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This category of submission is accepted at the discretion of the editor-in-chief, not refereed and does not qualify as a research publication for South African government subsidy purposes. The major criteria for acceptance are that the item is coherently written and does not require significant editing, that it is timely and it is likely to be of interest to readers.

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Editorial: Summer of 2024

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Acknowledging editors and reviewers

The Academy of Science of South Africa (ASSAf) recently released a [Statement on the Recognition of the Work of Editors and Peer Reviewers of Academic Journals and Books in South Africa](#). In the statement, ASSAf highlights the critical role that editors and peer reviewers play in maintaining academic standards in publishing and argues that universities and science councils should be doing more to recognise and value the tremendous work done by editors and peer reviewers – mostly as a voluntary service to the academic community.

With this issue of SACJ, we are publishing seven research articles. For every one article that is accepted, there are another two that are rejected after review (not counting the manuscripts that are desk rejected). Assuming three reviews per article, this translates into 63 reviews conducted by peer reviewers to reach this point of publishing these seven manuscripts. We salute the reviewers of SACJ and our sterling team of associate editors for finding reviewers (knowing that we sometimes have to send out ten invitations before finding a single willing reviewer). We value your contributions and rely on your continued support in maintaining the high standard of SACJ.

Submission statistics

For information, we present the following updated statistics around submissions, acceptance rates and the processing time of articles.

Year	2022	2023	2024
Submissions	111	95	91
Desk rejection	54	62	47
Desk rejection rate	49%	65%	52%
Final acceptance	17	12	
Acceptance rate	15%	13%	

Malan, K.M. (2024). Editorial: Summer of 2024 [Editorial]. *South African Computer Journal* 36(2), vii–viii. <https://doi.org/10.18489/sacj.v36i2.20775>

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The figures above translate into an overall rejection rate of approximately 86%. This may seem high, but it can be attributed to the large number of submissions from all over the world due to the indexing of SACJ on Scopus. In comparison, *South African Journal of Science*, which is also indexed on the Web of Science (Science Citation Index), reported a rejection rate of 95% in 2023.

In terms of submission processing time, the median time to a first decision (*desk reject / send to review*) for 2023-2024 was 4 days and the median time to final decision for submissions sent to review (2022-2023) was 5 months.

Research in this issue

The research papers in this issue cover many areas of computing from Computer Science topics such as design patterns, teaching automata theory, and embedded computing, to IT and Information Systems topics such as career choice models, big data analytics, mobile technology and AI adoption. Authors of these papers are based at eight different higher education institutions in South Africa, showing that SACJ remains an important publication outlet for South African researchers.

- *Formalizing solutions to network availability issues in low-resource environments: An offline storage design pattern for software systems* by Agbeyangi and Suleman.
- *Migrating teaching of automata theory to a digital platform* by Jordaan, Timm and Marshall.
- *An IT career choice model* by Calitz, Cullen and Twani.
- *Predicting the performance of ORB-SLAM3 on embedded platforms* by Matthee, Uren, van Schoor and van Daalen.
- *Big data analytics capabilities and the organisational performance of South African retailers* by Welbotha and van den Berg.
- *Exploring adoption dynamics: Mobile technology in agricultural information dissemination among smallholder farmers in Gokwe South District, Zimbabwe* by Musungwini, van Zyl and Kroeze.
- *Integrating the TOE framework and DOI theory to dissect and understand the key elements of AI adoption in sociotechnical systems* by Smit, Eybers, van der Merwe, Wies, Human and Pielmeier. This is the first paper of a special issue of extended papers from the SAICSIT 2023 conference.

Thank you to all authors for submitting your manuscripts to SACJ and for entrusting us with your research!

Formalising solutions to network availability issues in low-resource environments: An offline storage design pattern for software systems

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ABSTRACT

In most software systems operating within low-resource environments, the persistently encountered challenges related to network availability often result in compromised performance or even complete system failure. To address this issue, software developers frequently resort to ad hoc measures to mitigate these challenges. To offer a more comprehensive solution, this paper introduces an all-encompassing approach in the form of a design pattern. This design pattern uses offline functionalities with localised storage, emphasising the distinction between offline storage and synchronisation, presenting a versatile and high-level methodology for overcoming the recurrent network-related challenges intrinsic to low-resource environments. We describe the use of the design pattern in some real-world use cases, thereby illustrating how a single design pattern is the foundation for many seemingly disparate software engineering approaches. This design pattern holds the potential to significantly redefine the manner in which network availability challenges are approached and addressed.

Keywords design pattern, software systems, low-resource environment, data synchronisation, delay tolerant networks

Categories • Software and its engineering ~ Design patterns, Reusability

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1 INTRODUCTION

In modern software systems, many measures are taken to ensure that the programs and related configuration files, documentation, etc., that operate together function in a way that reduces network traffic, even on high-bandwidth networks. One goal is to ensure the effective and efficient use of the programs in the event of network downtime, particularly in low-resource

Agbeyangi, A. and Suleman, H. (2024). Formalising solutions to network availability issues in low-resource environments: An offline storage design pattern for software systems. *South African Computer Journal* 36(2), 1–30. <https://doi.org/10.18489/sacj.v36i2.19976>

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environments where network access has been observed to be minimal (Abou-Khalil et al., 2021) and is occasionally unavailable.

A low-resource environment is one where resources are scarce, typically in low- and middle-income countries (Akhigbe et al., 2022; Kutoane et al., 2021). Often identified in low-resource environments are a lack of infrastructure, low income, affordability, a lack of basic literacy and digital literacy, and many other factors that contribute to limited access to networks and, as a result, degraded access to software systems. The speed of data retrieval is a crucial factor in user experience and a requirement in almost all commercial applications. Today, a number of factors affect response time, such as network infrastructure, protocols, hardware, software, and Internet speed. The strategic objectives of any organisation are seriously harmed when response times are impacted. To improve interoperability and efficiency in software systems owing to a purposeful or unintentional lack of Internet connectivity, an optimal way to ensure software systems function unfettered in either a resource-rich or low-resource environment is required. In the past (Nungu & Pehrson, 2011; Surana et al., 2008) as well as more recently (Phokeer et al., 2020; Suleman, 2021), attempts made to provide relief for this problem have produced some results; however, the solutions are ad hoc and there is no general framework to guide software developers in low-resource environments. The design pattern proposed in this study is centered on leveraging offline storage to provide a resilient solution that ensures continued functionality even when network access is restricted or unavailable. The pattern not only addresses the immediate challenges of low-resource environments but also offers a framework that enhances the overall robustness and efficiency of software systems across various scenarios. By distinguishing between offline storage and data synchronisation, our approach emphasises the importance of maintaining seamless operations without relying on real-time network connectivity, thus offering a novel perspective in the domain of software engineering for low-resource contexts.

The methodology for deriving this design pattern is grounded in both extensive literature review and practical experience (Phiri et al., 2012; Suleman, 2019, 2022; von Holy et al., 2017) gained from developing software systems in low-resource environments. We thoroughly examined existing methods, pinpointing areas for enhancement, which guided the development of the offline design pattern. This dual approach of leveraging theoretical knowledge and practical experience not only validates the robustness of our pattern but also ensures its applicability in a wide range of low-resource scenarios, thereby contributing a valuable framework to the software engineering community. The increasing prevalence of users' inability to maximally use software systems in low- and middle-income countries, such as remote and rural areas, disaster-stricken regions, and resource-constrained IoT devices, further strengthens our desire to have a framework as a design pattern to address the challenges when network connectivity is unreliable or limited. These challenges are particularly prevalent in some African regions, where the design pattern offers a robust solution to enhance system efficiency and reliability.

The main contribution of our paper lies in *formulating and presenting a novel offline design pattern optimised for software systems operating within resource-constrained environments*. Other

objectives of this study include:

- Addressing the critical gap in data syncing systems by providing a practical solution to enhance application performance in challenging scenarios.
- Tackling emerging challenges in future use cases, such as remote healthcare, and smart agriculture, for better and more efficient data localization through offline storage.

The pattern prioritises offline storage to sustain software functionality in low-resource environments with limited or intermittent network availability. By emphasising offline storage, our approach ensures seamless operation without real-time data synchronisation dependency. While data synchronisation is included, the core emphasis remains on offline storage as the fundamental solution for low-resource environments. The remaining sections of the paper are organised as follows: [Section 2](#) discusses the literature review, emphasising some background concepts of offline operation, design patterns, and related approaches. [Section 3](#) introduces the methodology, and the description of the pattern is presented in [Section 4](#). [Section 5](#) discusses the evaluation of the pattern through the case studies. The results are discussed in [Section 6](#), while [Section 7](#) concludes the paper with some future directions.

2 LITERATURE REVIEW

2.1 Offline Operation and local storage mechanism

The concept of local storage and offline operation has been used in various areas of the computer/networking sectors for a while and there are various implementation strategies depending on the use case. According to Xu et al. (2022), several people found offline operation or a hybrid mix to be a more practical alternative to relying solely on cloud-based systems. This is so because local storage offers comprehensive, security-oriented control over the data and better data access performance than cloud storage. For keeping the data that is regularly accessed, local storage is compact, quick, albeit sometimes costly to implement (Xu et al., 2022). Due to network latency and data constraints in low-resource environments, it is feasible to think of offline operation and local storage as a more general approach to software systems.

Local storage is any kind of computer storage that can be used without the need for network access. Examples of local storage devices include hard drives, memory and removable disks on end-user devices. When using a web application, local storage technology can be used to store user status, cached data, temporary data, permanent data, and more (Harjono et al., 2010).

The user experience is increasingly being prioritised by many Web applications, which are inextricably linked to offline operation and local storage solutions. Local storage is mostly used for server-side reasons, with the goal of storing locally accessible versions of Web applications that were previously kept on the server. Liu (2014) emphasises the benefits of offline operations and local storage as a solution that relieves server-side stress and can also save a significant amount of network traffic, enabling faster software data queries. With offline operation and local storage, users of software systems (mobile or desktop applications) can engage

with them even when there is no network connection because of offline synchronisation, which is facilitated by local storage. A local data store is where changes are kept. These changes are synchronised with the remote server after the device has been brought back online.

Software applications that employ online and offline synchronisation using local storage make the software useful even when the network is unavailable. On the other hand, users must wait for data to load from the servers every time they request it when using an online-only, no-local-storage approach. This is an unpleasant experience because mobile or broadband networks in many low- and middle-income countries are generally slow, unreliable, and occasionally unavailable. Even when the data is accessible, loading it takes a few seconds. This contradicts the objective of providing a speedy and dependable software experience to software system users even in low-resource environments.

Despite the fact that the majority of people have access to the Internet in most advanced countries, there are still situations where software systems might not be able to connect to the Internet. The basement of an industrial facility or inside a plane are two notable examples, and every organisation must plan for contingencies. To address this issue, some modern applications, notably mobile applications, have introduced the concept of offline-first architecture. At any time the device is offline, the app remains semi-usable according to its architecture; for example, users of a messaging app can see their list of chats and message history. However, fresh messages cannot be sent.

The following are some of the foundational ideas of the offline-first architecture:

- Only data from local storage (e.g., database and key-value store) is displayed in the application's user interface.
- The application user interface never asks remote devices for data directly – all data access is via local storage.
- A synchronisation action keeps the local data current with the remote device data.

In most typical local storage synchronisation operations during the availability of networks, an application would check the remote device for updated or new data before storing it locally. Synchronisation operations can be started in a variety of ways, such as when a user opens a screen or receives a push notification saying that fresh data is available on the remote device. In contrast, some of the existing data syncing systems have been seen to focus on high-resource environments mostly (Jannes et al., 2021; Singh & Hasan, 2019). We observed a lack of a dedicated approach targeting low-resource environments, making our approach unique and valuable.

In order to achieve long-term gains in data quality and software system performance in low-resource environments, Ramanujapuram and Malemarapuram (2020) argued that the absence of an essential resource, such as a good network, is a significant barrier. As can be seen in low-resource environments, particularly in rural African regions, it is believed that despite the fact that many Internet users now have access to high bandwidth and high-speed networks,

there are still some low-resource environments where broadband services are either incredibly expensive or simply unavailable (Jebessa & Alemayehu, 2009; Tang et al., 2021; USDA, 2019).

2.2 Design patterns

Design patterns are blueprints that provide solutions to specific problems encountered during software development (Hussain et al., 2018; Leimeister et al., 2021; Meheden et al., 2021). Leimeister et al. (2021) believe that design patterns support developers in addressing technological challenges and crafting solutions by codifying best practices and making them applicable for future use. This plays a critical role in both practice and research. They represent a fundamental aspect of modern software engineering, offering structured solutions to recurring design challenges that span various domains (Hussain et al., 2018; Jiang & Mu, 2011; Seidl et al., 2017). Their purpose extends beyond individual projects (Leimeister et al., 2021), as they address recurring issues across diverse applications. While it is true that prior solutions might exist for certain problems, design patterns offer a standardised framework that transcends isolated solutions (Barakat, 2019). They encompass the collective experience and insights of the software community, distilled into templates that facilitate informed decision-making and expedite the development process.

The study by Gamma et al. (1995), mostly called Gang of Four (GoF), introduced the concept of software design patterns. In 1995, they released a book that served as a framework for discussing design patterns. These design principles are commonly utilised in the creation and operation of large software systems (Rasool & Akhtar, 2019). The GoF design patterns have become an industry-standard reference and offer a set of tried-and-tested answers to common design issues in object-oriented software development (Rath et al., 2019).

