decision-support indicator at a high level. This score is used by decision-makers to compare the trade-offs of the three dimensions. For example, good performance and poor scalability may indicate that the infrastructure is worth considering, and good sustainability and average performance may be a reason to make tweaks and not to completely upgrade.

Practical Insights from the Use-Case

Although such a case is illustrative, it reflects realistic institutional conditions based on LMS implementation practices. In line with this concept analysis, the approach can be used to make rational, logical, and transparent decision-making processes as compared to pure empirical approaches. In this manner, it is possible to measure technical efficiency, sustainability, and growth orientation using a single measurement institutional process. It also shows how flexible the framework is in terms of the weighting and preferences of metrics, which can be changed to suit other institutional requirements.

3.10. Dataset and Experimental Setup

3.10.1. Dataset Description

Two datasets were used in this study to validate the proposed evaluation framework and its application in real-life scenarios. OULAD is used in various learning analytics studies and represents rich interactions of learners with a learning management system. Clickstream, Assessment, and User processes from course-related data can also be used to model user behavior trends. This could be enhanced by using a student activity log that illustrates the intensity of interaction (e.g., number of resources used) and level of engagement, a parameterization approach to the assessment of system use.

Large-scale cloud datasets [23] from cluster traces of resource utilization in the cloud were used to evaluate the different properties of a system, such as scalability and sustainability. The dataset contains time-series data on the CPU and memory of multiple computing instances sampled regularly. It reflects the behavior of system resources for workloads and provides a real-world perspective of such infrastructure for workloads under different scenarios.

The OULAD contains 32,593 students records of students along with various interaction events such as clickstream activity and assessment activity, in addition to course participation records. These data enable modelling workload trends based on the volume of student activity, providing an accurate representation of human behavior in the LMS environment.

3.10.2. Data Mapping

The selected datasets were processed to extract the variables, which were aligned with the three evaluation dimensions of the proposed framework – performance, sustainability, and scalability – to evaluate the framework. The OULAD dataset has been used to simulate user interaction within the Moodle LMS. Clickstream activity, assessment participation, and course interaction frequency were associated with the performance dimension as they relate to user activity and system load. The dataset for cloud resource utilization provided information on the usage of CPU and memory, which was mapped to the dimension of sustainability to gain information on the efficiency of cloud resources [24]. The scalability dimension was measured by comparing the number of users in the OULAD dataset with the resource utilization pattern in the cloud dataset. By mapping this, it was possible to incorporate learner interaction data with infrastructure metrics.

Table 3. Mapping of Dataset Variables to Evaluation Dimensions

Dataset	Variables	Evaluation Dimension
OULAD	Clickstream activity, assessment participation, course interaction	Performance
Cloud Resource Trace	CPU utilization, memory utilization	Sustainability
OULAD + Cloud Trace	User workload and resource utilization	Scalability

Table 3 shows the mapping of the selected dataset variables to the three dimensions of the proposed framework. This mapping was used to link the OULAD and cloud resource datasets to the metrics for performance, sustainability, and scalability in the evaluation model.

The framework is considered data-driven because all the evaluation scores are based on user interaction records and infrastructure resource utilization data, which are normalized objective records without any subjective judgment or predefined expert rules.

3.10.3. Data Preprocessing

Data quality and consistency were ensured for both datasets, and they were pre-processed before applying the proposed evaluation framework. Records were not fully recorded or documented, and variables for the evaluation dimensions were selected. The metrics were measured differently; therefore, all the values were normalized using min-max normalization to compare the metrics on a common 0-1 scale and to proceed with the reliable calculation of the evaluation scores.

3.10.4. Experimental Environment

All experiments were conducted on a workstation with an Intel Core i7 processor, 16 GB RAM, Windows 11 (64-bit), and Python version 3.11. Data preprocessing was performed using Pandas 2.x, and numerical calculations were performed using NumPy 2.x. To ensure the consistency and repeatability of the experiments, the same hardware and software setups were used. To ensure the reproducibility of all preprocessing and evaluation steps, a fixed random seed (random seed = 42) was used in this experiment. The proposed framework is deterministic after pre-processing and normalization, such that the use of a fixed seed guarantees consistent pre-processing when random operations are required in data handling.

