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Research article

Architectural Consideration for Gamified Learning Systems: An Exploration of Offline-First Progressive Web Application

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ABSTRACT

This paper presents a detailed exploration of the architectural development of an offline-first Progressive Web Application (PWA) prototype, specifically designed for gamified learning systems. The core research involves the technical examination of the PWA prototype, emphasizing its architectural design and crucial offline capabilities in the context of gamification elements. The study highlights the critical architectural components necessary for offline-first PWAs in educational settings, including the usage of PWA service workers and caching mechanisms. Key gamification features were identified and integrated, differentiating between those suitable for offline settings (like Points Systems, Badges/Achievements, Progress Tracking) and those requiring online connectivity (like Global Leaderboards and Social Interactions). The prototype, built using the React frontend framework and Supabase BAAS for the backend, demonstrates the potential of offline-first strategies in educational technology. It provides practical insights into the challenges and opportunities of maintaining engaging, uninterrupted learning experiences, particularly in low-connectivity environments. In conclusion, while offline-first PWAs effectively support learning activities with intermittent internet access, the research suggests that a careful balance must be managed between robust offline functionality and the richness of dynamic online interactivity to fully maximize the benefits of gamification.

1. Introduction

The integration of digital technology into educational environments has led to innovative teaching methodologies, with gamified learning systems gaining significant prominence. These systems utilize game design elements in non-game contexts to enhance student engagement and learning outcomes [1]–[3]. The scholarly discourse continues to confirm this trend, highlighting the positive effects of gamification on student motivation [34]. Gamification in education is not a new concept, but the evolution of web technologies has introduced new opportunities and challenges in implementing gamified elements [1], [2].

Progressive Web Applications (PWAs) have emerged as a significant advancement in the online system development landscape, offering unique advantages, especially in scenarios characterized by intermittent or poor internet connectivity [4]. This technology has increasingly been explored for its abilities to provide a seamless, app-like experience through web-based platforms. This type of application can be leveraged to provide consistent and engaging learning experiences, independent of network availability, thereby making quality educational resources more accessible [4].

Despite the growing interest in gamified learning systems, there is a noticeable gap in academic discourse regarding the specific architectural considerations for developing effective offline-first PWAs

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[1]–[5]. The complexity of designing gamified systems, especially in low-connectivity settings, has been identified as a significant challenge in recent literature. This limitation restricts potential advancements in creating scalable and robust gamified learning platforms that are equally efficient in both online and offline settings. Addressing this gap is essential for the advancement of inclusive and versatile educational technologies.

This study aims to bridge this knowledge gap by identifying and analyzing the critical architectural components necessary for the development of offline-first PWAs in educational settings. It examines the challenges and opportunities unique to offline-first environments and contrasts them with the characteristics of traditional online web applications. Furthermore, the paper presents a prototype of an offline-first PWA learning system, offering practical insights into its development and delineating the capabilities and limitations of offline functionalities compared to their online counterparts.

2. Materials and Methods

The evolution of web technologies has played a pivotal role in shaping the landscape of educational systems. This transformation has been marked by the integration of a range of technologies, from early web applications to the latest developments in PWAs, each contributing uniquely to the enhancement of learning environments [6], [7].

The evolutions led to the development of Learning Management Systems (LMS), which have become integral to modern education [8]. LMSs provide structured platforms for managing courses, tracking student progress, and facilitating online learning. They have been instrumental in the shift towards more personalized and flexible learning experiences, allowing students to learn at their own pace and according to their own schedules [8].

The proliferation of mobile technologies has further transformed educational systems. Mobile applications have made learning more accessible and convenient, allowing students to engage with educational resources anytime and anywhere [9]. They have also enabled more interactive and engaging learning experiences through the incorporation of multimedia content and techniques that enhance learner engagement [10].

2.1. Progressive Web Application Technology Development

PWAs, as one of the latest developments in web technologies, have brought significant changes to educational systems. They combine the best features of web and mobile applications, offering the accessibility and simplicity of web platforms alongside the performance and user experience typical of native mobile applications [11], [12]. PWAs have been used to develop sophisticated educational platforms that provide seamless, engaging, and interactive learning experiences [13], [14].