The rigour of a design pattern approach lies in its holistic consideration of factors that extend beyond the immediate problem, including scalability, maintainability, and adaptability. Therefore, even when solutions have been suggested in prior work, design patterns offer a refined lens through which to examine, evaluate, and potentially enhance those solutions. This paper's contribution, framed within a design pattern context, provides a systematic, tested perspective that augments existing solutions and serves as a robust foundation for addressing the complex challenges software systems face in low-resource environments, specifically under limited or no network access. The design pattern approach, which is the basis of this paper, is not intended to provide new experimental validation of a specific solution. Instead, it is to extrapolate from multiple past experimental results to specify a generalizable approach that can apply to future problems.

2.3 Related Approaches

In the literature, efforts have been made, though not explicitly as design patterns, to address issues with network connectivity (Nungu & Pehrson, 2011; Phokeer et al., 2020; Suleman, 2021; Surana et al., 2008), offline operation (Demers et al., 1994; Kistler & Satyanarayanan, 1992;

Liu, 2014; Satyanarayanan, 1989; Satyanarayanan et al., 1990; Terry et al., 1995), and software resilience (Cámara et al., 2014; Quinn et al., 2015) in low-resource environments. Notable among these techniques for offline operations is *Coda* (Satyanarayanan, 1989), a distributed file system design that helps improve software performance by ensuring data availability even during server crashes or network partitions. According to Satyanarayanan et al. (1990), it was designed for large-scale distributed computing environments, ensuring resiliency to server and network failures through server replication and disconnected operation mechanisms. One other notable historical technique for efficiently transferring and synchronising files between two locations is *RSync* (Tridgell & Mackerras, 1996). It is particularly useful for offline operation, as it allows users to synchronise files across devices or networks, even when the network connection is unreliable or intermittent. It achieves this by only transferring the parts of files that have changed since the last synchronisation, reducing the amount of data transferred, and minimising network overhead. Other offline data syncing frameworks that use permanent integration and continuous synchronisation to local storage include *Azure Offline Sync*¹, *Realm Mobile Database*², *Back4App*³, *AWS Amplify*⁴, *Firebase*⁵, and *Kinvey*⁶. The study of historical tools and techniques, as well as common offline data syncing frameworks, has provided valuable knowledge about the methods and approaches used in developing software systems that can operate with limited network access. These tools and techniques represent significant milestones in the development of offline functionality in software systems.

The request/reply pattern (Brahma & Sadhya, 2022; Buschmann et al., 2007) for software system communication is a similar approach, in which one component, the client, submits a request to another, the server, who then answers with a reply containing the required data or by carrying out the requested action. It is frequently employed in client-server architectures, distributed systems, and service-oriented architectures (SOA) (Abdellatif et al., 2018). The idea is also similar to what can be achieved in an environment of edge computing, where base station edge servers are placed close together (Zhang et al., 2020). Due to this, high-speed links can be used for data sharing and communication between neighbouring edge servers.

The mobile offline-first pattern (Biørn-Hansen et al., 2018; Vanhala, 2017) is another important pattern that has attracted attention as a valuable method in mobile app development. It emphasises the importance of developing applications that can perform well in offline environments, allowing users to interact with the app even when connectivity is intermittent or non-existent. Other approaches and perspectives include device-to-device file transfers (Scott, 2016; Z. Wang, 2022) and service-based mobile application frameworks (Brunette et al., 2017), which encompass an event-driven offline approach. These approaches allow for direct communication between devices, enabling efficient file transfers without needing an Internet con-

¹ <https://learn.microsoft.com/en-us/azure/developer/mobile-apps/azure-mobile-apps/howto/data-sync>

² <https://www.mongodb.com/docs/realm-legacy/products/realm-database.html>

³ <https://www.back4app.com/>

⁴ <https://aws.amazon.com/amplify/>

⁵ <https://firebase.google.com/>

⁶ <https://devcenter.kinvey.com/rest/guides/core-overview>

nection. On the other hand, service-based mobile application frameworks utilise a centralised server that handles offline events and synchronises data across devices once connectivity is restored. These approaches provide flexibility and robustness for offline mobile applications. However, our proposed offline design pattern extends beyond the mobile environment to provide a generalised solution that can be used for a wide range of software systems that face intermittent network access and resource constraints.

Examining the four elements of the proposed design pattern and their connection to relevant methods like *Coda*, *RSync*, and selected Offline Data Syncing Frameworks (*Azure Offline Sync*, *Realm Mobile Database*, *Back4App*, *AWS Amplify*, *Firebase*, and *Kinvey*), these tools ensure the availability of data by synchronising crucial data locally during software system installation. The ‘pre-populate’ process establishes the groundwork for offline functionality, allowing users to retrieve and modify data saved locally without depending on network connectivity. During the ‘offline operation’ phase, these tools enable apps to operate smoothly in situations where there is no Internet connection, allowing users to access and modify data stored locally. This can be seen with *Firebase* operations that allow applications to access and modify data stored locally, ensuring uninterrupted functionality without network connectivity. The ‘update’ stage enhances the continuous functionality by synchronising data changes with remote servers when the connection is restored. During the ‘post-populate’ stage, these tools ensure data consistency across local and remote sources by synchronising any locally made changes with the server-stored information. This indicates the offline operation cycle within the offline design pattern. Furthermore, caching, MQTT (Message Queuing Telemetry Transport) (Haque et al., 2021) and CoAP (Constrained Application Protocol) (Herrero, 2020) are useful technologies for enhancing efficiency and facilitating communication in online contexts. Caching mitigates high traffic rates by actively storing frequently accessed content in users’ local memories (Maddah-Ali & Niesen, 2014; J. Wang, 1999). MQTT⁷ is an OASIS standard messaging protocol designed for the Internet of Things (IoT). It is a lightweight publish/subscribe messaging transport that is ideal for connecting remote devices with limited code size and bandwidth constraints (Hunkeler et al., 2008). CoAP (Bormann et al., 2012), unlike MQTT, is another lightweight messaging protocol specifically designed for constrained environments, with a focus on low power consumption and simplicity. Both protocols offer efficient communication solutions for IoT devices, but CoAP is more suited for resource-constrained environments where minimal code size and energy consumption are critical factors (Thangavel et al., 2014). However, they are strongly dependent on Internet connectivity for the synchronisation of data. The offline design pattern we offer gives priority to local storage and operation, ensuring smooth functionality even in situations when Internet connectivity is limited or unavailable. Our pattern prioritises offline storage, providing a dependable standardised solution in the form of a design pattern for software systems that operate in low-resource environments. It overcomes the constraints of internet-dependent technologies and improves system resilience in offline situations.

The studies that focus on technology deployment in low-resource environments provide

⁷ <https://mqtt.org/>

invaluable insights into the strategies, challenges, and best practices associated with software system effectiveness. Pentland et al. (2004) conducted a notable study on DakNet, highlighting creative methods to address connectivity challenges in rural regions. The study emphasises the effectiveness of community-based networks (such as the Inethi project (Phokeer et al., 2020)) in easing the distribution of data. Similarly, the deployment of the Open Data Kit (ODK), as highlighted in Hartung et al. (2010), Brunette et al. (2013), and Brunette et al. (2017), provides essential frameworks for designing information services tailored to the needs of developing regions. Likewise, research conducted by Chandwani and Kumar (2018) provides insight into the significance of telemedicine in areas with limited resources, highlighting the necessity of establishing interconnected systems to enhance healthcare provision. Insights from these studies enrich our understanding of the challenges and opportunities inherent in technology deployment in low-resource contexts.

While influenced by the mobile offline-first concept and other related approaches, our design pattern broadens the basic concepts of these approaches to accommodate a broader range of scenarios applicable to various software engineering domains. We have improved and expanded the fundamental concepts of offline functionality and local storage usage, making them applicable to a wide range of scenarios and settings. The inclusion of this broader viewpoint not only strengthens our design pattern's conceptual framework but also improves its versatility and adaptability in addressing the intricate issues faced in low-resource environments and beyond. The design pattern provides a standardised solution to the persistent issue of network connectivity limitations. As such, the design pattern represents a significant standardised solution to the challenges of network connectivity constraints.

3 METHODS

The design pattern is developed through extensive experience and concepts from related approaches in the literature, addressing the specific challenges of creating software systems in low-resource environments. The approach is based on the qualitative synthesis of practical insights and existing theoretical frameworks. The design pattern seeks to offer a resilient solution for maintaining software system functionality in scenarios of intermittent or unavailable network connectivity, emphasising the importance of offline storage over real-time synchronisation.

The proposed pattern is evaluated through a series of six case studies, which illustrate the practical application and effectiveness of the pattern in real-world scenarios. These case studies were chosen based on specific criteria to ensure they accurately depict the challenges faced in low-resource environments. The selection criteria for the case studies include:

- i. Relevance to low-resource environments – demonstrate scenarios where network connectivity is limited or intermittent
- ii. Diversity of application domains – chosen from different domains, such as data collection, navigation, and content distribution

iii. Implementation of offline storage – showcase the implementation of offline storage as a critical component

In evaluating the pattern a uniform methodology was employed across all chosen case studies. This entailed thoroughly examining how each case study integrated the design pattern and its sub-patterns, emphasising the four sub-patterns: pre-populate, offline operation, update, and post-populate. For each case study, we examine:

- The specific challenges addressed by the pattern.
- The implementation process and any adaptations made to fit the unique requirements of the case.
- The outcomes and effectiveness of the pattern in enhancing system functionality and resilience

By analysing these aspects, we can identify commonalities and differences in applying the pattern, comprehensively evaluating its utility and versatility. This approach validates the proposed design pattern and offers insights into its practical implications and potential for further refinement based on future use in various low-resource environments.

4 THE OFFLINE PATTERN AND SUB-PATTERNS

To begin the process of designing an offline system, the first step is to manage the data that is processed at the remote end and synchronise it to the local storage. Processing a particular collection of data along with a time frame, location, and other parameters in order to accomplish efficient data synchronisation can lead to optimisation of the data. Since it determines the application's overall functionality, the synchronisation approach is a key component of any offline infrastructure. The synchronisation approach is what determines how much weight offline data should be given compared to online data. The network connectivity options available to the user, the importance of the data, and any other requirements for continuity should all be taken into consideration when selecting the appropriate synchronisation approach. **Figure 1** illustrates the key components of the pattern, for which an overview follows:

- **Pattern Name** – Offline pattern
- **Pattern Description** – The pattern to address network availability issues of software systems in low-resource environment
- **Problem** – Inability of software systems to function maximally due to partial or complete unavailability of the external network
- **Solution** – Incorporate the use of offline operation and local storage in the architecture of software systems

- **Use When** – Shall be used when access to the network is poor or unavailable
- **Example** – Examples are illustrated as case studies (Section 5).

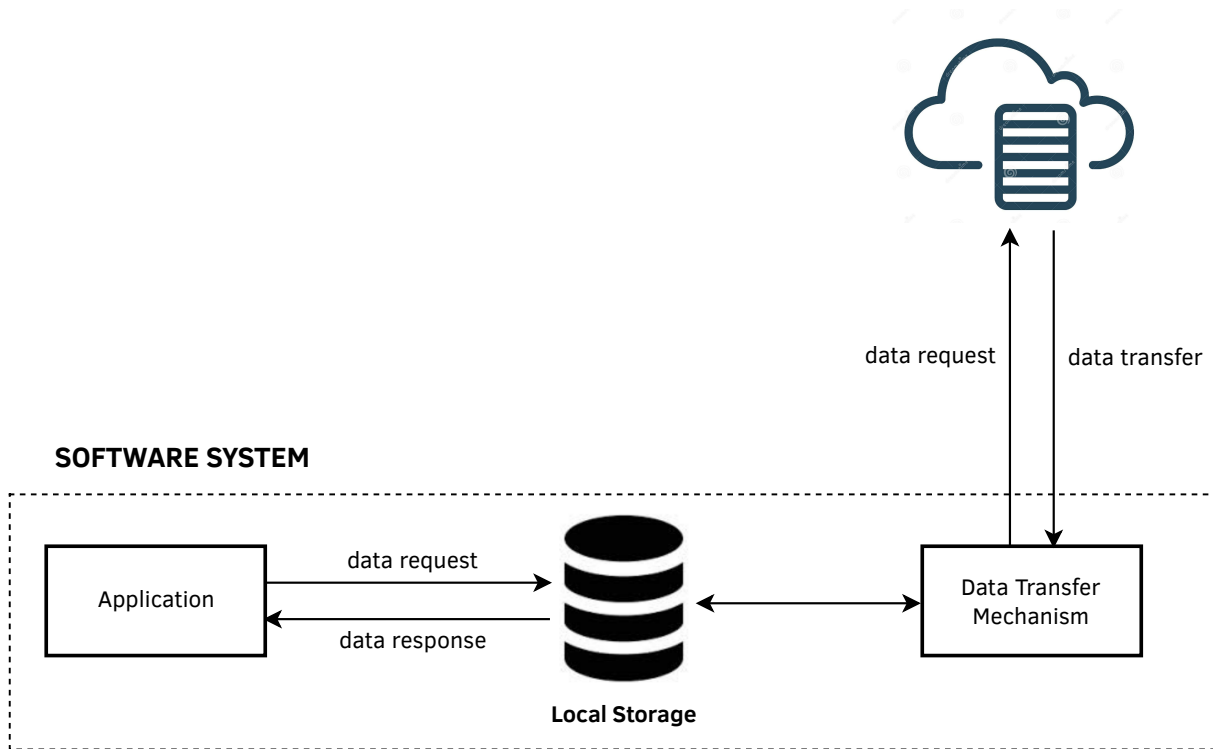


Figure 1: The Design Pattern Components

4.1 Offline storage

When users of software systems try to access stored data and services online in low-resource environments, there seem to be times when Internet access is limited or unavailable, thus impairing the ability of users to use the software system. With the advantages presented by the use of local storage, users of software systems now have the chance to deploy, evaluate, and use new software and application tools offline even when they have little to no access to the Internet.