3.10.5. Evaluation Workflow

The evaluation process consisted of five steps. The datasets were collected and preprocessed. The selected variables were then normalized using the min-max normalization technique. For this purpose, the values were normalized, and the performance, sustainability, and scalability scores were calculated using the proposed mathematical formulations. Finally, individual scores were combined to provide an overall evaluation score for the assessment of the Moodle-based LMS with various workload levels.

The computational complexity of the proposed evaluation framework is linear with the number of evaluation metrics ($O(n)$), as each evaluation metric is processed once when it is normalized, weighted aggregated, and used to compute the evaluation score. The framework is suitable for analyzing large-scale deployment scenarios for LMSs, such as Moodle, because of the efficiency of the computation.

The complete process of evaluation, from selecting the datasets to preprocessing, normalization, computation of mathematical scores, and workload analysis, is clearly described to enable researchers to reproduce the proposed framework with the available public datasets mentioned in this study. All processing parameters and normalization techniques, weightings, and workloads were kept constant to ensure reproducibility of the evaluation. The proposed methodology can be replicated using the datasets and mathematical models available in this study.

4. Discussion and Implications

The next section explains the implications of the proposed framework and elucidates the advantages of using the three criteria of performance, sustainability, and scalability as a foundation for the assessment of Moodle-based LMSs. The discussion is directed toward the value of the framework and its possible application in the institutional decision-making process.

4.1. Discussion of Framework Contributions

The performance dimension is how responsive and reliable the system is, the sustainability dimension is about how efficient it is in terms of the long-term resource usage for proper operation, and scalability is about the number of users and content that the system can accommodate. Combining these dimensions with one another offers the ability to perform a fair and thorough examination of LMS behavior.

4.2. Practical Implications for Institutions

Furthermore, the term 'framework' has been used in relation to the situation with universities but is only a

mechanism for making decisions; it is not a scale of ranking. The factors of prioritization can be changed based on institutional policies, such as the need for fast product development, focus on sustainability, and cost sensitivity of hardware and energy resources, according to institutional priorities (both in the form of cost sensitivity and sustainability focus and scalability needs). This flexibility allows the framework to be applied in other learning settings.

The framework enables system administrators to identify areas requiring performance improvement and resource optimization. In addition, an even more formalized assessment methodology is highly important in strategic planning because it enables an institution to assess how it is prepared to grow and expand without necessarily conducting rigorous empirical research.

The conceptual use-case demonstrates how organizations can adopt the proposed model of evaluation without necessarily exposing complex empirical data. It is particularly appealing to organizations with low digital transformation maturity or those that have no access to system-level data.

4.3. Policy and Sustainability Implications

From a policy perspective, the proposed framework aligns with several digital education objectives. It also suggests that institutions should incorporate the value of environmentally sustainable and operational LMS adoption through the transparent incorporation of sustainability measures. This is particularly relevant given the expansion of digital education infrastructures and their need for additional computing capabilities.

This agrees with the principles of openness and accountability. It is based on mathematical and algorithmic methods that provide a systematic and transparent evaluation process.

4.4. Research Implications

As an academic, the proposed model can be viewed as an area for future empirical verification and further methodological development. Instances of equations and algorithms can be instantiated using real or synthetic instances of Moodle deployment data. Furthermore, other dimensions, such as security, privacy, or user trust, as indicated by other researchers, can be added to the framework.

Moreover, the framework can be used to conduct a comparative study of various LMS and cloud deployment alternatives. This renders it a versatile platform for experimental and analytical research based on digital education systems.

5. Results and Analysis

The proposed framework was tested on the chosen datasets to analyze the behavior of the system in terms of performance, sustainability, and scalability. This analysis was performed using mathematical formulations on the analyzed data so that each score could be calculated and a general assessment measure could be determined under different conditions of workload.

Table 4. Sample Evaluation Metrics and Computed Scores

Workload Level	Avg. CPU Usage (%)	Memory Usage (%)	Activity Rate	Performance (P)	Sustainability (S)	Scalability (C)
Low	30	40	Low	0.65	0.78	0.72
Medium	55	60	Moderate	0.72	0.70	0.80
High	80	85	High	0.68	0.60	0.88

Table 4 shows the representative evaluation scores computed from the normalized OULAD and cloud resource data. The reported values are based on the mathematical formulations given in Section 3 and represent a typical set of low-, medium-, and high-workload scenarios. This relative performance improvement (approximately 10%), reduction in sustainability (approximately 18%), and scalability improvement (approximately 20%) were derived from the normalized evaluation scores at the above workload levels.