Table 1 The main requirements for a web application to be considered a PWA

Num	Requirement	Description
1	Progressive	They work for every user, regardless of browser choice, because they are built with progressive enhancement as a core tenet.
2	Responsive	They fit any form factor, including desktop, mobile, tablet, or whatever is next.
3	Connectivity independent	They are enhanced with service workers to function offline or on low-quality networks.
4	App-like	They use the app-shell model to provide app-style navigation and interactions.
5	Fresh	They are always up to date thanks to the service worker update process.
6	Safe	They are served via HTTPS to prevent snooping and ensure content has not been tampered with.
7	Discoverable	They are identifiable as applications, thanks to W3C manifests and service worker registration scope, allowing search engines to find them.
8	Re-engageable	They can access the re-engagement user interfaces (UIs) of the Operating System, such as push notifications.
9	Installable	They allow users to "keep" apps they find most useful on their home screen without requiring an app store.
10	Linkable	They can easily be shared via a URL and do not require complex installation.

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PWAs are web applications that use modern web capabilities to provide an app-like experience for users. Built using standard web technologies such as HTML, CSS, and JavaScript, they behave and feel similar to traditional mobile applications [15]. PWAs can work offline, receive push notifications and even access device hardware, such as the camera or GPS.

There are several key requirements for a web application to be considered as a PWA [14]–[19], shown in table 1. While PWAs can operate offline, not all are designed using an offline-first approach [19]. An online-only PWA can handle network requests normally when a network connection is available but may fail when connectivity is lost. On the other hand, an offline-first PWA is intentionally designed to operate primarily without network access [19]. Offline-first PWAs rely on service workers to cache necessary resources during the installation process. When a user initiates a request, the service worker first attempts to fulfill it using cached resources [20], [21]. If the resource is not in the cache, the service worker then attempts to fetch it from the network. This approach ensures that the PWA remains functional even when the network is unavailable or unreliable. In educational contexts, offline-first PWAs can be particularly valuable. They allow students to access learning materials and complete assignments even in the absence of reliable internet connectivity. This capability can be transformative in environments with limited access to the internet, making greater accessibility and inclusivity in education.

2.2. Gamification for Learning

Gamification, the practice of incorporating game-design elements into non-gaming contexts, has become a significant trend in online education [22], [23]. This strategy aims to boost learner engagement and motivation, making the learning process more interactive and enjoyable.

Online learning environments increasingly integrate gamification features to enrich educational experiences [24]. For example, lessons can be tailored to specific topics and enhanced with immersive elements such as role-playing and teamwork collaboration [25]. Many platforms also provide teachers with administrative controls to modify or adjust lesson content [26], enabling the creation of interactive web pages for each lesson and further enhancing the student learning experience [27].

Gamified online learning platforms typically comprise of several key elements [28]–[32] are shown in Table 2:

Table 2. The elements of gamified online learning platforms

Num	Element	Description
1	Virtual Learning Environments	These spaces are created for students and teachers, providing an open, bounded area where users can interact with objects and manipulate digital components.
2	Learning Material	These include presentations, video tutorials, and other instructional resources integrated into the platform.
3	Interactive Features	Many platforms allow communication through chat, comments, or similar tools, facilitating collaboration and interaction among students.
4	Gamification Features	Lessons incorporate immersive gamified features such as role-playing, challenges, and teamwork, to enhance engagement and improve learning experience.

2.3. Challenges and Opportunities in Web Based Gamified Learning Systems

Gamification, the practice of incorporating game-design elements into non-gaming contexts, has become a significant trend in online education [3], [24], [24], [33]. This strategy aims to enhance learner engagement and motivation, making the learning process more interactive and enjoyable.

However, achieving an appropriate balance between educational objectives and game elements can be challenging [34]. The integration of game mechanics should enhance, not overshadow, the learning goals [35]. Excessive gamification may distract learners from the content, while insufficient gamification may fail to sustain user engagement [36]. Additionally, effectively integrating technology into curriculum design presents both advantages and difficulties. Well-designed systems can provide interactive and engaging content that improves the learning experience [37]. However, keeping pace with rapid technological changes to continually updating instructional materials is an ongoing concerns [38].