How can software systems optimised for low-resource environments take advantage of on-premises data storage (local storage) to overcome the persistent challenge of intermittent network connectivity?

Data caching (Copps et al., 2021; Zhang et al., 2020), online/offline mode and computation offloading are a few techniques used in low-resource environments to address software system

network unavailability. There is no need to download or search a database for a resource that has been cached (Durner et al., 2021). Even when a query is optimised, the database still needs to be queried, which involves network traffic and potentially expensive database-level computation (Mertz et al., 2021). Avoiding these steps reduces application latency and increases user responsiveness. Additionally, it makes it possible for the application to manage and function effectively under a growing or increased workload. The proposed approach to ensure data availability at all times is to initially store the needed data in the local storage before requesting it again. The software systems can then operate offline without the need for network access by using the data that was previously stored locally for subsequent requests for the same data. This prevents the need to re-fetch data. The application requests fresh data from the stored data when it needs to use it. If the information is present in the local storage, it returns the instance of the information that was previously saved. If the local storage does not have the data, an attempt could be made to connect to the network to access an online data repository (which could be a file, a database, etc.), fetch the data and then return it to the application. When that information is subsequently requested again, the stored data is returned. This process repeats for the duration of the application's lifecycle.

Local storage enables Web-based programmes to run offline, saving data in local storage that can be accessed without requiring a network connection. In comparison to a server-side database, local storage has a number of benefits, such as quick response times, offline functionality, and reduced network latency.

Therefore,

Use local storage as a primary data storage mechanism. To support offline operation, where necessary, transfer data to local storage, perform updates during operation and/or transfer data from local storage to remote devices.

Initially, data needs to be transferred to a local storage device by some mechanism, whether it is network-based or not. Then, at any time network connectivity is available, a data update can occur, and the locally stored content can be updated if changes have occurred to the remote device's data.

4.2 Detailed Description of Sub-Patterns

In order to provide a thorough understanding of the proposed design pattern, it is further divided into four essential sub-patterns. Each sub-pattern addresses specific data management and system functionality aspects in low-resource environments with intermittent or limited network connectivity. By outlining these sub-patterns, we intend to present a clear framework that can be consistently applied to various scenarios, enhancing the resilience and efficiency of software systems operating under constrained conditions. In the following sections, we will explore each sub-pattern in detail, explaining their roles, implementation strategies, and the benefits they bring within the broader design pattern.

As illustrated in [Figure 2](#), the sub-patterns are:

- a. Pre-Populate
- b. Offline Operation
- c. Update
- d. Post-Populate

Pre-Populate

During installation, an application must ensure that the minimum data required to operate the application can be found locally. [Figure 2\(a\)](#) illustrates this sub-pattern, which ensures the local storage keeps sufficient data to start the application locally. This must be done in order to guarantee that the essential data for the user interface can be found in the local storage. This ensures that the application can start up regardless of whether there is an active Internet connection.

Offline Operation

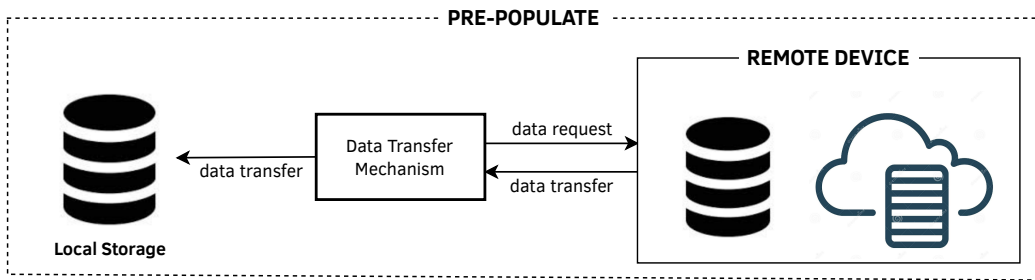
During normal operation, an application will only read data from and write data to local storage. This ensures that the application will work without a network connection or online access to remote devices. This is as described in [Figure 2\(b\)](#).

Update

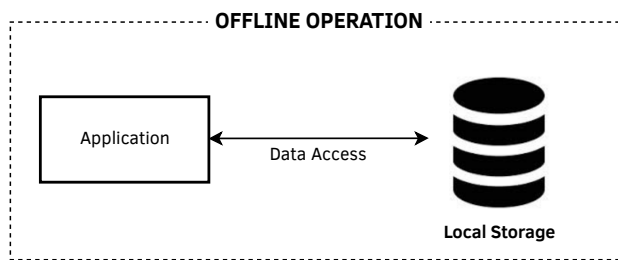
This process connects to the data source stored on the remote device so that new modifications can be synchronised with the local storage. It is the task of the pull operation (data request), which is sent out, to retrieve updated data from the remote location and save it in local storage ([Figure 2\(c\)](#)). Data updates can also be sent from the local storage to the remote device.

Post-Populate

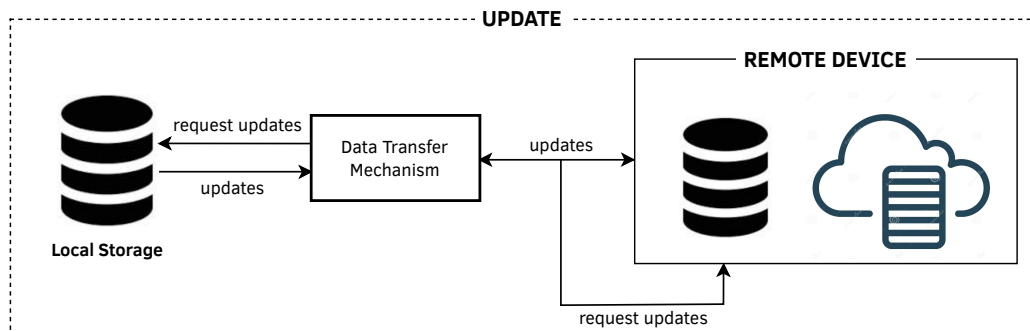
It may be necessary to ensure that the contents of the local storage are consistent with the information that is stored on the remote device, particularly when data has changed locally. If the application produces data rather than consumes it, a transfer of this data may be required to some remote device. The data set in the local storage is moved using a transfer operation ([Figure 2\(d\)](#)).



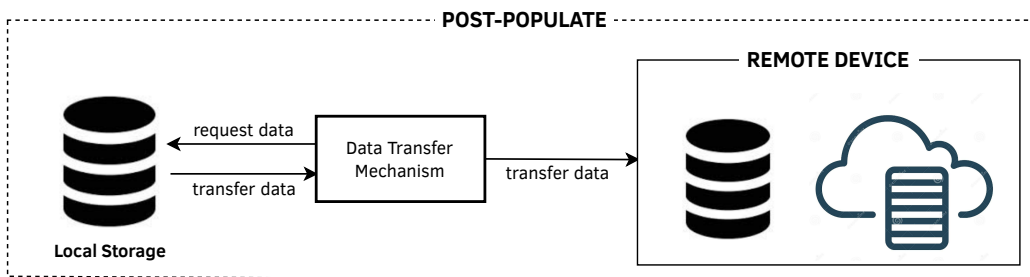
(a) Pre-Populate sub-pattern



(b) Offline Operation sub-pattern



(c) Update sub-pattern



(d) Post-Populate sub-pattern

Figure 2: Sub-Patterns of Offline Pattern Modules

The combined sequence diagram illustrating the offline pattern is shown in Figure 3.

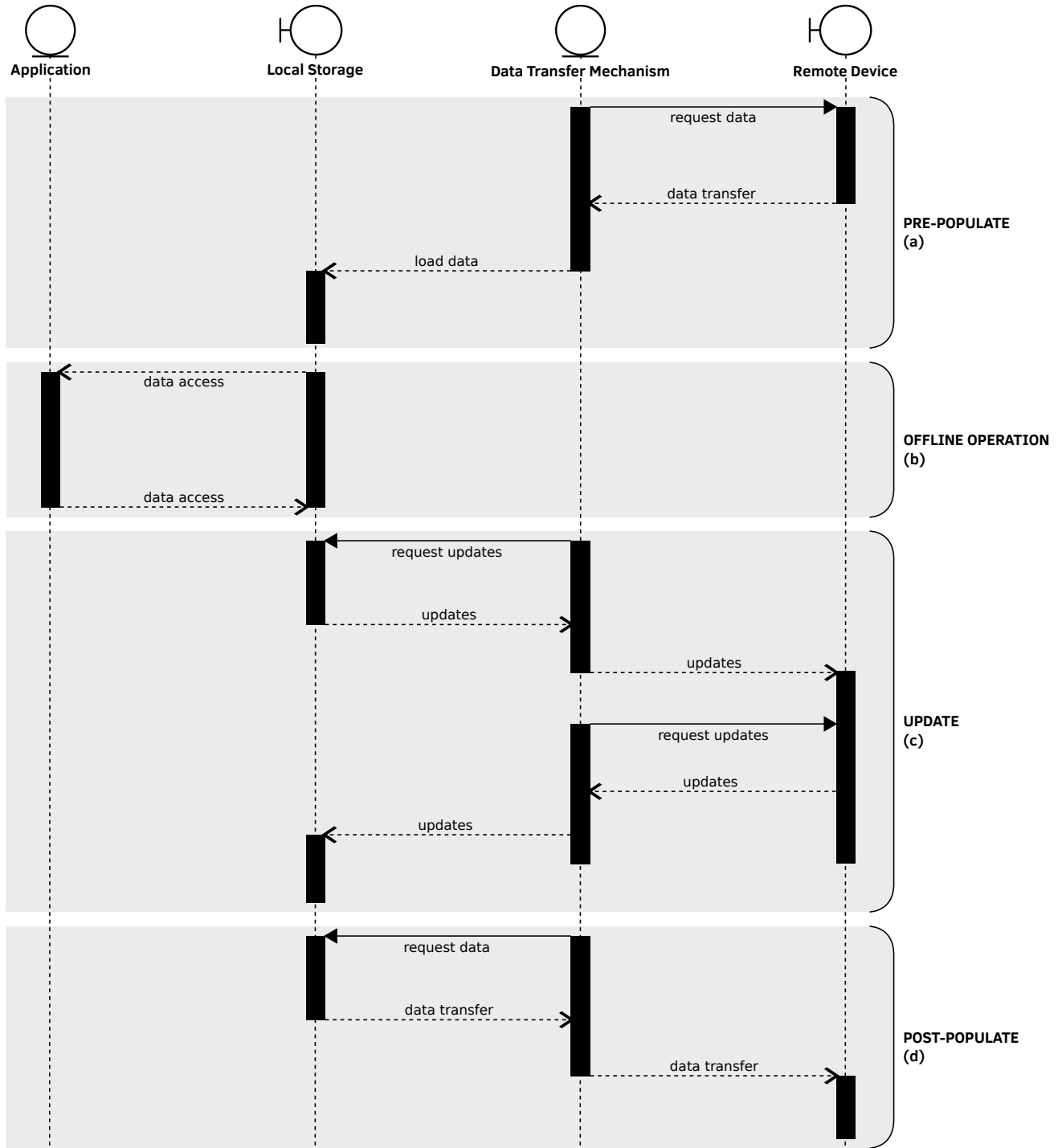


Figure 3: Offline Pattern Flow Process

4.3 Synchronisation

With all the sub-patterns, the data transfer mechanism of the application should be in charge of controlling data transfer to and from remote devices. Synchronisation methods should be used to ensure that data is synchronised in both directions between local storage and remote devices, using push and pull notifications and incorporating conflict resolution mechanisms. Data consistency conflicts can occur when the same data has been updated on local storage and on a remote device – in such a case, the specific use case should include a resolution mechanism. A use case that disallows simultaneous updates to data on local storage and remote devices will attain greater data consistency.

To avoid data consistency errors on local storage and remote devices, each request and response operation can include data and operation timestamps to enable correct sequencing of operations. Timestamps will also allow partial updates of data to be transmitted and maintained. This strategy protects against inconsistencies while making the most efficient use of available time, processing, and networking resources.

It is appropriate to consider deletions, whether they occur online or offline, to be the same as modifications. In all sub-patterns, the list of data that has been modified both on the remote device and in the local storage must be maintained, along with the date/time on which each modification was made. This is necessary in order to maintain records of modifications made. During an *update* or *post-populate* operation, recently modified data in local storage can be sent to and from a remote device on the basis of the relevant timestamps.

In some use cases, it is not uncommon for users to have more than one device, which can make managing offline applications and local storage more of a challenge. When a user attempts to synchronise data from two different devices to the remote device, a data consistency conflict may result. This conflict needs to be resolved in the *data transfer mechanism* of the remote device. This can be accomplished using a client-wins system⁸, a server-wins system, a time-based resolution, or a version control system.

When using the client-wins approach, the data stored on the local storage will take precedence over any previously stored information in the remote device. In the case of the server-wins approach, the data on the remote device will take precedence over the potentially contradictory data from the local storage. The time-based resolution determines whether the most recent data will be stored in the application regardless of whether the data is currently stored in the local storage or the remote device. Version-controlled resolver functions in a manner that is analogous to that of the git repository. If a disagreement arises, the user should be given the option to select which version of the data should be maintained within the system.

5 CASE STUDIES

The case studies presented are selected based on their relevance to low-resource environments, particularly within the African context. These include projects like OAI-PMH, iNethi, GitHub

⁸ <https://www.bigthinkcode.com/insights/offline-first-application>

Desktop, Freedom Toaster, Navigation and Mapping, and Data Collection, which illustrate the practical applications and benefits of the offline design pattern.

5.1 Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH)

The Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH) is a standard protocol in the digital libraries community that is used for transferring metadata among digital repositories and metadata-based service providers (Lagoze & Van de Sompel, 2003). The protocol was developed in response to a need to aggregate metadata from multiple repositories to create high-quality discovery tools for researchers. Federation of search queries was the previously-used technique, but its reliance on the network meant that the number of sources was equal to the number of potential sites of failure, and failures were not uncommon. In contrast, harvesting requires a once-off transfer of metadata to an aggregator, which can then provide discovery services, such as search engines, to end-users without further use of the data provider repository.

The remote device is referred to as the data provider, and the local device is the service provider. OAI-PMH predominantly uses the *pre-populate* sub-pattern (Figure 2(a)) as the first request for data is often for the entire dataset. The first request has a format such as:

```
http://some.server/OAI?verb=ListRecords&metadataPrefix=oai_dc
```

Thereafter, the service provider will request regular (often daily) updates from the data provider using a protocol request that includes a last-modified timestamp each time, such as:

```
http://some.server/OAI?verb=ListRecords&metadataPrefix=oai_dc&from
↪ =2023-04-15
```

These operations are robust in that network and remote device failures do not affect the ability of the service provider to provide services to its users. Also, since only timestamp-driven updates are transferred, updates consume very little Internet bandwidth and duplication is minimised. Thus the protocol is robust and resource-efficient, even in low-resource environments.

Data is transferred only in one direction so there is no *post-populate* sub-pattern. Data consistency is also not a problem because all updates and deletions are tracked using timestamps, and updates only occur in one direction (from data provider to service provider).

The stability of OAI-PMH also allows for hierarchical aggregators where meta-aggregators will obtain metadata from data providers that are themselves aggregators. This approach is used in the Networked Digital Library of Theses and Dissertations, where its international Union Archive (Suleman, 2004) uses OAI-PMH to obtain metadata from universities as well as university consortia and even some national consortia (like the UK's British Library and the

Brazilian national ETD project). Each of the consortial projects maintains its own data aggregator for member sites. In such a hierarchical system, updates filter from the source through multiple layers of aggregation. Data consistency is weakest at higher levels of aggregation, but most aggregators update their local stores daily so service providers are at most 2-3 days out of sync with the source archives of electronic theses.

Most service providers provide online search services to users, but do this on the basis of local storage and offline operations (Figure 2(b)) so only the end-user interface is network-dependent and all data processing and data access is local. This substantially improves the quality of service, resource requirements and robustness for such service provision.

5.2 Navigation and mapping

Navigation and mapping software applications allow end users to view maps and navigate road networks in real-time; most such tools work in low-resource environments because of a local storage and offline operation basis of operation.

The navigation and mapping applications following the offline pattern can store and retain map data locally on the device by making use of the sub-pattern *pre-populate* (Figure 2(a)). This may include maps of entire regions or simply the places that the user is most likely to visit during their trip. If the user's map data is stored locally, then even if there is no network connection, the user can still consult the map and navigate even though there is no network connection. Additionally, the application is able to locally record route information on the device itself. This can include information such as distance, estimated journey times, and turn-by-turn directions to the destination. Because this information is stored locally, it allows the user to continue following the journey even if there is no network connection. Locally on the device, the user's preferences can be saved based on the past log entries of searches. This can include things like recommended routes, favourite destinations, and settings like voice guidance and distance units, among other things. Because these preferences are stored locally, the user does not have to re-enter this information each time they use the application. In addition to this, the users will have access on their device to a number of interesting and significant points of interest, which can continue to be updated at any time the application can access the Internet for new updates (using the *update* sub-pattern: Figure 2(c)) This can include establishments such as hotels, restaurants, and service facilities for gasoline.

5.3 iNethi Community Network

The iNethi Community Network is a project in a peri-urban township of Cape Town, South Africa, that is community-driven and attempts to deliver affordable and accessible Internet connectivity to places that are not currently served (Phokeer et al., 2020). The primary purpose of the iNethi Community Network's local storage component is to enable offline content caching and to provide local service provision.

The iNethi Community Network can use the offline pattern for content caching to locally cache frequently visited material (*pre-populate* sub-pattern: Figure 2(a)). This can include things that are often accessed by community members, such as web pages and multimedia files. The system first determines if a requested piece of content is present in local storage when a user requests it. If so, accessing the Internet and relying on the network connection is not necessary because the content can be obtained straight from the local storage.

The offline pattern can be used to optimise the use of resources in the iNethi Community Network. For instance, during periods of high network connectivity, commonly used data or resources can be preloaded onto the local storage, making them immediately accessible for offline access later on when the network connection is weak or unavailable (*update* sub-pattern: Figure 2(c)) This helps to decrease the need for frequent queries to external services, saves bandwidth, and enhances the system’s overall performance and responsiveness.

The offline pattern can be used for offline data collection by the iNethi Community Network as well. Members of the community, for instance, can gather data using applications or tools that are installed locally and then save it in local storage. The data can be synchronised with the central server or online database for additional processing or analysis when a network connection becomes available (Figure 4).



Figure 4: Use-case for iNethi Community Network

5.4 GitHub Desktop

For managing Git repositories on a local computer, a programmer can use a Git client such as GitHub Desktop⁹. For offline use and to support managing Git repositories, it has features that allow data to be stored locally on the user’s computer.

In the GitHub desktop application, a user can still view and use a repository offline if they have previously used GitHub Desktop to clone it, and the repository files are stored locally on the local machine (*pre-populate*: Figure 2(a)). Thus, even without an online connection, they may use GitHub Desktop to monitor the commit history, edit files, create and manage branches, and carry out other Git-related tasks inside the local repository.

⁹ <https://github.com/>

Furthermore, since all branch-related information and commit history are stored locally, users can continue to create, switch between, and merge local branches using GitHub Desktop even when there is no network connection. However, an Internet connection would be necessary in order to push changes to or get updates from a remote repository, which can use *update* sub-pattern (Figure 2(c)). Figure 5 further illustrates this.



Figure 5: Use-case for GitHub desktop

5.5 Freedom Toaster

A free and open-source project called the Freedom Toaster¹⁰ enables users to quickly replicate digital data, like software, documents, and multimedia files, onto their own blank CDs or DVDs. Its goal is to facilitate access to knowledge and information in locations where Internet access may be difficult to find or expensive.

The operation of the Freedom Toaster is based on a large collection of CD or DVD images being stored on its hard drive (local storage) for distribution to users who physically visit the Freedom Toaster. A visitor inserts a blank CD or DVD into a DVD writer on the device and uses the touch-screen or other user interface to burn or “toast” a copy of free software or free data, such as educational material.

The Freedom Toaster conceptually uses the offline pattern twice. In the first instance, the Toaster itself uses the *pre-populate* sub-pattern (Figure 2(a)) to maintain its local collection of CD/DVD images. Then, each visitor also uses the same offline pattern in burning their CDs/DVDs as they leave with portable data stores that are pre-populated and can support offline access on their home computers. There is no post-populate or update (Figure 6).

¹⁰ <https://brandsouthafrica.com/108893/freedom-toaster/>

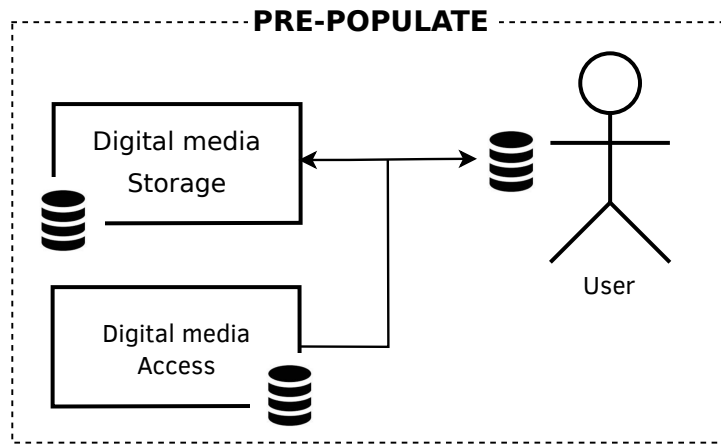


Figure 6: Use-case for Freedom Toaster

5.6 Data Collection

In the last use case, a need may arise where data is collected locally and transferred to a remote device. This scenario uses the *post-populate* sub-pattern. The data is collected locally for onward transfer to a remote device.

The *post-populate* pattern (Figure 2(d)) is used for data collection tasks even in the absence of network connectivity by collecting data locally on the local device during network unavailability and synchronising with the remote device once the network becomes available. This enables data gathering while network connectivity fails and, afterwards, synchronisation with the remote device (Figure 7).

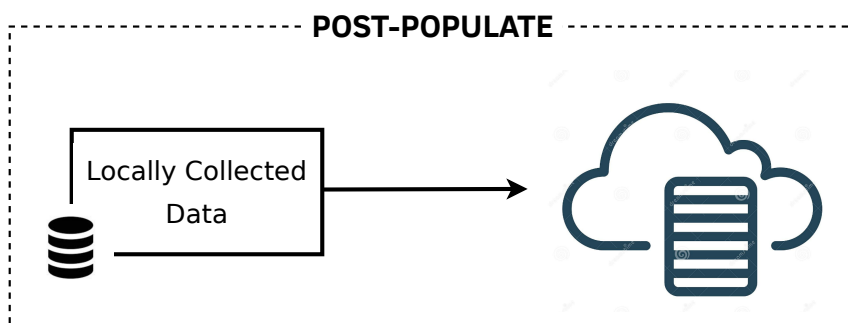


Figure 7: Use-case for Data collection

Bird et al. (2014) developed the Aikuma mobile application that runs on smartphones to collect and annotate audio data, as an example of the data collection use case in low-resource environments. Their application was deployed in remote villages with no external network connectivity, so the application ran completely offline using local storage. To avoid data

loss, data was exchanged within a small team of people, but this data could only be shared externally at a later point in time.

5.7 Comparative Analysis of Sub-Patterns

In analysing the application of the offline pattern across various case studies, it becomes evident that the effectiveness and necessity of each sub-pattern—pre-populate, offline operation, update, and post-populate—vary depending on the specific requirements and constraints of each case. For instance, in the OAI-PMH case study, the pre-population sub-pattern played a pivotal role in ensuring that essential metadata was available offline, thereby enabling uninterrupted access to digital archives. Conversely, the iNethi project prioritised the offline operation sub-pattern to empower community members to access and share information without depending on continuous Internet connectivity.

Similarly, the GitHub Desktop case demonstrated the importance of the Update sub-pattern, as it required regular synchronisation of local repositories with remote servers to maintain code consistency. On the other hand, the Freedom Toaster project highlighted the efficiency of the Post-Populate sub-pattern, guaranteeing the updating and alignment of locally stored software packages with external repositories when reconnecting to the Internet. The navigation and mapping use case showcased the comprehensive application of all sub-patterns, addressing the crucial requirement for preloaded maps, offline functionality, and periodic updates. Meanwhile, the data collection use case highlighted the importance of both the offline operation and update sub-patterns, with data collection occurring offline and subsequent synchronisation with central databases. **Table 1** highlights which sub-patterns were used and their significance in each context.

Table 1: Comparative analysis of sub-patterns in each case

Case Study/Use Case	Pre-Populate	Offline Operation	Update	Post-Populate
OAI-PMH	High	Medium	Low	Low
iNethi	Medium	High	Low	Medium
GitHub Desktop	Medium	High	High	Medium
Freedom Toaster	High	High	Medium	High
Navigation and Mapping	High	High	High	High
Data Collection	Medium	High	High	Medium

As shown in **Table 1**, the Pre-Populate and Offline Operation sub-patterns played a crucial role in ensuring initial data availability and enabling offline functionality in the OAI-PMH and Freedom Toaster projects. Both the OAI-PMH project, which required less frequent updates, and the Freedom Toaster project, which needed consistent updates for software version maintenance, relied heavily on these sub-patterns. Similarly, the iNethi and GitHub Desktop projects prioritised offline operations to facilitate continuous usage without connectivity, with

GitHub Desktop also emphasising the Update sub-pattern to synchronise local and remote repositories. On the other hand, a comprehensive application of all sub-patterns was necessary for the navigation, mapping, and data collection use cases. While navigation and mapping relied on constant updates and synchronisation to maintain accurate and relevant map data, data collection focused on offline operations for uninterrupted data gathering and subsequent synchronisation to ensure data integrity. These case studies highlight the flexibility and adaptability of the offline pattern in addressing diverse challenges in low-resource environments. This analysis not only demonstrates the practical use of the pattern but also offers a framework for its application in future projects.

In each case study, the decision to include or exclude specific sub-patterns was based on the unique requirements and operational settings of the projects (see Table 2). In the OAI-PMH case, the *Pre-Populate* sub-pattern was given priority due to the need for offline availability of metadata for archiving purposes. The Update and Post-Populate sub-patterns were considered less crucial due to the static nature of the archived data. For the iNethi project, *Offline Operation* was of utmost importance, as the project aimed to deliver Internet-like services in areas with unreliable connectivity, making continuous offline functionality essential.

Table 2: Justification for sub-pattern use/omission across case studies (orange coloured patterns were omitted, the rest were used).

Pre-Populate	Offline Operation	Update	Post-Populate
Case study: OAI-PMH Ensured metadata is available offline for archival purposes.	Enabled interaction with data without Internet connectivity.	Infrequent updates needed for archived metadata.	Minimal need for synchronisation due to the static nature of metadata.
Case study: iNethi Initial data availability is crucial to provide Internet-like services.	Allowed continuous service delivery in areas with unreliable connectivity.	Static nature of content meant updates were less critical.	Ensured data consistency upon reconnection.
Case study: GitHub Desktop Facilitated initial setup with necessary data for development workflows.	Critical for uninterrupted development workflows without connectivity.	Frequent synchronisation of local and remote repositories is necessary.	Maintained consistency between local changes and remote repositories.
Case study: Freedom Toaster Ensured software is available offline for installation.	Enabled users to install and use software without Internet access.	Necessary for incorporating new software versions and updates.	Maintained consistency of software across devices.
Case study: Navigation and Mapping Made maps available offline for continuous use.	Allowed for uninterrupted usage of navigation and mapping features without connectivity.	Critical for maintaining accuracy and relevance of maps over time.	Ensured data consistency between local and remote sources to keep maps up to date.
Case study: Data Collection Provided initial data setup for offline data gathering.	Essential for collecting data in environments without Internet access.	Enabled synchronisation of collected data once connectivity is restored.	Ensured eventual consistency of collected data with remote databases.

In the GitHub Desktop case, the *Update* sub-pattern played a crucial role in maintaining

synchronisation between local and remote repositories, mirroring the ever-changing nature of software development workflows. The Freedom Toaster project, which aimed to distribute software in regions with intermittent Internet access, heavily depended on the *Post-Populate* sub-pattern to guarantee that users would receive the most up-to-date software versions upon reconnecting.

Navigation and mapping applications need to fully implement *all sub-patterns* to ensure that maps are preloaded, available offline, and regularly updated for accuracy. Conversely, the data collection use case prioritises *Offline Operation* and *Updates*, necessitating robust data collection mechanisms that can operate without Internet access and synchronise collected data upon restoring connectivity.

Similarly, the iNethi project emphasised *Pre-Population* and *Offline Operations* to offer Internet-like services in areas with unreliable connectivity, using *Post-Population* to ensure data consistency upon reconnection, and omitting the update sub-pattern due to the static content nature. The cases of GitHub Desktop and Freedom Toaster both emphasised the importance of *Pre-Population* and *Offline Operations* for initial setup and seamless functionality. The *Update* sub-pattern was crucial for synchronisation, while *Post-Population* ensured consistency. Navigation and mapping relied on all sub-patterns to ensure continuous offline map usage, accuracy, and relevance. In data collection, *Offline Operation* for data gathering without Internet access is essential, utilising *Updates* for synchronisation and *Post-Population* for consistency with remote databases. These case studies demonstrate the adaptability and effectiveness of the offline pattern and its sub-patterns in addressing specific requirements and limitations in low-resource environments.

6 RESULTS AND DISCUSSION

The proposed offline pattern was evaluated through six distinct case studies: OAI-PMH, iNethi, GitHub Desktop, Freedom Toaster, navigation and mapping, and data collection. These cases were carefully selected to represent various low-resource environment scenarios and to showcase the flexibility of the pattern. The results indicate that the offline pattern significantly improves the reliability and functionality of software systems in such environments. Each case study emphasised the pattern's effectiveness in data management and its ability to sustain operations despite intermittent or limited network connectivity. The consistent application of the pattern across different scenarios underscores its strength and adaptability.

An analysis of the case studies reveals the diverse applications and effectiveness of the offline pattern and its sub-patterns. For example, the *Pre-Populate* and *Offline Operation* sub-patterns were universally essential, enabling initial data availability and uninterrupted functionality, respectively. The *Update* sub-pattern demonstrated its value, particularly in scenarios such as GitHub Desktop and data collection, where real-time synchronisation was less critical but periodic updates were necessary. The *Post-Populate* sub-pattern proved notably beneficial in cases such as Freedom Toaster and iNethi, where offline-collected data needed to be reliably uploaded once connectivity was restored. This comparative insight highlights the

pattern's adaptability to address specific needs within different low-resource settings.

The strengths of the proposed offline pattern lie in its modularity and scalability. Decomposing the pattern into four distinct sub-patterns allows for tailored applications based on specific requirements, enhancing its utility across various domains. However, one limitation is its reliance on local storage, which could be restrictive in very resource-constrained environments. Furthermore, the pattern's effectiveness is closely tied to the initial setup and configuration, requiring thorough planning and implementation to fully realise its potential. Despite these limitations, the pattern represents a notable advancement in data management and ensuring operational continuity in low-resource scenarios.

The study suggests several recommendations for software practitioners. Firstly, software practitioners should thoroughly assess the operational environment to determine the most suitable sub-pattern combination. prioritising the Pre-Populate and Offline Operation sub-patterns can establish essential functionality. In contrast, the Update and Post-Populate sub-patterns can be applied selectively to address specific data synchronisation and upload needs. Practitioners should also account for potential constraints on local storage and develop strategies to address any limitations. Lastly, continual monitoring and iterative refinement of the implementation are essential to adapting the pattern to evolving requirements and improving its effectiveness in low-resource environments.

7 CONCLUSION

In low-resource environments, software systems often face limitations in processing power, memory, and network connectivity, making reliance on cloud storage challenging. Despite the use of strategies such as MQTT, CoAP, and caching to mitigate these issues, they remain dependent on network connectivity. In these contexts, the offline pattern introduced in this paper leverages local storage to enhance the functionality of software systems. By focusing on local storage, the offline pattern improves system efficiency and reliability, particularly for low-end devices. This distinction between offline storage and synchronisation is crucial, as it ensures that systems can maintain functionality independently of network availability, thus enhancing their reliability and usability in varied and often challenging conditions.

For the offline pattern to be implemented effectively, software developers should identify key functionalities that benefit from this approach, especially in low-resource settings. During design, pre-populating local storage with essential data is crucial to ensure seamless operation without network access. Emphasis should be placed on offline operation, minimising the need for real-time synchronisation. Regular updates are necessary to keep local storage synchronised with external data sources, facilitating smooth transitions between online and offline modes. Employ post-population techniques to maintain consistency between local and remote data, ensuring accurate data integration upon connectivity restoration. Future research could delve deeper into optimising local memory usage within the offline pattern, addressing storage challenges in hardware-constrained environments. Investigating the scalability and flexibility of the offline pattern in various settings will also be important to understand its

broader applicability.

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Migrating teaching of automata theory to a digital platform

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ABSTRACT

This research explores the challenges of teaching automata theory in computer science and proposes a digital solution to enhance learning experiences. Traditionally taught through pen and paper, automata theory often appears daunting to students due to its abstract nature. This study advocates for a shift towards a more interactive, digital approach. It presents a detailed analysis of current teaching practices, highlighting the need for digital innovation. Based on the categorisation of common question types in traditional assessments, the research introduces *AutomaTutor*, a mobile application designed for this specific educational context. *AutomaTutor* features a user-friendly interface with a guided exercise system and an interactive editor for experimentation. It offers immediate feedback, hints, and varied problem sets, promoting self-guided learning. An experimental evaluation with postgraduate students demonstrated a preference for *AutomaTutor* over conventional methods, confirming the hypothesis that a digital platform can significantly improve the understanding of automata theory. The study represents a step forward in making theoretical computer science more accessible and engaging, benefiting both teachers and students. It underscores the potential of integrating technology with traditional teaching principles in automata theory education.

Keywords Automata theory, computer science education, digital learning

Categories • Social and professional topics ~ Computer science education

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1 INTRODUCTION

Theoretical computer science, encompassing the study of formal languages, automata, and complexity theory, is foundational for understanding computing principles. However, its abstract nature often poses challenges for students, impacting their engagement and comprehension. The shift to digital platforms in education presents an opportunity to revitalise the teaching of these concepts, particularly in automata theory.

This article investigates the migration of teaching theoretical computer science to a digital platform, with a focus on automata theory. Traditionally, this subject has been taught using static and text-heavy methods, which can obscure the dynamic and interactive nature of the

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field. Our work proposes *AutomaTutor* – a mobile application designed to provide an interactive and engaging learning experience. Through this digital approach, we aim to enhance student understanding and engagement by transforming the way theoretical computer science is taught. Currently, *AutomaTutor* is limited to finite automata and regular expressions.

1.1 Objectives and Methods

The primary objective of this research was to develop and evaluate a digital platform that can effectively teach automata theory, a core component of theoretical computer science. To achieve this, we first conducted a comprehensive literature review to identify current teaching practices and their limitations. We then developed the *AutomaTutor* application, which incorporates interactive exercises, real-time feedback, and a user-friendly interface. The app was designed to accommodate various learning styles and to provide a more intuitive understanding of automata theory.

An experimental study was conducted with students to evaluate the effectiveness of the *AutomaTutor* app compared to traditional teaching methods. The study measured various outcomes, including student performance, engagement, and satisfaction.

1.2 Summary of Findings

The results of the experimental study indicate a significant improvement in student performance and engagement when using the *AutomaTutor* app compared to traditional methods. Students reported a better understanding of automata theory concepts and expressed a preference for the interactive and immediate feedback provided by the app. These findings suggest that a digital approach to teaching theoretical computer science can offer substantial benefits in terms of learning outcomes and student satisfaction.

1.3 Implications and Conclusions

This research contributes to the field of computer science education by providing evidence of the potential benefits of digital learning platforms. The *AutomaTutor* app demonstrates how interactive and engaging tools can enhance the learning experience in theoretical computer science. The findings suggest that such digital platforms can be an effective supplement or alternative to traditional teaching methods.

In conclusion, this research marks a step towards modernising the teaching of theoretical computer science. By embracing digital technologies, educators can provide students with a more engaging and effective learning experience. Future work will focus on expanding the app's content, exploring its application in other areas of computer science, and further refining its features based on user feedback.

2 RELATED WORK

The field of automata simulation tools has evolved significantly since its inception in the early 1960s. Coffin et al.'s (1963) seminal work on simulating a Turing machine on a digital computer marked the beginning of this journey. They emphasised the practicality of such simulations for problem solving, algorithm validation, and education in programming fundamentals. This early venture laid the groundwork for subsequent developments in automata simulation tools.

Over the past several decades, a variety of tools have been developed, each contributing uniquely to the domain. Chakraborty et al.'s (2011) comprehensive review of fifty years of automata simulation provides a valuable classification of these tools. This review, despite being over a decade old, remains a relevant starting point for understanding the evolution of automata tools.

2.1 Classification of Automata Simulation Tools

Automata simulation tools can be broadly classified into three categories: language-based, table-based, and canvas-based tools.

2.1.1 Language-Based Tools

Language-based tools represent automata as programs of a programming language. Knuth and Bigelow's (1967) introduction of a simplified symbolic notation for automata in 1967 was a pivotal development in this category. This notation, resembling assembler language, made automata theory more accessible and programmable.

Subsequent works by Harris (2002), Chakraborty (2007), Romero (2021), Middleton et al. (2020), and others have furthered this approach. Notably, Romero's (2021) Pyformlang and Middleton et al.'s (2020) FL-AT have contributed significantly to the field. The MOD-EST language and toolset, as detailed by Bohnenkamp et al. (2006) and Hartmanns and Hermanns (2014), have been instrumental in modeling and verifying complex automata structures, including Markov automata, as elucidated by Butkova et al. (2021). FL-AT encompasses an entire toolset from construction to the simulation of automata (Middleton et al., 2020).

These tools enable a robust and precise formal definition of automata. The use of programming languages allows for detailed and accurate representation of automata behaviours and properties. Furthermore, these tools are well-suited for users who are well-versed in automata theory, providing a platform for deep exploration and analysis. However, the mathematical and programming-oriented nature of these tools introduces a high skill floor, making them less accessible for beginners in the field. The complexity of the language and formalism can be daunting for those without a strong background in mathematics and programming. Overall, this classification risks overemphasising formalism at the expense of intuitive understanding.

2.1.2 Table-Based Tools

Table-based tools constitute a significant advancement in the field of automata simulation, characterised by their use of transition tables for the construction of automata. This approach, exemplified by the works of Hannay (2002), Hamada (2008), and Jovanović et al. (2021), has been particularly influential in enhancing the learning process. The system developed by Jovanović et al. (2021), for instance, has substantially facilitated the visual simulation of finite automata and the conversion of regular expressions into deterministic and nondeterministic finite automata.

One of the primary benefits of table-based tools is their ability to reduce the barrier to entry for novices in the field. By abstracting some of the more complex formalisms of automata theory into a structured transition table, these tools offer a more intuitive and less error-prone approach to defining automata. This abstraction is especially advantageous in educational settings, aiding in the foundational understanding of automata theory. The structured format of transition tables also assists learners in conceptualising automata operations, providing a clear and organised overview of state transitions and automata behaviour.

Despite these advantages, table-based tools are not without their limitations. While they simplify the process of defining automata, a fundamental understanding of the underlying formalisms of automata theory remains necessary. Users of these tools must still grasp the basic principles of automata to effectively utilise them. Moreover, while table-based tools represent a step towards a more visual construction process, they do not offer the comprehensive visualisation capabilities of more advanced, canvas-based tools. This limitation can be a significant drawback for users who prefer or benefit from a fully graphical representation of automata. Additionally, there is a risk of oversimplification inherent in the tabular format of these tools. The nuances and complexities of more advanced automata concepts might not be fully captured or appreciated within the confines of a transition table.

2.1.3 Canvas-Based Tools

The evolution of automata simulation tools witnessed a pivotal shift with the advent of canvas-based simulators in the 1990s, a movement marked by significant technological innovation. Early contributions in this domain, such as LoSacco and Rodger's (1993) FLAP. Robinson et al.'s (1999), Java-based tool, and Cogliati et al.'s (2005) research on visualisation in computing theory, set the stage for a more interactive and visually engaging approach to automata simulation. These tools, enabling users to draw automata as state-transition diagrams, greatly enhanced the visual and interactive aspects of simulation, making complex automata concepts more accessible and comprehensible.

Prominent among the canvas-based tools are JFLAP by Rodger and Finley (2006) and jFAST by White and Way (2006). JFLAP, in particular, stands out for its comprehensive feature set and versatility, offering support for a wide range of automata types. It has been widely recognised as the de facto standard for automata simulation tools for many years. However, its last update in 2018 and the lack of focus on user experience have made it less suitable for

beginners, catering more towards users with an advanced understanding of automata theory.

The paper by Vayadande et al. (2022) introduces a canvas-based editor specifically for deterministic finite automata (DFA) construction, highlighting the continuous evolution and specialisation within this category. However, it focuses exclusively on DFA, and the construction process is a hybrid between canvas- and table-based tools.

A significant advancement in this category is the Automata Tutor v3 (D'Antoni et al., 2020). This tool represents a substantial improvement over its predecessors, particularly in its ability to automatically grade and provide feedback on a variety of problems. It supports tasks ranging from creating regular expressions and context-free grammars to pushdown automata and Turing machines. Moreover, it allows for the generation of new problem instances, making it a valuable tool for educators and students alike. Despite being more beginner-friendly than JFLAP, the user interface of Automata Tutor v3 still leaves room for improvement.

The popularity of canvas-based tools persists today, with their interactive and visual approach proving highly effective in teaching and understanding automata theory. However, their sophistication and range can sometimes be a double-edged sword. While they offer an immersive and detailed environment for learning and experimentation, the complexity and depth of features can be overwhelming for beginners. Furthermore, the focus on visual representation, though beneficial for conceptual understanding, might sometimes detract from the formal mathematical understanding of automata theory.

2.2 Recent Advances and Mobile Applications

The landscape of automata simulation tools has recently expanded beyond traditional desktop applications, embracing the mobile domain with innovative applications designed for handheld devices. This shift towards mobile platforms reflects an overarching trend in educational technology, prioritising accessibility and portability. Key players in this new wave include FLApp (Pereira & Terra, 2018) and Automata Simulator (Singh et al., 2019). These mobile applications have introduced a touch-based methodology for constructing and simulating various types of automata, such as finite automata, pushdown automata, Turing machines, and transducers, directly on mobile devices.

FLApp, introduced by Pereira and Terra (2018), targets beginners in the field of formal languages and automata. It stands out for its simple interface and comprehensive feature set, making it particularly effective for instructional purposes. FLApp is distinguished as the first mobile application in this domain that prioritises the learning process, rather than merely serving as a tool for automata construction and simulation.

Singh et al. (2019) present another mobile application, inspired by the capabilities of JFLAP but with a more limited feature set. This app has been well-received by students for its usefulness, although it is often preferred as a supplementary tool in conjunction with JFLAP, rather than as a standalone learning solution.

2.3 Educational Impact

The role of automata simulators in educational settings, particularly at the university level, has been increasingly recognised for its significant impact. Studies conducted by educators and researchers such as Rodger et al. (2009), Bezáková et al. (2022), and Stamenković and Jovanović (2021) have collectively highlighted how these tools have revolutionised the teaching and learning of automata theory.

Rodger et al. (2009) showcased the enhanced engagement in automata theory facilitated by JFLAP, an interactive formal languages and automata package. Their study underscored the effectiveness of interactive simulation tools in increasing student interest and understanding in this traditionally challenging subject area. The interactive nature of these simulators allows for a more hands-on approach to learning, making abstract concepts in automata theory more tangible and comprehensible to students.

Bezáková et al. (2022) conducted a study to ascertain the most effective types of feedback for students learning automata theory. They discovered that feedback in the form of witnesses - specific examples where a student's solution fails - significantly improved student performance and persistence in the course. This finding highlights the importance of tailored feedback in educational simulators, as it can directly impact student comprehension and retention of automata concepts.

Along a similar vein, Stamenković and Jovanović (2021) addressed the challenges in teaching compiler theory, a field closely related to automata theory. Their research introduced educational simulators as a means to enhance student participation and learning. These simulators provide visual representation tools for complex concepts like lexical and syntax analysis, thereby improving the teaching process and making the subject matter more accessible to students.

2.4 Game-Based Learning Approaches

Our work also relates to game-based approaches to learning automata theory, as exemplified by Silva et al.'s (2010) Automata Defense 2.0 and Vieira and Sarinho's (2019) AutomataMind. These approaches incorporate educational elements into game formats, offering an engaging and interactive way to introduce basic concepts of automata theory.

2.5 Summary

Existing research in automata simulation tools, while extensive and varied, predominantly focuses on developing technical capabilities and enhancing theoretical understanding. However, a common limitation across these tools is the emphasis on formalism and complexity, which can be a barrier for beginners and hinder usability. Furthermore, the integration of these tools into formal university courses has been somewhat limited, often lacking a focus on the overall user experience. Our research addresses these gaps by concentrating on the integration of automata simulation tools into a formal university curriculum. We place a specific emphasis

on usability and user experience, ensuring that the tools are not only technically proficient but also accessible and engaging for all levels of learners, from beginners to advanced students. This approach aims to make automata theory more approachable and comprehensible, thereby enhancing the educational impact of these simulation tools.

3 TEACHING AND ASSESSMENT OF AUTOMATA THEORY

In this section we review the classical approach of teaching and assessment of automata theory, implemented at several universities in South Africa. For conciseness, we focus on the class of finite automata which represent regular languages. The discussed concepts can be straightforwardly generalised to further classes such as pushdown automata and Turing machines. We start with a brief recap of the foundations of finite automata and regular expressions.

3.1 Foundations of Finite Automata and Regular Expressions

Within the field of automata theory a finite automaton is a computational model that can serve as a recogniser of a regular language. Finite automata are foundational for understanding the properties and limitations of algorithms and are crucial in both theoretical study and practical applications in computer systems. A finite automaton can be either deterministic or non-deterministic. A deterministic finite automaton is defined as follows:

Definition 3.1 (Deterministic Finite Automaton). A deterministic finite automaton (DFA) is a tuple $M = (Q, \Sigma, \delta, q, F)$ where:

- Q is a finite set of states,
- Σ is a finite set of symbols known as the alphabet,
- $\delta : Q \times \Sigma \rightarrow Q$ is the transition function,
- $q \in Q$ is the start state, and
- $F \subseteq Q$ is the set of accepting states.

A DFA can process finite input strings $w = w_1 \dots w_n$ where each w_i is a symbol from the alphabet Σ . Processing an input string results in a run of the automaton that either leads to the acceptance or the rejection of the string, refer to [Definition 3.2](#).

Definition 3.2 (Run, Acceptance, and Rejection). Let $M = (Q, \Sigma, \delta, q, F)$ be a DFA and let $w = w_1 \dots w_n$ be a string over Σ . Then the run of M over w is the sequence of states $q_0 \dots q_n$ such that

- $q_0 = q$, and
- $q_{i+1} = \delta(q_i, w_i)$ for all $i < n$.

The DFA M accepts the string w if q_n is an accepting state of the automaton. Otherwise, M rejects w .

The set of all strings accepted by an automaton is known as the language of the automaton, refer to **Definition 3.3**.

Definition 3.3 (Language of a DFA). Let M be a DFA over the alphabet Σ . Then the language $L(M)$ of M is the set of all strings over Σ accepted by M :

$$L(M) = \{w \mid w \text{ is accepted by } M\}.$$

As an illustrating example we consider the language $L = \{w \mid w \text{ ends with } 01\}$ over the alphabet $\Sigma = \{0, 1\}$. This language is recognised by the deterministic finite automaton $M = (Q, \Sigma, \delta, q, F)$ where:

- $Q = \{q_0, q_1, q_2\}$,
- $\Sigma = \{0, 1\}$,

• $\delta :$

	0	1
q_0	q_1	q_0
q_1	q_1	q_2
q_2	q_1	q_0

- $q = q_0$, and
- $F = \{q_2\}$.

The automaton M can be equivalently represented by the state-transition diagram depicted in **Figure 1**. In the diagram circles represent states and arrows represent transitions. The incoming arrow into q_0 indicates that q_0 is the start state and the double circle around q_2 indicates that q_2 is an accepting state.

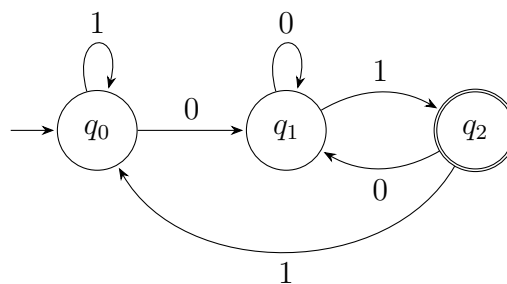


Figure 1: DFA with language $L = \{w \mid w \text{ ends with } 01\}$.

The second type of a finite automaton is a non-deterministic one – refer to **Definition 3.4**.

Definition 3.4 (Non-Deterministic Finite Automaton). A non-deterministic finite automaton (NFA) is a tuple $M = (Q, \Sigma, \delta, q, F)$ where:

- Q is a finite set of states,
- Σ is a finite set known as the alphabet,
- $\delta : Q \times \Sigma_\epsilon \rightarrow \mathcal{P}(Q)$ is the transition function where $\Sigma_\epsilon = \Sigma \cup \{\epsilon\}$,
- $q \in Q$ is the start state, and
- $F \subseteq Q$ is the set of accepting states.

In this definition ϵ refers to the empty string. In contrast to a DFA, the transition function of an NFA maps each pair of a state and a symbol from the alphabet to a *set* of possible successor states. This implies that for an input string w *multiple* corresponding runs of an NFA may exist. The NFA accepts an input string if at least one of the corresponding runs is accepting. The language of an NFA M is again the set of all strings w accepted by M .

The language of our running example can be also represented by an NFA which is depicted in [Figure 2](#).

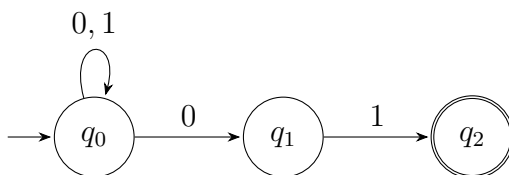


Figure 2: NFA with language $L = \{w \mid w \text{ ends with } 01\}$.

As can be seen, the automaton is non-deterministic in the sense that in state q_0 the symbol 0 allows the automaton to either transition to q_0 again or to q_1 . Moreover, the automaton also maps certain pairs of states and symbols to the *empty* set of successor states, which is for instance the case for the state q_1 and the symbol 0. It implies that q_1 does not have a successor state for the symbol 0. If we consider the example input 001, then we can see that there exist the two possible runs $q_0q_0q_0$ and $q_0q_1q_2$ of the automaton. Since at least the latter run ends in an accepting state, the string ‘001’ is contained in the language of the NFA.

Every language that can be recognised by a DFA can also be recognised by a NFA and vice versa. It should be noted that NFAs typically allow to represent languages with fewer states and transitions than DFAs. The class of languages that can be described by DFAs and NFAs are the *regular languages*. An alternative way to define regular languages is via regular expressions.

Mathematically, a regular expression comprises symbols from an alphabet and regular operators, where the alphabet is a finite set of symbols. The language of a regular expression is the set of strings it generates, refer to [Definition 3.5](#).

Definition 3.5 (Regular Expression). Let Σ be an alphabet. The set of regular expressions $R(\Sigma)$ over Σ can be defined recursively as follows:

- The empty string ϵ is a regular expression over Σ , denoted by $\epsilon \in R(\Sigma)$.
- The empty set \emptyset is a regular expression over Σ , denoted by $\emptyset \in R(\Sigma)$.
- If $a \in \Sigma$, then $a \in R(\Sigma)$.
- If $r \in R(\Sigma)$, then $r^* \in R(\Sigma)$.
- If $r_1, r_2 \in R(\Sigma)$, then $r_1 \cup r_2 \in R(\Sigma)$.
- If $r_1, r_2 \in R(\Sigma)$, then $r_1 \cdot r_2 \in R(\Sigma)$.

The Kleene star closure of a regular expression r , denoted by r^* , generates the set of all possible strings that can be formed by repeating r zero or more times. The union of languages generated by two regular expressions r_1 and r_2 , denoted by $r_1 \cup r_2$, is the set of all strings that can be generated by either r_1 or r_2 . Moreover, the concatenation of languages generated by two regular expressions r_1 and r_2 , denoted by $r_1 \cdot r_2$, is the set of all strings that can be generated by concatenating a string generated by r_1 and a string generated by r_2 . For simplicity we will typically just write $r_1 r_2$ for a concatenation $r_1 \cdot r_2$.

The language of our running example is defined by the regular expression

$$(0 \cup 1)^* 01.$$

That is, the concatenation of an arbitrary string over the alphabet $\Sigma = \{0, 1\}$ and the suffix 01 .

An integral part of teaching automata theory is to provide students with an understanding that deterministic finite automata and non-deterministic finite automata as well as regular expressions are equally powerful concepts. Moreover, students need the skills to convert these different representations of regular languages into each other. In the following section, we discuss the types of assessment questions that are commonly used to let students develop their understanding and skills.

3.2 Assessment Questions on Finite Automata and Regular Expressions

With a foundational understanding of regular languages, finite automata and regular expressions as outlined in [Section 3.1](#), the focus now shifts to effective assessment methodologies for these concepts. As indicated in [Table 1](#), certain question types can be used in evaluating students' comprehension and application skills in this field.

A concrete instance of each of these question types can be provided based on our running example from [Section 3.1](#):

- Construct a DFA that recognises the language $L = \{w \mid w \text{ ends with } 01\}$ over the alphabet $\Sigma = \{0, 1\}$.

- Construct a regular expression that defines the language $L = \{w \mid w \text{ ends with } 01\}$ over the alphabet $\Sigma = \{0, 1\}$.
- Convert the regular expression $(0 \cup 1)^*01$ into a DFA with the same language.
- Is the string ‘001’ contained in the language of the regular expression $(0 \cup 1)^*01$?

Table 1: Question Types and their Descriptions

Question Type	Description
Construct a finite automaton	Given a regular language, construct an automaton that recognises it.
Construct a regular expression	Given a regular language, construct a regular expression that defines it.
Convert between different representations of regular languages	Convert an NFA to a DFA, convert a regular expression to a finite automaton, and vice versa.
Determine string matching	Determine if a given string is recognised by a given regular expression or automaton.

The solutions to these questions can be derived from our running example.

Constructing an automaton for a given regular language is a primary question type. This requires students to embody abstract language rules into a tangible automata model, whether it be a DFA or an NFA. Regular expression constructions expect students to encapsulate the rules of a language using regular expressions, thereby testing their grasp of how these expressions delineate patterns within a language. Equally crucial is the ability to convert between different types of automata. This skill is assessed by requiring students to transform one automata form, such as a DFA, into another, like an NFA or a regular expression. This not only demonstrates their understanding of each automata type but also their proficiency in recognising the equivalences and differences between them. Lastly, assessing students on their capability to determine string matching with regular expressions is vital. This type of question is aimed at evaluating whether students can effectively apply regular expressions to ascertain the recognition of strings in a language.

Effective assessment requires the instructor to provide students with questions of different types and different levels of difficulty, let the students solve the questions, and eventually provide the students with feedback on their solutions. Questions can be provided in the form of exercise sheets and homework assignments as well as tests. In the following section we outline how the assessment process is currently implemented in the course *Theoretical Computer Science* at a South African university.

3.3 Assessment Process

This section integrates the discussion of the types of questions used in assessments, illustrated in Table 1, with an analysis of the assessment process in the course *Theoretical Computer Science* with about 200 students at a South African university. An integral part of the assessment process is a weekly homework assignment. Figure 3 graphically illustrates the assignment-based assessment process.

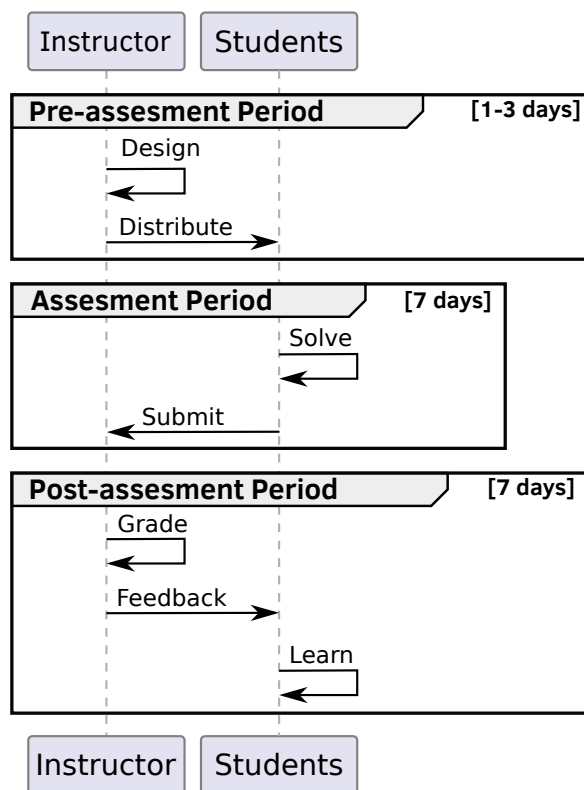


Figure 3: Classical Assessment Process

We will now discuss the major steps of the process in further detail.

3.3.1 Design

This step involves careful consideration of the learning objectives and outcomes that the assessment is intended to measure. The instructor designs an assignment worksheet. This requires the instructor to handcraft questions of the previously introduced types or to adopt questions from educational resources such as textbooks. Moreover, the instructor needs to develop a grading scheme for each question. The simplest form of a grading scheme is to provide marks for a fully correct solution only. The types of questions on regular languages also allow for a more differentiated grading scheme: Half of the marks if the student solution accepts all strings

that are contained in the given language representation, and the other half of the marks if the student solution rejects all strings that are not contained in the given language representation. This scheme can be further refined by providing a concrete list of strings that must be accepted and a list of strings that must be rejected, and awarding a mark for each correctly accepted or correctly rejected string, respectively.

The completion of the design step may require multiple days, since the instructor needs to ensure that the questions have an adequate level of difficulty. Moreover, the instructor needs to verify that the memorandum solutions and the grading schemes are error-free.

3.3.2 Solve

After receiving the assignment sheet, students have one week to solve it and submit their solutions. Students may work with pen and paper or may use an automata editor such as JFLAP.

JFLAP allows students to test their solutions by running simulations with different input strings. But the students will only be informed whether their solutions are correct after the grading step has been completed.

3.3.3 Grade and Provide Feedback

Teaching assistants grade the student submissions, which typically takes a week for a course with 200 students. Students receive feedback by means of marks and possibly counterexamples that indicate where the submitted solutions are erroneous. Constructive feedback is crucial for the students' learning process, as it helps them understand their mistakes and grasp the concepts more effectively.

JFLAP may be used to aid the grading step, which however does not allow to automatise the grading. Teaching assistants are still required to explicitly test certain input strings. Manual grading may involve grading errors.

3.3.4 Learn

One week after the submission students receive their marks and feedback.

The delay between the submission and the feedback can lead to a disconnection for students, who might lose the context or the line of reasoning that led them to their original solutions.

3.4 Conclusions of the Assessment Process

We illustrated the assessment process based on a homework assignment on finite automata. Different types of assessments such as tests, and assessing different topics of automata theory involve similar steps and efforts. As pointed out, the use of existing automaton simulation tools

can help students to test their solutions, and it can support graders in the marking step. However, the process still has several limitations and drawbacks. Students only receive delayed feedback and the quality of the feedback depends on the grader. Moreover, designing questions, grading as well as providing feedback is error-prone and requires manual effort, which increases with the number of students in the course.

In the next section, we present our novel digital framework for teaching and assessment of automata theory and we discuss how the framework allows to overcome several drawbacks of the classical assessment process.

4 DIGITAL FRAMEWORK FOR TEACHING AND ASSESSMENT OF AUTOMATA THEORY

AutomaTutor is a digital platform crafted to improve the teaching and learning of automata theory and to enable a digitally enhanced assessment process. It is designed with dual interfaces, catering to both students and instructors: the student interface is a mobile application, offering a dynamic and interactive learning experience, while the instructor interface, currently accessible through the source code, allows for the generation of new exercises and assignments. This educational tool focuses on core areas such as usability, feedback, and generation, featuring two primary components – a *sandbox* which is an editor for free-form exploration and creation of automata as depicted in [Figure 4\(a\)](#), and a digital *tutor* for structured learning and assessment, seen in [Figure 4\(b\)](#). The tutor allows students to solve instructor-generated exercises and assignments within the app. *AutomaTutor* provides a flexible and user-centric learning environment, accessible via <https://automatutor.netlify.app> and optimised for mobile phone use.

4.1 Core Features

At the heart of *AutomaTutor* lies a fundamental commitment to user engagement, encapsulated through its trio of core features: usability, feedback, and generation. These features are designed to not only simplify the interaction with the tool but also to sustain and enhance the learning experience. Usability ensures a smooth and intuitive engagement with the application, feedback mechanisms aim to retain and deepen this engagement by providing meaningful insights, and generation features serve to broaden the scope and extend the longevity of user engagement.

4.1.1 Usability

Addressing a key gap in existing automata tools, *AutomaTutor* has been purposefully designed with a mobile-first approach to offer an intuitive and user-friendly interface. Optimised for touch-based interactions, it incorporates gestures such as taps and swipes for the seamless construction and modification of automata. Central to its usability is the automatic arrangement

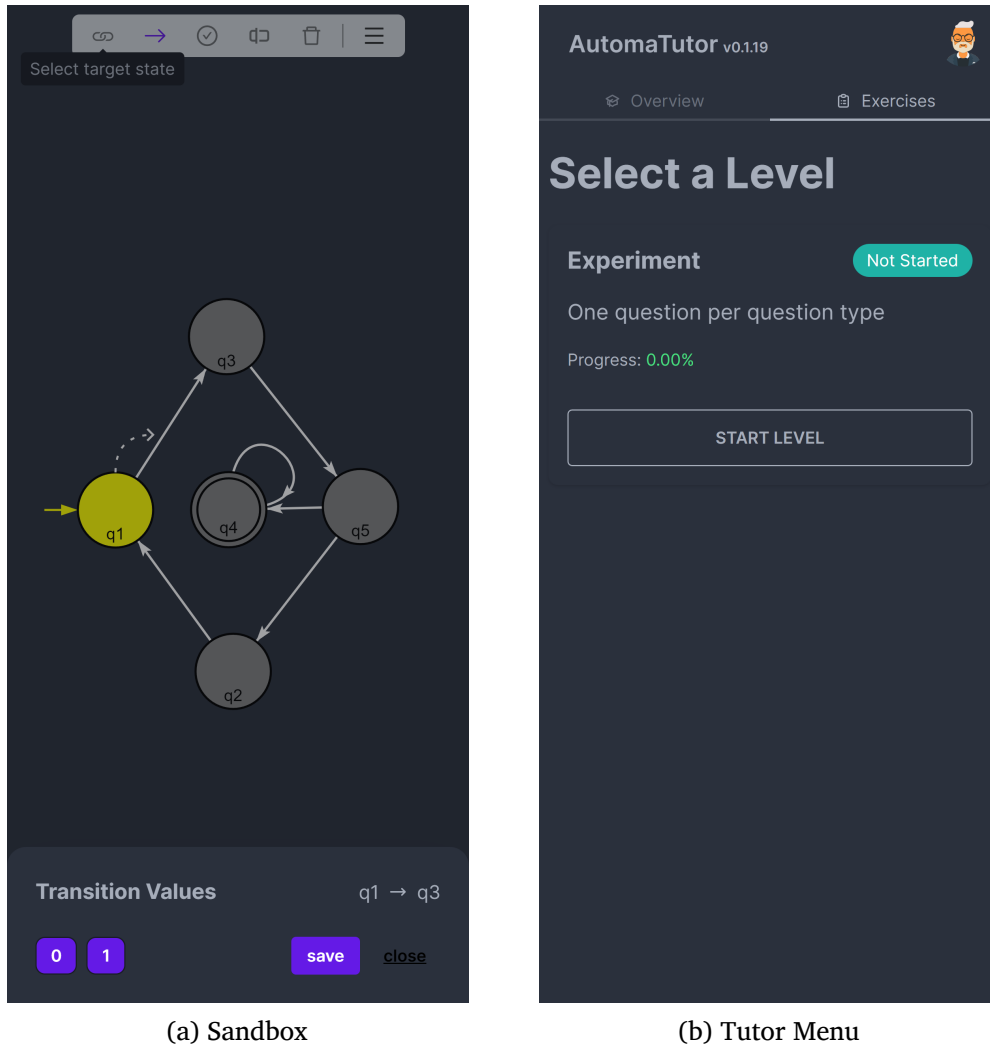


Figure 4: Core Components

of automata components, ensuring a visually organised and clear presentation. The interface dynamically adjusts the zoom level and diagram positioning, providing an optimal screen view. This adaptability is crucial, particularly when dealing with larger automata, as it maintains readability and ease of interaction, embodying modern mobile application standards in gesture-based navigation.

4.1.2 Generation

AutomaTutor allows to automatically generate questions on regular languages that can be used as exercises or assignments, and it allows to generate counterexamples that illustrate where an incorrect student solution differs from the memorandum solution.

Regular Expression Generation We present algorithms for generating regular expressions that centre on substrings, string length, and the synergistic use of these elements through concatenation and union operations. We begin by considering exercises related to substrings. Specifically, these exercises involve identifying strings that either begin with, end with, or contain certain substrings. Here, we propose **Algorithm 1** to generate corresponding regular expressions for these scenarios.

Algorithm 1

Require: Alphabet Σ , length of substring l , mode of operation $mode$

Ensure: A regular expression RE

- 1: Initialise an empty regular expression RE
 - 2: Generate a random substring s from Σ with length l
 - 3: Construct a regular expression R_Σ using union operations among all symbols in Σ
 - 4: Apply the Kleene star to R_Σ to get R_{Σ^*}
 - 5: **if** $mode ==$ ‘begin’ **then**
 - 6: $RE \leftarrow sR_{\Sigma^*}$
 - 7: **else if** $mode ==$ ‘end’ **then**
 - 8: $RE \leftarrow R_{\Sigma^*}s$
 - 9: **else if** $mode ==$ ‘contain’ **then**
 - 10: $RE \leftarrow R_{\Sigma^*}sR_{\Sigma^*}$
 - 11: **end if**
 - 12: **return** RE
-

In the following we provide a number of examples that show **Algorithm 1** in use.

- **Example 1:** Alphabet set $\Sigma = \{0, 1\}$, length of substring $l = 2$, mode of operation ‘begin’
The algorithm would randomly generate a substring s of length 2 from Σ , say ‘01’. The regular expression would then be $01(0 \cup 1)^*$, which matches any string that begins with ‘01’.
- **Example 2:** Alphabet set $\Sigma = \{a, b\}$, length of substring $l = 1$, mode of operation ‘end’
The algorithm would randomly generate a substring s of length 1 from Σ , say ‘b’. The regular expression would then be $(a \cup b)^*b$, which matches any string that ends with ‘b’.
- **Example 3:** Alphabet set $\Sigma = \{0, 1, 2\}$, length of substring $l = 3$, mode of operation ‘contain’
The algorithm would randomly generate a substring s of length 3 from Σ , say ‘120’. The regular expression would then be $(0 \cup 1 \cup 2)^*120(0 \cup 1 \cup 2)^*$, which matches any string that contains ‘120’.

Next we consider regular expressions that are focused on string length, specifically, regular expressions that require identifying strings of exact length, strings that are at least of a certain

length, or strings whose length is divisible by a particular value. **Algorithm 2** below outlines the method for generating a regular expression based on a given alphabet Σ and the constraints on string length.

Algorithm 2

Require: Alphabet set Σ , length constraint l , mode of operation *mode*

Ensure: A regular expression RE

- 1: Initialise an empty regular expression RE
 - 2: Construct a regular expression R_Σ using union operations between all symbols in Σ
 - 3: Apply the Kleene star to R_Σ to get R_{Σ^*}
 - 4: **if** *mode* == ‘exact’ **then**
 - 5: $RE \leftarrow R_\Sigma^l$ \triangleright where R_Σ^l is an abbreviation for the l -times concatenation of R_Σ with itself
 - 6: **else if** *mode* == ‘at least’ **then**
 - 7: $RE \leftarrow R_\Sigma^l R_{\Sigma^*}$
 - 8: **else if** *mode* == ‘divisible’ **then**
 - 9: $RE \leftarrow (R_\Sigma^l)^*$
 - 10: **end if**
 - 11: **return** RE
-

Below we illustrate **Algorithm 2** with a few examples.

- **Example 1:** Alphabet set $\Sigma = \{0, 1\}$, length constraint $l = 3$, mode of operation ‘exact’
The algorithm would generate the regular expression $(0 \cup 1)(0 \cup 1)(0 \cup 1)$, which matches any string of exact length 3.
- **Example 2:** Alphabet set $\Sigma = \{a, b\}$, length constraint $l = 2$, mode of operation ‘at least’
The algorithm would generate the regular expression $(a \cup b)(a \cup b)(a \cup b)^*$, which matches any string of length at least 2.
- **Example 3:** Alphabet set $\Sigma = \{0, 1, 2\}$, length constraint $l = 2$, mode of operation ‘divisible’
The algorithm would generate the regular expression $((0 \cup 1 \cup 2)(0 \cup 1 \cup 2))^*$, which matches any string where the length is divisible by 2.

Finally, **Algorithm 3** generates complex regular expressions based on an input alphabet Σ and a specified number k of expressions to generate and combine.

Algorithm 3**Require:** Alphabet set Σ , number of expressions k , range r **Ensure:** A regular expression RE

- 1: Initialise an empty list of regular expressions REs
- 2: Construct a regular expression R_Σ using union operations among all symbols in Σ
- 3: Apply the Kleene star to R_Σ to get R_{Σ^*}
- 4: **for** $i = 1$ to k **do**
- 5: Generate a random length l within range r
- 6: $REs_i \leftarrow ((R_\Sigma)^l) \triangleright$ where REs_i indicates the i -th element of the list REs and $(R_\Sigma)^l$ is the l -times concatenation of R_Σ with itself
- 7: **end for**
- 8: Randomly decide between concatenation and union operations as a connector for each adjacent pair of expressions in REs to form the final expression RE
- 9: **return** RE

A few examples of more complex regular expressions are:

- **Example 1:** Alphabet set $\Sigma = \{0, 1\}$, number of expressions $k = 3$

Assume that the algorithm generates the random lengths 2, 1, and 3 for the three expressions. It selects to use concatenation to combine the first two and union to combine the resulting expression with the third one. The generated regular expression would then be $((0 \cup 1)(0 \cup 1)) \cdot (0 \cup 1)$ for the first part, and $((0 \cup 1)(0 \cup 1)(0 \cup 1))$ for the second part. The final expression becomes $((0 \cup 1)(0 \cup 1)) \cdot (0 \cup 1) \cup ((0 \cup 1)(0 \cup 1)(0 \cup 1))$, which matches any string composed of two characters followed by one character, or any string composed of three characters.

- **Example 2:** Alphabet set $\Sigma = \{a, b\}$, number of expressions $k = 2$

Assume that the algorithm generates the random lengths 1 and 3 for the two expressions. It selects to use union combine them. The generated regular expression would then be $(a \cup b) \cup ((a \cup b)(a \cup b)(a \cup b))$, which matches any string composed of either one character or a string composed of three characters concatenated together.

Exercise Generation The exercise and assignment generation of *AutomaTutor* has been implemented as follows: Based on specified parameters such as question type and difficulty level, the tool generates random regular expressions as described in Section 4.1.2. These expressions are then processed through standard conversion (Maheshwari & Smid, 2019) and minimisation algorithms (Brzozowski, 1962) to formulate exercise questions, presented in both textual (such as question text) and visual (such as an automaton) formats for enhanced understanding. Additionally, the automaton created from the conversion process doubles as a memorandum

solution. This enables the tool to generate specific counterexamples based on the student’s solution, providing targeted feedback in instances where discrepancies or errors exist. This approach not only aids in reinforcing correct concepts but also in pinpointing and rectifying misunderstandings, thereby enriching the learning experience.

Counterexample Generation Counterexamples are key in understanding where a student’s answer diverges from the memorandum solution. In order to define what counterexamples in the context of regular languages are, we first need a formal notion of exercises.

An exercise is given as follows: a student is presented with a description of a regular language, denoted D_T , of type T . Here, T could be textual, DFA, NFA, or Regex. The student is then asked to produce another description $D_{T'}$ of a different type $T' \neq T$ such that both descriptions represent the same language, $L(D_T) = L(D_{T'})$. The student’s solution $D_{T'_S}$ will then be validated against a memorandum solution $D_{T'_M}$.

Now we can formally define a counterexample in the context of regular languages: Counterexamples are categorised into two types, each being a set of strings:

- **Type I Counterexamples (Cex_{Extra}):** These include strings w where $w \in L(D_{T'_S})$ but $w \notin L(D_{T'_M})$. Essentially, these are strings wrongly included in the student’s solution. These can be intuitively considered as **false positives**
- **Type II Counterexamples ($Cex_{Missing}$):** These include strings w where $w \notin L(D_{T'_S})$ but $w \in L(D_{T'_M})$. These are strings wrongly excluded from the student’s solution. These can be intuitively considered as **false negatives**

The counterexamples can be mathematically determined as follows:

$$Cex_{Extra} = L(D_{T'_S}) \cap \overline{L(D_{T'_M})}$$

$$Cex_{Missing} = \overline{L(D_{T'_S})} \cap L(D_{T'_M})$$

Here, $\overline{L(D_{T'_M})}$ and $\overline{L(D_{T'_S})}$ represent the complements of $L(D_{T'_M})$ and $L(D_{T'_S})$ respectively. This is also a straightforward algorithm to compute.

By contrasting **Figures 5** and **6**, the distinction between the student’s solution ($D_{T'_S}$) and the memorandum solution ($D_{T'_M}$) becomes apparent. For example, the string ‘10’ is accepted by $D_{T'_S}$ but not by $D_{T'_M}$, making it a Type I Counterexample (Cex_{Extra}). Similarly, the string ‘110’ is accepted by $D_{T'_M}$ but not by $D_{T'_S}$, classifying it as a Type II Counterexample ($Cex_{Missing}$). These counterexamples are generated and used as targeted hints for students.

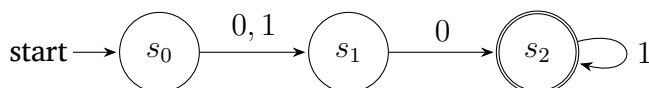


Figure 5: Automaton $D_{T'_S}$ representing the student’s solution.

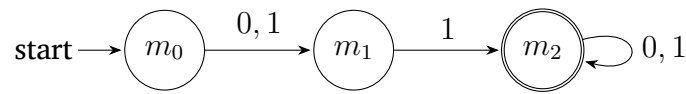
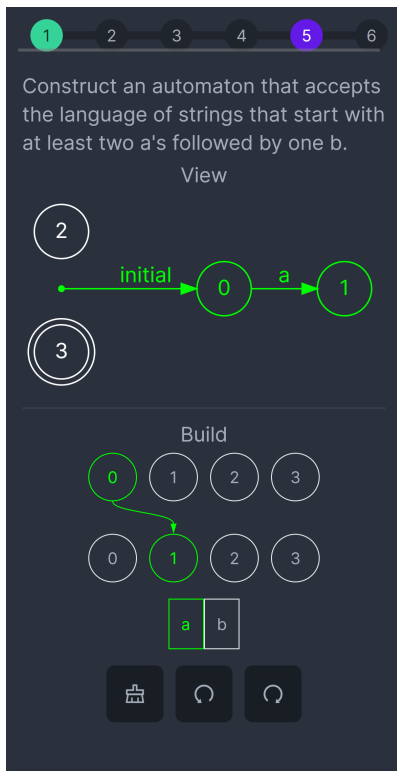


Figure 6: Automaton $D_{T'_M}$ representing the memorandum solution.

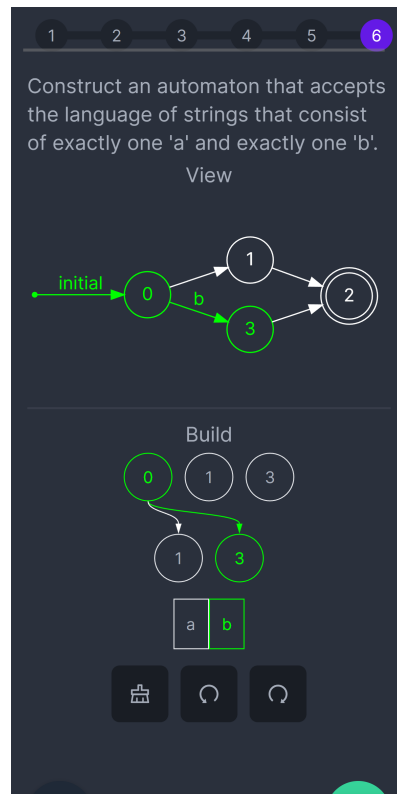
4.1.3 Feedback

Feedback in *AutomaTutor* serves as more than just a response, it is a proactive tool that guides and informs the student’s learning journey. This section details the feedback modalities, each designed to offer timely and constructive insights.

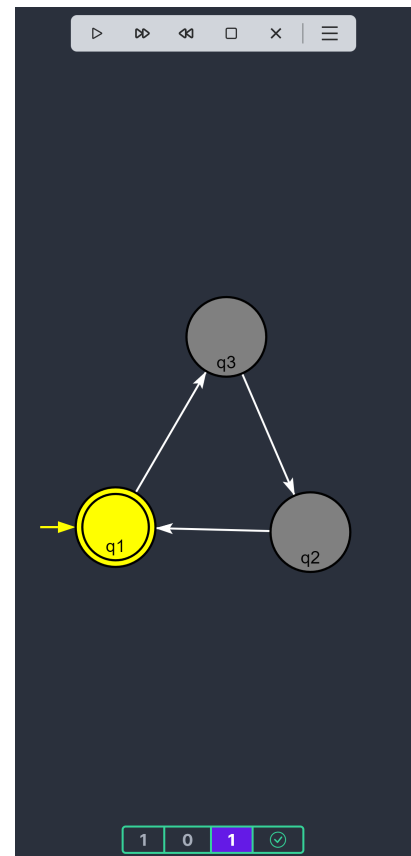
Hints, designed to scaffold problem-solving skills and alleviate user frustration, play a crucial role within the application. The application presents hints as textual prompts via a pop-up interface as seen in Figure 7(a). These hints are so far manually curated, and offer users a variety of suggestions to guide their problem-solving process.



(a) Requested Hint



(b) Counterexample



(c) Simulation Step

Figure 7: Examples of Feedback

Counterexamples to incorrect student solutions are another form of feedback that *Auto-*

maTutor offers. **Figure 7(b)** shows how a counterexample is presented to the learner by means of a pop-up. As discussed in the previous section, the application generates counterexamples automatically.

The *Simulation* (**Figure 7(c)**) feature in the application is primarily integrated within the sandbox. This allows users to construct automata and simulate string inputs against them, fostering an active learning experience. The automata simulation in the application utilises colour highlighting to indicate the active state and transitions during the simulation. The application also incorporates an animation that signifies the reading of the next input symbol. An accepted or rejected input is highlighted in green or red, respectively, providing clear feedback to the user.

Upon completing an exercise or an assignment, users are presented with a summary of their performance. This feedback includes basic metrics such as the number of submission attempts, time taken, and percentage correct (in case some questions were left incorrect or unanswered). This information helps users identify areas where they excelled and those where improvement is needed, guiding their future learning efforts.

4.2 Digitally Enhanced Assessment Process

The features of *AutomaTutor* allow to introduce a digitally enhanced assessment process that overcomes several shortcomings of the classical assessment process. This section delves into the specifics of this enhanced process (see **Figure 8**), illustrating how each step is redefined to facilitate a more effective and engaging learning environment.

4.2.1 Design

In *AutomaTutors* digitally enhanced assessment process, the design phase is streamlined. Instructors can specify the parameters for the assessment types and difficulty levels, and the tool automatically generates a variety of exercises and assignments, including memorandum solutions. This feature not only saves time but also ensures a diverse range of questions, tailored to meet the course's learning objectives effectively.

4.2.2 Solve

Students engage with *AutomaTutor* to solve the generated question sets. The usability features of the app, such as gesture-based interactions and automatic layout adjustments, make the solving process more intuitive and efficient. This immediate interaction with the tool facilitates an active and immersive learning experience, vital for understanding automata theory. If the question sets are used as exercises, then the app provides immediate feedback in the sense of hints and counterexamples. This instant feedback mechanism ensures that any misconceptions are addressed promptly, facilitating a more effective and responsive teaching environment. