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Design and Evaluation of an Offline-First Web Application for Inclusive Distance Learning in Low-Connectivity Environments Using the ADDIE Framework

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Abstract

The digital divide in low-connectivity regions continues to hinder the implementation of inclusive distance learning, particularly in developing countries. This study aims to design and evaluate an offline-first web application that is lightweight, data-efficient, and capable of operating under unstable network conditions. The research adopts a Research and Development (R&D) approach using the ADDIE framework (Analyze, Design, Develop, Implement, Evaluate). The application is developed using the Laravel framework and RESTful API, incorporating offline-first architecture and caching mechanisms to optimize data usage and accessibility. A field-based evaluation was conducted in Gunungkidul, Yogyakarta, involving 52 participants consisting of high school students and teachers. Evaluation metrics include functional testing, data transfer efficiency, latency measurement, and usability assessment using the System Usability Scale (SUS). The results indicate a high functional success rate of 94.8%, data transfer efficiency of 89.1%, an average payload of approximately 1 MB per session, and a median latency of 910 ms. The usability evaluation yields a mean SUS score of 74.2, categorized as acceptable to good usability. These findings demonstrate that the proposed offline-first approach integrated with the ADDIE framework provides an effective and practical solution for supporting inclusive distance learning in low-connectivity environments. The study highlights the feasibility and scalability of lightweight web applications in addressing the educational digital divide.

Keywords: ADDIE; distance learning; inclusive education; offline-first; RESTful API

1. Introduction

Inclusive education has become a global priority as emphasized in Sustainable Development Goal (SDG) 4, which aims to ensure equitable access to quality education for all. Despite various international commitments, including the Universal Declaration of Human Rights and the Convention on the Rights of the Child, the implementation of inclusive education in developing countries continues to face significant challenges, such as limited infrastructure, insufficient teacher training, and persistent socioeconomic disparities [1], [2], [3]. The COVID-19 pandemic further intensified these inequalities and highlighted the urgent need for innovative strategies capable of sustaining inclusive learning under constrained conditions [4], [5].

In Indonesia, the digital divide is particularly visible in remote, underdeveloped, and frontier regions (3T areas). Although internet penetration has increased in recent years, only a limited proportion of students effectively utilize digital technologies for online learning. Major barriers include unstable network infrastructure, low levels of digital literacy, and socioeconomic conditions that disproportionately affect students from rural and low-income communities [6], [7], [8]. These challenges are further exacerbated by

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limited device ownership and inadequate technological competencies among teachers, ultimately widening the educational gap [9], [10].

Previous studies have proposed various technological approaches to support distance learning in low-connectivity environments. These include the use of local intranet-based learning systems [11], Learning Management Systems [12], portable learning platforms such as EduPAL [13], low-bandwidth web-based learning systems [14], and Progressive Web Applications [15]. Although these studies provide valuable contributions, most of them primarily focus on infrastructure optimization or generic platform development. Consequently, they do not specifically address the contextual challenges of Indonesian 3T regions, where unstable network conditions, low-specification mobile devices, and limited digital literacy coexist as dominant constraints.

Based on these limitations, the primary research problem addressed in this study is how to design a lightweight and data-efficient web-based distance learning application that remains functional under low-connectivity conditions to support inclusive education. This issue is particularly relevant for Generation Z learners, who are highly accustomed to mobile-first digital interactions and expect responsive, fast, and accessible learning experiences. However, in low-connectivity environments, unstable signals and high data consumption frequently disrupt the continuity of online learning activities. Therefore, there is a need for a web application architecture that is adaptive, lightweight, and resilient to network fluctuations.

The novelty of this study lies in the integration of the ADDIE instructional design framework with the development of a lightweight web application using Laravel and RESTful API, supported by offline-first architecture and caching mechanisms. Unlike previous studies that mainly emphasize infrastructure or general platform functionality, this research focuses on the combination of instructional design and technical optimization within low-connectivity educational contexts. In addition, the proposed system is evaluated through a field-based evaluation involving Generation Z students and teachers in a real-world low-connectivity environment.

Therefore, this study aims to design and evaluate an offline-first web application for inclusive distance learning that is efficient, reliable, and usable in low-connectivity environments. The findings are expected to contribute both theoretically, by extending the application of instructional design in constrained digital contexts, and practically, by providing a scalable and data-efficient solution to support inclusive education in regions affected by the digital divide.

2. Research Methodology

This study employed a Research and Development (R&D) approach using the ADDIE framework, which consists of five stages: Analyze, Design, Develop, Implement, and Evaluate. The ADDIE model was selected because of its systematic yet flexible structure, making it suitable for developing and evaluating a web-based learning application in low-connectivity educational environments. Figure 1 presents the overall research workflow based on the ADDIE framework employed in this study.

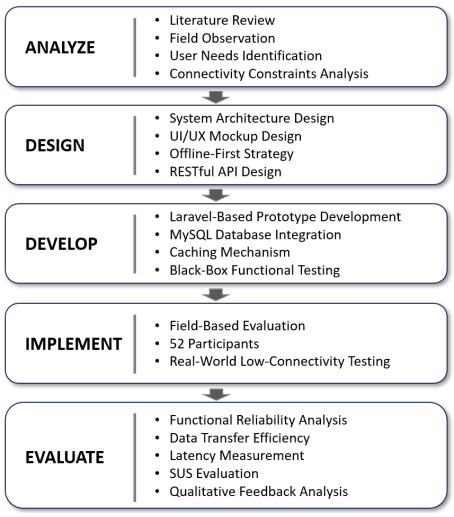

Figure 1. Research workflow based on the ADDIE framework.

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a. Needs Analysis

The initial stage focused on identifying user needs through literature review and field observation. The study was conducted in Gunungkidul, Special Region of Yogyakarta, Indonesia, because several areas in this region experience unstable and weak internet connectivity that resembles the characteristics of 3T regions. A total of 52 participants were involved, consisting of high school students and active teachers from several low-connectivity areas within Gunungkidul. The inclusion criteria required participants to have experienced online learning for at least one semester and to use smartphones as their primary learning devices. The increased number of participants was intended to provide broader usability and performance evaluation coverage across different user characteristics and device specifications.

Data were collected using questionnaires and semi-structured interviews to identify major challenges related to online learning, including unstable network quality, limited device capability, and digital literacy constraints. Quantitative data were analyzed descriptively, while qualitative responses were processed using thematic analysis to identify recurring issues and user expectations.

b. System Design

Based on the results of the needs analysis, the system was designed as a lightweight web-based learning application using the Laravel framework and RESTful API architecture. Laravel was selected because of its stability, mature ecosystem, extensive documentation, and rapid development capability, which aligns with the iterative nature of R&D-based system development.

The system architecture emphasized three main principles: lightweight performance, data efficiency, and accessibility in low-connectivity conditions. To achieve these objectives, the application incorporated offline-first architecture and caching mechanisms that allow users to access learning materials even during temporary network disruptions. The user interface was designed to be simple, responsive, and compatible with low-specification mobile devices commonly used in rural areas.

The design outputs included system blueprints and user interface mockups, which were subsequently reviewed by experts in information systems and educational technology to assess design feasibility and usability.

c. Prototype Development

The development stage involved implementing the system design into a functional prototype using Laravel 10 and MySQL database technology. RESTful API was utilized to manage communication between the client and server efficiently, thereby minimizing unnecessary data transfer.

Initial testing was conducted using black-box testing to verify the functionality of the core system features, including user authentication, learning material access, offline reading capability, and synchronization processes. System efficiency was evaluated using data transfer efficiency measurements formulated as follows:

$$E = \frac{D_s}{D_t} \times 100\%$$

where E represents data transfer efficiency, D_s denotes successfully transmitted data, and D_t represents the total transmitted data. The measurement data were obtained from server log records during the testing sessions.

d. Field Implementation

The prototype was implemented through a field-based evaluation involving the same participants in Gunungkidul. The implementation stage aimed to evaluate the application performance under real-world low-connectivity conditions. The broader participant involvement allowed the evaluation to capture more diverse usage patterns, device capabilities, and network variability conditions.

The evaluation instruments consisted of application usage logs and the System Usability Scale (SUS) questionnaire developed by Brooke (1996). The SUS instrument contains ten items measured using a five-point Likert scale ranging from strongly disagree to strongly agree. The SUS score was calculated using the standard formula:

$$SUS = \left(\sum_{i=1}^{n} S_i \right) \times 2{,}5$$

where S_i represents the adjusted score for each questionnaire item. Based on Bangor et al. [16], a SUS score of 68 or higher indicates acceptable usability.

e. Evaluation

The evaluation stage aimed to assess the overall performance and usability of the developed application using both quantitative and qualitative approaches. Quantitative evaluation included measurements of functional success rate, data transfer efficiency, synchronization performance, content loading latency, and SUS scores.

1. Additional testing was conducted to evaluate synchronization reliability during unstable network transitions, particularly during offline-to-online switching scenarios. The indicators measured included synchronization success rate and synchronization failure frequency recorded in the system logs.
2. The study defined three main success indicators:
    a) Functional success rate exceeding 90%,
    b) At least 75% of participants achieving SUS scores ≥ 68, and
    c) Average SUS scores above 70.

    The larger participant pool also improved the robustness of usability and performance observations obtained during the evaluation process.

Qualitative evaluation was performed by analyzing participant feedback regarding user experience, application accessibility, and perceived system limitations. The results were used to identify strengths, weaknesses, and recommendations for further system improvement.

3. Results and Discussion

a. Respondent Characteristics

This study involved 52 participants ($n = 52$) from Gunungkidul, Special Region of Yogyakarta, Indonesia, consisting of 38 high school students (73.1%) and 14 active teachers (26.9%). The evaluation was conducted in several low-connectivity areas within Gunungkidul to assess the feasibility and usability of the proposed application under real-world network constraints representative of 3T-like environments.

All participants used smartphones as their primary devices for accessing the application, with 40.4% of them using low-specification smartphones with RAM capacities of 3 GB or lower. In addition, all respondents had experienced online learning for at least one semester, making them relevant participants for evaluating the usability and performance of the proposed system under real-world conditions. Table 1 presents the demographic distribution of respondents, device characteristics, and prior online learning experience.

Table 1. Participant demographics and device characteristics ($n = 52$)

Characteristic	Category	Total	Percentage
Role	Student	38	73.1%
	Teacher	14	26.9%
Device	Smartphone RAM ≤ 3 GB	21	40.4%
	Smartphone RAM > 3 GB	31	59.6%
Online Learning Experience	≥ 1 semester	52	100%

The findings reflect the reality of many low-connectivity and rural educational environments, where smartphones serve as the dominant learning devices [17], [18]. The relatively high proportion of low-specification devices further strengthens the relevance of developing lightweight and data-efficient learning applications. The broader participant composition also allowed the study to capture more diverse patterns of user interaction and device performance under constrained connectivity conditions.

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b. Functional Reliability of the Application

The functional testing results indicate that the application achieved an average functional success rate of 94.8%. This value was obtained through scenario-based black-box testing using PASS/FAIL evaluation criteria across four core features: authentication, learning material access, offline reading, and synchronization, with evaluations conducted across multiple testing sessions involving diverse participant devices and connectivity conditions.

Authentication achieved the highest success rate at 98.0%, followed by offline reading functionality at 96.5% and learning material access at 95.5%. Meanwhile, the synchronization feature recorded the lowest success rate at 90.0%, primarily due to interruptions occurring during offline-to-online network transitions. The detailed functional testing results are presented in Table 2.

Table 2. Functional reliability testing results ($n = 52$)

Feature	Total Scenarios	Successful	Failed	Success Rate
Authentication	100	98	2	98.0%
Learning material access	110	105	5	95.5%
Offline reading	85	82	3	96.5%
Synchronization	100	90	10	90.0%

Figure 2 illustrates the comparative functional success rates across the evaluated application features. As shown in the figure, the synchronization feature achieved the lowest success rate compared to the other core features, indicating that offline-to-online transitions remain the most technically sensitive process in low-connectivity environments.

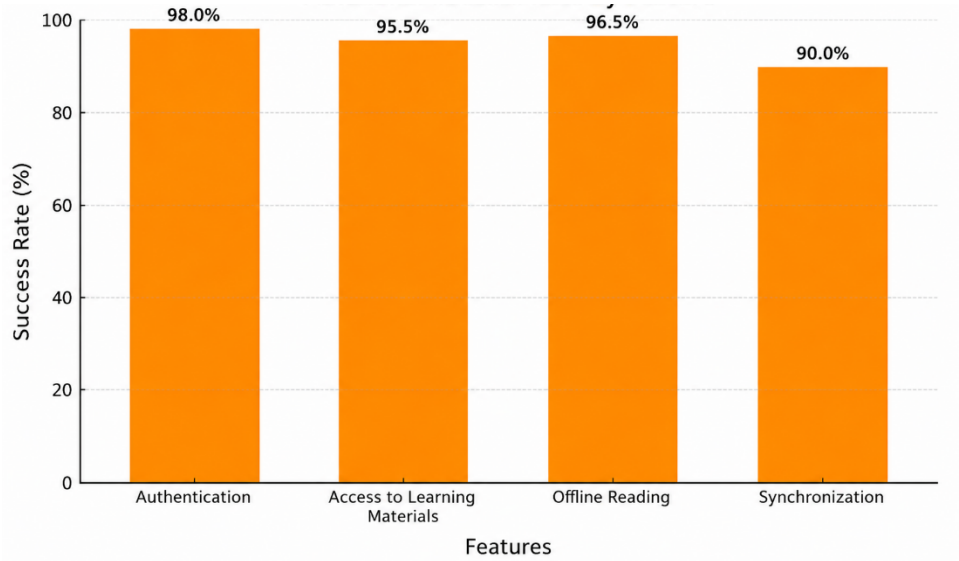

Figure 2. Functional success rate by feature

The results demonstrate that all core features exceeded the minimum functional success indicator of 90%, indicating that the implementation of offline-first architecture and caching mechanisms effectively maintained system availability under unstable network conditions. These findings are consistent with previous studies emphasizing the importance of lightweight and data-efficient solutions for supporting distance learning in constrained environments [19].

The synchronization feature, although still meeting the minimum success threshold, showed lower reliability compared to the other features. This finding confirms that synchronization processes remain one of the most technically sensitive aspects of offline-first systems, particularly when network conditions fluctuate rapidly during offline-to-online transitions.

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c. Data Transfer Efficiency and Latency

The performance evaluation results show that the application achieved an average data transfer efficiency of 89.1% with a standard deviation of 5.2. The median efficiency value was 90.3%, indicating relatively stable performance across testing sessions.

The application also demonstrated lightweight data consumption characteristics, with an average payload size of approximately 1.05 MB per session. In addition, the median content loading latency was recorded at 910 ms, which remains within an acceptable response time range for web-based applications operating under constrained network conditions.

The detailed performance metrics are summarized in Table 3.

Table 3. Data transfer efficiency, payload, and latency ($n = 52$)

Parameter	Mean	SD	Median	IQR
Efficiency (%)	89.1	5.2	90.3	86.4–92.7
Payload (MB/session)	1.05	0.21	1.04	0.92–1.18
Latency (ms)	915	180	910	780–1,160

The distributions of data transfer efficiency and content loading latency are presented in Figure 3. Figure 3(a) shows that most testing sessions maintained efficiency values above 85%, indicating stable data transmission performance under low-connectivity conditions. Meanwhile, Figure 2(b) demonstrates that the majority of latency measurements remained below one second, suggesting acceptable responsiveness for mobile-based distance learning applications.

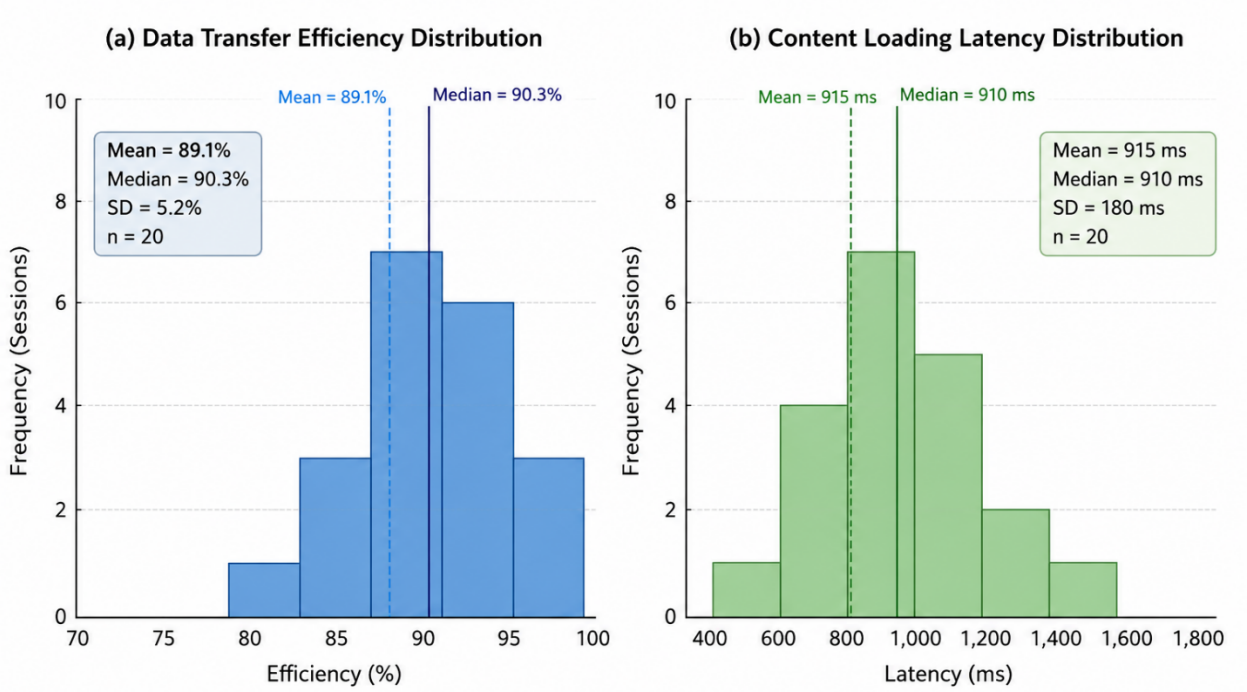

Figure 3. Performance evaluation results: (a) distribution of data transfer efficiency and (b) distribution of content loading latency.

The consistently high efficiency values indicate that the application successfully minimized unnecessary data transmission while maintaining system functionality. The average payload size of approximately 1 MB per session demonstrates the effectiveness of the lightweight system design, which aligns with low-bandwidth learning principles discussed in previous studies [14]. Furthermore, the relatively low latency suggests that the proposed application can still provide acceptable user responsiveness despite operating in unstable network environments. This is particularly important for mobile-first users who require fast and uninterrupted access to learning materials.

d. Usability (SUS)

The usability evaluation produced an average System Usability Scale (SUS) score of 74.2 with a standard deviation of 8.5 and a median score of 75. Approximately 75% of participants achieved SUS scores above the acceptable usability threshold of 68.

In addition, the SUS instrument demonstrated good internal reliability, with a Cronbach's alpha value of 0.83. The complete usability statistics are presented in Table 4.

Table 4. SUS evaluation results ($n = 52$)

Parameter	Value
Mean SUS	74.2
Standard Deviation	8.5
Median	75
Percentage ≥ 68	75%
Cronbach's Alpha	0.83

Based on the interpretation proposed by Bangor et al. [16] , the obtained SUS score falls within the acceptable to good usability category. Most participants reported that the application was easy to learn and simple to operate, particularly due to its lightweight interface and mobile-friendly design.

However, several respondents highlighted the lack of synchronization progress indicators during offline-to-online transitions. This suggests that although the technical performance was generally satisfactory, visual feedback and interaction transparency remain important usability considerations for future system refinement.

e. Additional Analysis

Additional analysis using Spearman correlation revealed a moderate negative relationship between latency and SUS scores, as well as a moderate positive relationship between data transfer efficiency and SUS scores. Although the observed correlations were moderate, further multi-site evaluations are still necessary to confirm the consistency of these relationships across broader low-connectivity educational environments.

These findings indicate that better technical performance, particularly lower latency and higher data efficiency, tends to contribute positively to user perceptions of usability. This observation is consistent with human-computer interaction principles stating that system responsiveness significantly influences user satisfaction and overall user experience (ISO 9241-210, 2019).

f. Qualitative Findings

The qualitative analysis identified four dominant themes from participant feedback. First, the offline caching feature was considered highly beneficial because it allowed users to continue accessing learning materials during temporary signal interruptions. Second, the simple and lightweight interface was perceived as suitable for smartphone-based learning environments.

Third, participants expressed the need for clearer synchronization progress indicators to improve user confidence during offline-to-online transitions. Finally, several respondents suggested additional features such as dark mode support, PDF download functionality, and last-read bookmarking.

These qualitative findings strengthen the quantitative results by confirming that lightweight performance and offline accessibility are highly valued by users in low-connectivity environments. At the same time, the findings highlight the importance of improving interaction feedback mechanisms to enhance overall usability and user trust.

g. Research Achievement and Implications

All predefined research performance indicators were successfully achieved, including functional success rates above 90%, average SUS scores exceeding 70, at least 75% of participants achieving SUS scores above 68, and data transfer efficiency approaching 90%.

These results demonstrate that the proposed Laravel–RESTful API web application integrated with offline-first architecture and caching mechanisms can serve as an effective solution for supporting inclusive distance learning in low-connectivity environments.

From a practical perspective, the proposed system has the potential to be adapted and replicated in other 3T regions with contextual adjustments to learning content and local infrastructure conditions. From a theoretical perspective, this study contributes to the growing discussion on integrating instructional design frameworks with lightweight web technologies for inclusive digital education.

h. Research Limitations

This study has several limitations. First, the evaluation was conducted within a single geographical region, limiting the broader generalizability of the findings across different 3T environments and network infrastructures.

In addition, this study did not evaluate device energy consumption, which may become an important consideration for users in areas with limited electricity access. Future studies are therefore recommended to involve larger multi-site evaluations and explore additional performance aspects, including synchronization robustness under highly fluctuating network conditions and mobile device energy efficiency.

4. Conclusion

This study successfully designed and evaluated an offline-first web application for inclusive distance learning using the ADDIE framework in low-connectivity environments. The proposed system, developed using Laravel and RESTful API with caching support, demonstrated strong functional reliability and efficient performance during the field-based evaluation conducted in Gunungkidul, Special Region of Yogyakarta, Indonesia. The evaluation involved 52 participants consisting of students and teachers from several low-connectivity areas within the region.

The evaluation results showed that the application achieved an average functional success rate of 94.8%, data transfer efficiency of 89.1%, and lightweight payload consumption of approximately 1 MB per session. In addition, the application obtained a System Usability Scale (SUS) score of 74.2, indicating acceptable to good usability among users. These findings suggest that the integration of offline-first architecture with instructional design principles can provide an effective and practical solution for supporting distance learning in low-connectivity educational contexts.

The study also revealed that technical performance factors, particularly data transfer efficiency and latency, tend to influence user perceptions of usability. Furthermore, qualitative feedback indicated that offline caching and lightweight interface design were highly beneficial for users, although synchronization processes still require improvement, especially in terms of progress indicators during offline-to-online transitions.

Despite these promising results, this study has several limitations, including the limited geographical coverage of the evaluation and the absence of multi-region implementation across different 3T network environments. Therefore, future studies are recommended to conduct larger multi-site evaluations across more representative 3T regions and to further investigate synchronization robustness and mobile device energy efficiency under fluctuating network conditions.

Overall, the findings demonstrate that lightweight offline-first web applications integrated with instructional design principles have strong potential to support inclusive digital education and reduce the educational digital divide in low-connectivity environments.

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