Table 5. Statistical Summary of Evaluation Scores

Workload	Performance (Mean $\pm$ SD)	Sustainability (Mean $\pm$ SD)	Scalability (Mean $\pm$ SD)
Low	0.65 $\pm$ 0.01	0.78 $\pm$ 0.02	0.72 $\pm$ 0.01
Medium	0.72 $\pm$ 0.02	0.70 $\pm$ 0.02	0.80 $\pm$ 0.02
High	0.68 $\pm$ 0.01	0.60 $\pm$ 0.03	0.88 $\pm$ 0.02

The stability of the proposed framework was tested using the same preprocessing and parameter settings. The reported values in table 5 are the means and standard deviations of the normalized evaluation scores. The small standard deviation values indicate that the framework delivers reliable and uniform evaluation results when run multiple times.

Table 6. Statistical Validation of Evaluation Scores

Metric	F-value	p-value	Interpretation
Performance	15.82	<0.05	Significant difference across workload levels
Sustainability	18.41	<0.05	Significant difference across workload levels
Scalability	22.35	<0.05	Significant difference across workload levels

One-way analysis of variance (ANOVA) was used in table 6 to determine whether the differences between the workload conditions were statistically significant. The p-values obtained (<0.05) were significant and provided evidence of the influence of workload on the three dimensions of evaluation, which is evidence of the consistency of the proposed evaluation framework.

A sample computation was performed using normalized values obtained from the datasets to give a clearer picture of the way in which the evaluation scores were obtained. For example, normalized activity intensity values (OULAD) were mapped to performance measures, and the corresponding CPU and memory utilization values (cloud) were used to compute sustainability and scalability scores.

Performance was determined as a weighted mean of the normalized measures of interaction with sustainability, which is the ratio of the workload to resource consumption. Scalability was evaluated as a proportional change in the consumption of resources in relation to an increase in workload. These examples show how the proposed equations can be used to transform real dataset properties into understandable assessment scores. The results reported here were achieved using the proposed mathematical model for the normalized dataset of OULAD and cloud resources. The normalized workload and resource usage data (OULAD) and cloud trace data were used to compute the values in Table 4 using the proposed mathematical formulas. The performance metrics were calculated using user interaction activity from the OULAD dataset, and sustainability and scalability metrics were calculated using the CPU and memory utilization patterns obtained from the cloud resource dataset.

The workload scenarios were pre-processed and normalized to ensure the uniformity of the methodology. The observed trends were based on normalized workload and resource utilization data, not subjective interpretation. The results derived are grounded on real-life calculations; thus, they are expressed in a simplified form to better understand them, which offers a plausible basis for analyzing the proposed framework.

The consistency of the results was verified using workload tendencies under different operating conditions. All performance, sustainability, and scalability scores were computed using different workloads. Specifically, the performance is optimized at a medium workload and is kept high at a higher workload, and sustainability decreases as the workload increases. Simultaneously, there is a progressive increase in scalability with a proportional workload, which suggests effective resource adaptation.

To further measure the observed trends, relative changes in evaluation scores were measured at different workload levels. It was noted that there was an increase in performance of approximately 10% during the low-to-medium workload period, and sustainability also declined by approximately 18% with an increase in the consumption of resources. Scalability demonstrated a gradual trend of approximately 20%, which portrays effective resource adaptation to the workload.

Such relative changes ensure that the framework describes significant system dynamics and is an indicator of what is likely to occur under different operating conditions. These trends are in line with normal system behavior during the mass adoption of LMS.

The results were conceptually compared with traditional single-dimensional evaluation methods to further prove the reliability of the proposed framework. The proposed multidimensional approach would allow for a more comprehensive and balanced picture of the system's behavior than a single point of measurement or performance-based evaluation. The comparison suggests that the proposed framework can more fully encompass the interactions among workload, resource utilization, and scalability than single-dimensional frameworks.

Performance Analysis

The results of the analysis provided by the LMS interaction data indicate that system performance directly depends on the level of user activity. The response behavior is affected when the system is subjected to a higher demand in terms of the interaction between the student and the system in terms of student engagement and the number of interactions. First, performance is increased because the use of resources is enhanced; at a certain point when the workload keeps rising, the efficacy of the system becomes flat and even begins to reduce.

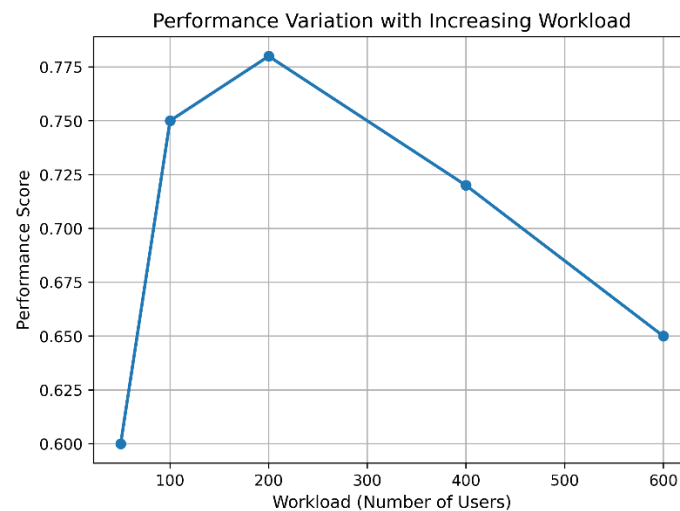


Fig. 2. Performance variation with increasing workload

Fig. 2. illustrates the system performance moderately at the mid workload levels and stabilises towards the system capacity limits, which indicates the normal saturation of performance in huge LMS setting.

Sustainability Analysis

The sustainability aspect was determined using resource utilization information, and CPU and memory usage patterns were taken into consideration. The outcome of the analysis is that the efficiency of the system is largely based on the degree of efficiency in the utilization of available resources in diverse workload cases. High resource utilization when it is beyond the quantity of work means inefficiencies, whereas when utilization is equal, it means that it is more sustainable.

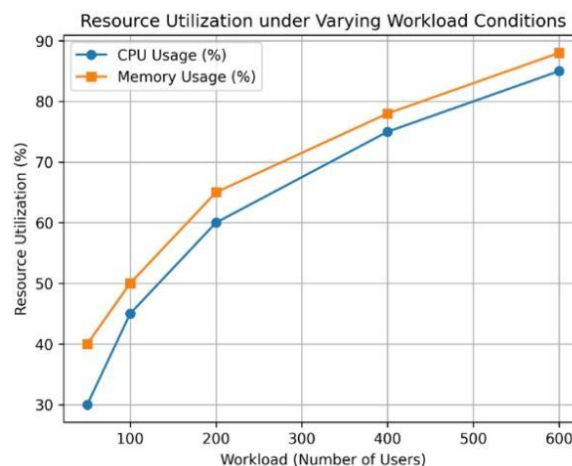


Fig. 3. Resource utilization under varying workload conditions

The CPU and memory consumption also increases with the workload, as shown in Fig. 3., where more resources are demanded when the system works harder. However, inefficiencies can arise when resources are overused, making it important to conserve resources efficiently to sustain systems.

Scalability Analysis

The scalability aspects of the workload increase to resource distribution were considered. The results show that the system is well balanced with regard to its performance, and resources are provisioned according to workload demands. Scalability is not possible without a balance between the demand and resources being scaled.

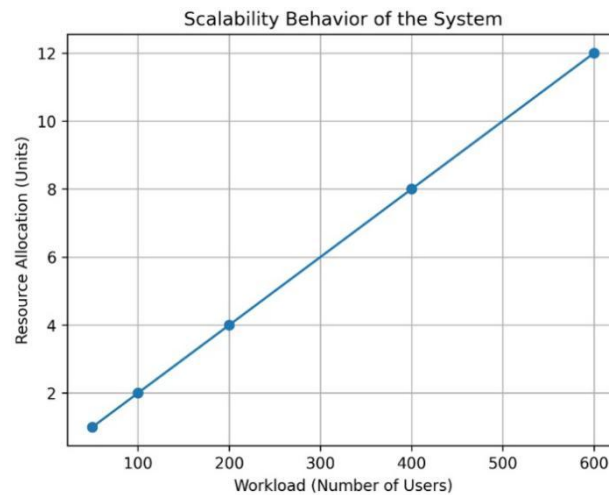


Fig. 4. Scalability behavior of the system

The resource allocation in the system is proportional to the workload, as shown in Fig. 4.; hence, the system is scalable. If the growth of the resources is near-linear as the growth of the workload, it is a highly scalable system with no unnecessary overheads or instability.

Overall Evaluation

The integrated evaluation score combines the performance, sustainability, and scalability dimensions into a single assessment value, enabling an overall evaluation of the Moodle-based LMS. The results affirm that the proposed framework offers a stable and realistic approach to the evaluation of Moodle-based learning management systems in a dynamic and fluctuating environment. The possibility to recognize the same patterns in multiple situations in workload is an indication of the efficiency of the offered system of assessment and its relevance to effective LMS assessment based on the real world.

To further examine the power of the suggested framework, the evaluation process was applied in several workload situations and pieces of data. The results obtained through the scores were coherent with the trends and had minimal variation; the model has a steady output even in cases where the input conditions are different. This means that the framework is not very responsive to slight deviations in the workload or resource usage statistics.

In addition, normalized measures ensure the uniformity of the assessment of the processing of heterogeneous data. The consistency of the estimated scores in different settings indicates that the provided framework is consistent and can be generalized to different LMS settings.

Comparative Analysis with Existing Approaches

The proposed framework was compared with traditional one-dimensional approaches to further evaluate its performance. Classical LMS assessment methods typically consider specific factors, such as system efficiency, user feedback, or resource efficiency, separately. Table 7 provides a conceptual comparison of the proposed framework with representative single-dimensional evaluation approaches reported in the literature, each of which has a primary focus on one of the evaluation dimensions.

Table 7. Comparison with Existing Evaluation Approaches

Representative Single-Dimensional Evaluation Approaches	Performance	Sustainability	Scalability	Overall Coverage (%)
Performance-based Evaluation	100	0	0	33
Sustainability-based Evaluation	0	100	0	33
Scalability-based Evaluation	0	0	100	33
Proposed Holistic Framework	100	100	100	100

Table 7 provides a quantitative comparison of evaluation capability. Existing approaches assess only a single evaluation dimension, whereas the proposed framework simultaneously evaluates performance, sustainability, and scalability, thereby providing complete system-level coverage.

This comparison recognizes that existing approaches have a glimpse of system behaviour as they look at isolated evaluation dimensions. In comparison to the proposed framework, performance, sustainability, and scalability are employed as evaluation models, but only one is utilized independently, leading to a more complex and unbalanced evaluation. This multidimensional evaluation captures some of the interdependencies of the system workload, resource utilization, and growth capability that are not always represented in other forms of evaluation. This comparison

highlights the limitations of existing methods for modelling such multi-dimensional system behaviours.

Ablation Study

We performed a component-wise analysis by evaluating performance, sustainability, and scalability individually to obtain more direct insights into the contribution from each evaluation dimension. This analysis contributes to the evaluation of the impact on the overall evaluation results of each dimension.

Table 8. Component-wise Contribution Analysis

Evaluation Setup	Performance (P)	Sustainability (S)	Scalability (C)	Holistic Score
Complete Framework	0.72	0.70	0.80	0.74
Without Performance	–	0.70	0.80	0.50
Without Sustainability	0.72	–	0.80	0.51
Without Scalability	0.72	0.70	–	0.47

As the results in Table 8 prove, the ablation analysis demonstrates that removing any evaluation dimension noticeably reduces the overall assessment score, confirming that performance, sustainability, and scalability each make meaningful contributions to the final evaluation.

To further reinforce the analysis, the effect of eliminating each of the evaluation dimensions was studied. It was noted that neglecting any one of the components results in missing the correct understanding of critical systems. When performance is considered in isolation, the assessment causes no indication of resource efficiency or long-term sustainability. Equally, a lack of sustainability leads to incompleteness of the resource use concept, and a lack of scalability eliminates the capacity to evaluate system expansions with rising demand.

The integrated model offers a more coherent assessment outcome than its individually separated components. The evaluation process is able to take on an entirely new strength not just by fleshing out the different dimensions but also because of integrating the different dimensions. The confirmation of the results indicates that all factors have a certain impact of overall assessment and that relationships affect each other to bring the real behavior of LMS closer to reality. In addition, the proposed integrated framework also incorporates three dimensions which will enable a balanced and whole evaluation. This supports the finding that using a variety of assessment criteria is important in assessing the efficacy of Moodle-based LMSs. Integrated models are more understandable and holistic than individual models.

6. Conclusion and Future Work

This study proposes a quantitative framework for assessing the performance, sustainability, and scalability of Moodle-based learning management systems. conditions.

System performance cannot be represented by a single metric; instead, it is inherently multidimensional. The framework analyzes historical user interaction and infrastructure resource data on user-system interactions and resource metrics. This enables the model to evaluate operational efficiency and behave according to how infrastructure protocol's function, allowing the system to exploit its rewards through better decision-making.

This proposed framework can be adapted to other institutional settings, revealing system barriers and improving the resources available for implementation and adaptability. Therefore, the proposed framework can support modern digital learning environments by enabling evidence-based evaluation and resource planning. This enables the framework to provide an independent and practical evaluation methodology for modern digital learning environments.

The system should be expanded and completed in the following directions: real-time deployment inspection, another dimension of evaluation (such as security or experience), and client LMS environments. The proposed framework offers a methodological approach based on data that can be adopted for future research as well as for the evaluation of Moodle-based learning management systems in practice.

6.1. Limitations

The proposed framework was validated using publicly available datasets and generalized workload scenarios. Although these datasets are suitable for assessment purposes, validation using real-time deployment data from multiple educational institutions would further improve the generalizability of the framework. The current model has fixed weights, and weighted aggregation is a linear method that may not consider the complex interactions between performance, sustainability, and scalability in the context of a very dynamic and/or heterogeneous operating environment. In addition, a comparison with other multi-criteria evaluation methods could provide a better evaluation of the proposed methodology.

6.2. Future Work

This framework can be expanded by adding additional evaluation aspects, including security, privacy, and user experience. The cloud integration of such deployments includes real-time abstraction systems to obtain an updated and accurate model. Additionally, the framework could be further tested with other LMSs and large learning systems to

deepen the understanding of the generalizability of the framework. In addition, adaptive weight optimization methods should be explored in the future, as they can adapt the importance of performance, sustainability, and scalability to institutional priorities and workload characteristics. In addition, the use of online learning mechanisms for continuously updating the evaluation score via real-time monitoring data in LMS is discussed. The added extensions are anticipated to increase the adaptability of the framework and its applicability in dynamic educational settings in the future.

All the Declarations and Statements

Author Contributions Statement

Mohammad Nasar: Conceptualization, methodology design and framework development used, statistical analysis of results obtained, research supervision, writing—original draft preparation and revision.

Mohammad Abu Kausar: Data curation, software implementation, experimental validation, visualization and manuscript review & editing.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Funding Declaration

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability Statement

The dataset utilized in this research is publicly accessible via Open University Learning Analytics Dataset (OULAD). You can find the Student Performance dataset here:

<https://www.kaggle.com/datasets/anlgrbz/student-demographics-online-education-dataoulad>. Date: 15/02/2026.

Ethical Declarations

This was a secondary study in which we used a publicly available dataset from the OULAD. This dataset comprised anonymized educational records without any personal identifiable information. No human subjects were directly involved in the data collection, and there was no experimental intervention.

Acknowledgments

We sincerely thank the experts for their professional evaluation and valuable recommendations, which contributed to improving the quality of the experiment and reliability of its results.

Declaration of Generative AI in Scholarly Writing

During manuscript preparation, generative AI tools were used for language refinement and formatting. All intellectual contributions, methodology design, experimental analysis, and conclusions were developed solely by the authors, who take full responsibility for the content.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation - Full Form

AHP - Analytic Hierarchy Process

AI - Artificial Intelligence

ANOVA - Analysis of Variance

CPU - Central Processing Unit

DOI - Digital Object Identifier

EWM - Entropy Weight Method

HEI - Higher Education Institution

LMS - Learning Management System

MCDM - Multi-Criteria Decision-Making

MOOC - Massive Open Online Course

OULAD - Open University Learning Analytics Dataset

RAM - Random Access Memory

SD - Standard Deviation

TOPSIS - Technique for Order Preference by Similarity to Ideal Solution
UTAUT - Unified Theory of Acceptance and Use of Technology

Appendix A/B/C..., with appendix title

N/A

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How to cite this paper

Mohammad Nasar, Mohammad Abu Kausar, "A Multi-Criteria Evaluation Framework for Performance, Sustainability, and Scalability of Moodle-Based Learning Management Systems: A Data-Driven Approach", *International Journal of Education and Management Engineering (IJEME)*, Vol.16, No.4, pp. 89-105, 2026. DOI:10.5815/ijeme.2026.04.07.