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Creating positive user experiences in both online and offline settings requires thoughtful design. User interfaces should be intuitive and supportive of collaborative activities [37]. Providing a seamless experience across contexts can be complex [39]. Nevertheless, when thoughtfully designed, gamified learning systems offer numerous benefits. They can increase student motivation, enable personalized learning, facilitate peer interaction, and provide low-stakes environments for skill development [40], [41]. With deliberate design considering specific learning objectives and contexts, gamification strategies can significantly enhance educational outcomes.

2.4. Methodology

This study explores the architectural considerations and practical implications of developing offline-first PWAs for gamified learning systems. The approach is grounded in software engineering principles, emphasizing the iterative development and analysis of a PWA prototype. This methodology enables an in-depth examination of the technical aspects of offline-first architecture and its application within educational contexts. The development of the offline-first PWA prototype is central to our research. This process are shown in Table 3.

Table 3 PWA Prototype Development Process

Num	Stage	Description
1	Initial Design Considerations	Identifying the essential features and capabilities of the PWA, with particular emphasis on enhancing offline accessibility and user engagement in a learning environment.
2	Technology Stack Selection	Selecting technologies and frameworks optimized for offline functionality and seamless performance.
3	Implementation Process	Constructing the prototype through iterative development cycles, integrating offline capabilities alongside gamification elements specifically designed for educational purposes.
4	Testing and Iteration	Conducting comprehensive evaluations of offline performance, user experience, and the effectiveness of gamification features, followed by iterative refinements based on testing results and observations

Next, we examine the architectural intricacies of the developed PWA prototype. Key areas of focus include the implementation of service workers for offline support, efficient caching mechanisms, robust data synchronization methods, and the seamless integration of gamification elements within an offline-first architecture.

A comparative analysis is then conducted between the developed offline-first PWA prototype and conventional online web applications. This comparison examines architectural differences, with particular attention to how offline-first considerations influence design decisions, functionality, and the overall user experience in an educational settings. The analysis aims to highlight the unique advantages and challenges of offline-first PWAs, especially regarding accessibility and engagement in learning environments.

2.5. Architectural Considerations and Implementation

The offline-first PWA is architected for gamified learning systems, integrating key components such as service workers, caching mechanisms, database management, and an engaging user interface. This architecture is specifically designed to facilitate an effective and interactive learning experiences, even in offline environments.

2.5.1. PWA Service Worker

The service worker is central to this architecture, enabling offline capabilities, while caching mechanisms ensure rapid access to essential resources. Database management plays a crucial role in tracking user progress, and the user interface is designed to deliver a user-friendly and engaging learning experience.

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Fig 1. Lifecycle and Operational Mechanism of an Offline-First PWA

Fig 1 provides an overview of the operational lifecycle of a PWA. Understanding this lifecycle is critical for appreciating how PWAs provide a seamless and efficient user experience, combining the capabilities of traditional web applications with the benefits of native mobile applications [6], [16], [19]. The lifecycle of an Offline-first PWA are shown in Table 4.

Table 4 The lifecycle of an Offline-first PWA

Num	Stage	Description
1	Initial User Access	The process begins when a user accesses the PWA through a web browser. This step is crucial, as it triggers the subsequent registration and installation of the service worker.
2	Service Worker Registration	Upon the first visit, the PWA initiates the registration of a service worker. The service worker is a script that operates in the background, independent of the web page, and is responsible for managing the caching of app resources and enabling offline functionality.
3	Caching of Assets	After registration, the service worker installs and caches key assets of the web application, including HTML, CSS, JavaScript files, and images. This step is fundamental to enabling offline operation and performance under low-network conditions.
4	Activation of Service Worker	Following installation, the service worker is activated. This stage is crucial for enabling offline capabilities, as the service worker can now intercept network requests and retrieve assets from the cache as needed.
5	Readiness for Offline Use	With essential assets cached, the PWA is prepared for offline usage, ensuring functionality irrespective of network connectivity.
6	User Interaction	Users interact with the PWA as they would with any standard web or mobile application, experiencing smooth and uninterrupted operation.
7	Network Availability Check	The service worker monitors network availability when the app attempts to fetch new data. This check determines whether to retrieve data from the network or the cache.
8	Data Fetching and Caching	If the network is available, fresh data is fetched from the server and the cache is updated for future offline use. If the network is unavailable, the service worker retrieves the required data from the cache.

2.5.2. Service Worker and Caching Strategies

The service worker, a script executed by the browser in the background, is pivotal in enabling the PWA's offline functionality. It manages caching strategies that store and update resources. Balancing the storage of enough resources for offline access with the efficient use of storage space is critical. This study explored several caching strategies to determine the most suitable approach for diverse types of resources within the learning application [16], [19]. These strategies are shown in Table 5.

2.5.3. Database Management and Data Synchronization

For offline-first PWAs, the integration of client-side databases is essential, with particular emphasis on IndexedDB. This database system was selected for its proficiency to store large volumes of structured data within the browser, which is crucial for maintaining offline functionality in PWAs [16], [18], [19]. Our method involves categorizing data into three main types: educational content, user progress, and gamification-related data. To efficiently manage these data, which range from text to multimedia content, we apply serialization methods. These techniques ensure efficient storage and retrieval while optimizing space. Effective synchronization between local and server data is a cornerstone of offline-first PWAs. Our synchronization strategy aims to minimize data transfer and optimize server

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communication. We utilize a differential synchronization method, updating the server only with changes made offline, thus reducing the overall data payload.

Conflict resolution is another critical component of our synchronization approach, especially when concurrent modifications occur in both offline and server data occur. Our strategy ensures data integrity and prevents the loss of vital user information, such as learning progress or gamification achievements, during synchronization. The synchronization process also includes updating new or modified learning content from the server, guaranteeing that users consistently have access to the most current educational resources.

Table 5. Service Worker Caching Strategies

Caching Strategy	Description
Cache-First	Prioritizes serving resources from the cache; fetches from network if not in cache.
Network-First	Tries to fetch resources from the network first and falls back to the cache on network failure.
Cache-Only	Serves resources directly from the cache, suitable for assets known to be available offline.
Network-Only	Always fetches resources from the network, suitable for uncached or real-time data.
Stale-While-Revalidate	Serves cached content while making a network request to update the cache in the background.
Cache and Network Race	Simultaneously fetches from cache and network; uses the first response to arrive and discards the other.
Background Sync	Queues network requests for offline use and sends them when connectivity is restored.
Cache-Falling-Back-to-Network	Serves content from the cache and updates the cache in the background with a network request.
Cache-Update-and-Refresh	Serves content from the cache, checks for updates in the background, and notifies the user to refresh if needed.
Cache and Update	Serves cached content and updates it in the background if updates are available.

2.5.4. Integration of Gamification Elements

Gamification has been shown to increase motivation and engagement in learning environments [3], [24]. In offline-first PWAs, where internet connectivity may be intermittent, the implementation of gamified elements requires careful consideration to ensure they remain effective and engaging. In this paper, we identified which elements can be effectively incorporated in offline settings and which require an active internet connection to operate optimally [22], [35], [37], [42].

Gamification Elements Suitable for Offline Settings: (1) Points System: Accumulation of points through learning activities can be tracked and stored on the device, then synchronized when online. (2) Badges and Achievements: Awarding badges for tasks or milestones can be saved locally and updated online upon reconnection. (3) Progress Tracking: Monitoring user progress through educational content can be stored locally and synchronized online for device consistency. (4) Offline Challenges: Encouraging engagement through challenges completed without internet, with outcomes stored locally and later synchronized online.

Gamification Elements Requiring Online Connectivity: (1) Global Leaderboards: Requiring online access for reflecting current rankings globally, serving as a motivational benchmark. (2) Social Interactions: Dependent on online connectivity for features such as chat, forums, and collaborative challenges, crucial for community building and collaborative learning.

2.5.5. Learning Material: Modern JavaScript Language

While the learning material is not the primary focus of this paper, it is noteworthy to mention its role within the context of the PWA prototype. The chosen subject matter for our prototype is Modern JavaScript, a relevant and dynamic programming language widely used in contemporary web development [43]. This material serves as a test case to demonstrate the adaptability and functionality of the offline-first PWA in a real-world educational scenario. It is important to note that the architectural

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design and implementation of the PWA are content-agnostic. Although Modern JavaScript is used in this instance, the system is designed to accommodate distinct types of educational materials, making it versatile and applicable across diverse learning contexts.

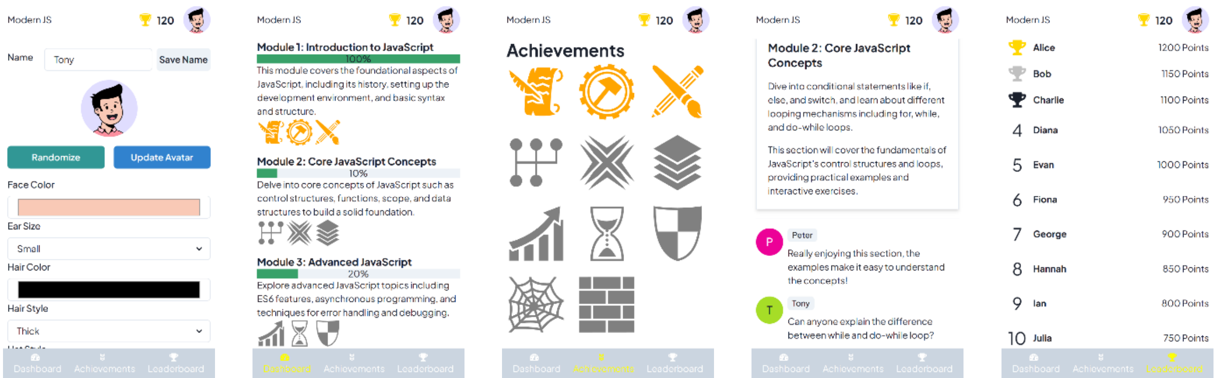
2.5.6. Prototype Development

In the development of the PWA prototype, selecting an appropriate front-end framework was an important choice. The options considered included React, Vue, and Angular, which are prominent in modern web development [44]–[46].

React was ultimately chosen due to its comprehensive support for offline-first PWA functionalities. The framework's component-based architecture allows the efficient development of reusable and maintainable UI components [47]. Additionally, the React ecosystem provides extensive tools and libraries that support PWA development. Among the libraries selected were React Nice Avatar [48], Chakra UI [49], and React Icons [50]. These libraries helped streamline the development of an appealing user friendly interface.

Backend architecture decision also involved careful evaluation. The first option considered was developing a custom backend using a web framework. This approach offers total control over the backend environment and is beneficial for projects with unique requirements. However, it demands greater development and maintenance resources. Such a backend can be developed from scratch or leverage web framework such as NestJS [51], Laravel [52], or Django [53].

The second option deliberated was employing Backend as A Service (BAAS). BAAS offers ready-to-use backend services, simplifying development, integration, and scaling processes. This approach is ideal for projects where quick deployment is a priority. The downside of this option is the less flexibility and control compared to a custom backend. Services which fall into this category are ones such as Firebase [54], Supabase[55], or AWS Amplify [56]. Supabase BAAS was selected as the backend solution for the prototype. The decision to go with BAAS was motivated by the need for a streamlined development process on the prototype development.



(A) (B) (C) (D) (E)

Fig 2. Offline-first PWA Prototype

In Fig 2, the components of the prototype offline-first PWA are laid out to detail the user experience within the learning platform under varying connectivity conditions.

Fig 2 (A) portrays the User Profile, which provides personalization through avatar customization, operating offline. It also includes a points system that tracks learning achievements without needing an internet connection, syncing with the server upon re-establishment of connectivity.

Fig 2 (B) displays the Learning Modules, with a focus on progress tracking that is maintained offline. Learners' progress percentages are recorded on the device and are designed to synchronize across devices when online connectivity is resumed, ensuring continuity in the learning experience.

The Achievements section in Fig 2 (C) illustrates the mechanism for rewarding learners with badges for completed tasks or milestones. This is designed to function in an offline mode by storing these achievements locally, with an update to the online system when connectivity allows.

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Fig 2 (D) details the Social Interaction component, which depends entirely on online connectivity. This feature facilitates community interaction and peer support, which are active only with an internet connection, thus not available in the offline mode of the PWA.

Finally, Fig 2 (E) highlights the Leaderboard, which integrates an online-dependent feature that updates and displays global learner rankings. While it serves as a motivational tool, it requires an active connection to retrieve and display live data.

These components are structured to provide an integrated learning environment that leverages offline capabilities to ensure uninterrupted learning progress while also incorporating online elements that enhance the educational experience through community interaction and global benchmarking.

3. Result and Discussion

This study explores the use of offline-first architecture in developing a gamified PWA. The findings affirm its effectiveness in improving the availability of gamified learning system under limited connectivity, while also highlighting significant challenges inherent to the offline-first model.

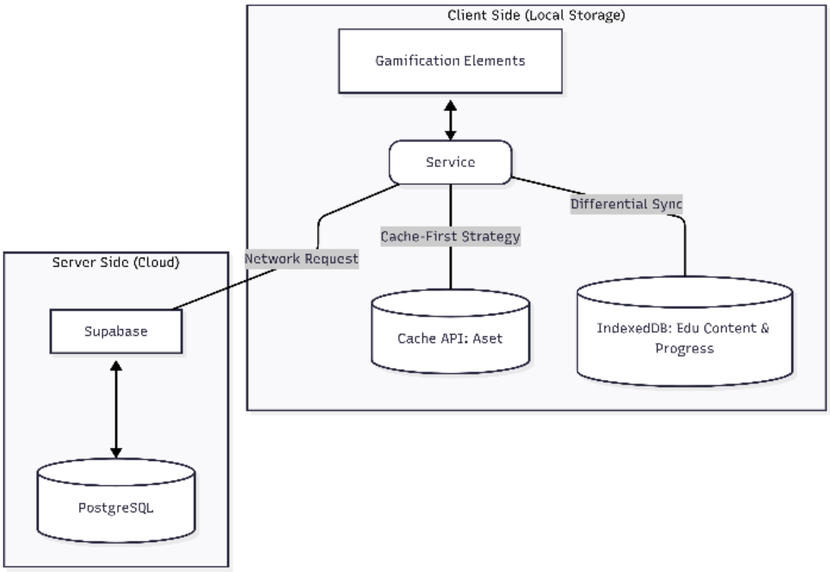

Fig 3. Offline-first architecture in developing a gamified PWA

In Fig 3, the offline-first architecture demonstrated that offline caching and local storage could effectively maintain user progress and engagement through gamified elements such as points and badges. However, the inability to provide real-time feedback or support live social interactions in the absence of an internet connection represents a notable limitation to the user experience. The absence of these dynamic elements can potentially reduce the immediacy and hinder social learning opportunities, which are essential for motivation and sustained engagement in online learning environments.

Compared to traditional web applications in Table 6, the PWA's offline capabilities showed strong resilience to connectivity disruptions, suggesting that such systems can be particularly beneficial in situations where internet access is unreliable or inaccessible. However, the study's focus on a single subject area and the prototypical nature of the application limits the generalizability of the results.

Certain aspects of offline implementation, such as caching strategies, require fine-tuning to what assets or data must be available offline. Gamification features such as points, progress tracking, badges, and personal profile customization can operate offline with different caching mechanism. Whereas social interaction and leaderboard cannot function meaningfully without connectivity, leaving limited strategies to how to use them in offline setting. Thus, the findings are thus preliminary and should be interpreted with caution when considering their application to other educational contexts or gamification implementations.

The challenges of implementing gamification in an offline context highlight the need for innovative design approaches that balance learner engagement with educational effectiveness. While

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offline gamification can motivate learners, the complexity of design increases significantly when attempting to replicate the same level of interactivity found in online systems.

Table 6. Comparison of traditional web applications with Offline-First PWA Architecture

Feature	**Traditional Web Application (Online-Only)**	**Offline-First PWA Architecture**
Network Dependency	Requires a continuous and stable internet connection to function.	Designed to operate primarily without network access.
Core Components	Standard browser-to-server request-response cycle.	Utilizes a Service Worker as a background script to manage requests.
Data Storage	Data is primarily stored on the server; limited local caching.	Uses IndexedDB for large-scale structured data storage in the browser.
Asset Loading	Relies on the network to fetch HTML, CSS, and JS files for every session.	Uses Service Workers to cache and serve assets even when offline.
Caching Strategy	Basic browser caching (unreliable for full offline use).	Advanced strategies like Cache-First or Stale-While-Revalidate.
User Experience	Displays "No Internet" or error pages when connectivity is lost.	Provides a seamless, "app-like" experience regardless of network status.
Data Syncing	Immediate server updates; if the network fails, data may be lost or not saved.	Uses Differential Synchronization to upload changes once connectivity returns.
Gamification	Requires internet for all updates and interactions.	Core features (points, badges) work offline; social features are network-only.

The technologies chosen for the prototype development also affected the discoveries. React, as the frontend framework, allowed the prototype to be built using a wide range of ready to use libraries. These libraries offer ease of development and good base user experience. The Supabase BAAS albeit restrictive in its usage has offered adequate platform for the prototype. The APIs provided by the platform has allowed rapid backend development. Moreover, as the BAAS is an online service there is no need of special deployment and resource provisioning allowing for streamlined system maintenance.

The practical implications of this study extend to educators and instructional designers, suggesting that an offline-first approach can be a viable solution for delivering educational content in areas or occasions where the system need to be used with limited internet access. However, the development process, technological choices, and long-term maintenance of such systems require careful consideration to balance offline functionality with the richer interactivity provided by online features.

This study contributes to the exploration of offline-first principles in educational technology. Future research should explore the scalability of the prototype, its effectiveness over an extended period, and its applicability to a wider range of educational content and learning settings. In conclusion, while the offline-first PWA prototype offers a promising direction for educational technology, particularly in low-connectivity environments, the complexities and limitations identified signal the need for further research. The integration of offline and online features remains a delicate balance, one that must be carefully managed to ensure that the educational benefits of gamification are not diminished by the constraints of offline-first architecture.

4. Conclusion

This study establishes a validated architectural framework for offline-first Progressive Web Applications (PWA) in education, confirming that the Service Worker Lifecycle and differential synchronization successfully bridge the gap between web accessibility and native application resilience. The results explicitly highlight a functional dichotomy: individual motivational elements—such as points and badges (Fig 2A-C)—function seamlessly through local storage, whereas social constructivist features like global leaderboards (Fig 2E) are inherently limited due to their dependence on real-time connectivity–. These findings provide a critical contribution to the field by defining a hybrid design strategy in which developers must prioritize individualized learning loops using Cache-First strategies (Table 1) to ensure continuity, while treating social interactions as Network-Only enhancements that degrade gracefully during connectivity disruptions. Ultimately, this research offers a technical blueprint

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for inclusive digital education, proving that robust gamified learning experiences are achievable in low-connectivity environments through specific architectural trade-offs.

Author Contributions

I. D. Fibrian: Conceptualization, data curation, formal analysis, funding acquisition, methodology, project administration, resources, supervision, validation, and writing – original draft. T. P. Utomo: Data curation, formal analysis, funding acquisition, project administration, resources, supervision, validation, visualization, and writing – review & editing. I. Lukmana: Conceptualization, data curation, formal analysis, funding acquisition, investigation, project administration, resources, software, supervision, validation, and writing – original draft. Z. Muttaqin: Formal analysis, funding acquisition, investigation, methodology, supervision, validation, and writing – review & editing.

Declaration of Competing Interest

We declare that we have no conflict of interest.

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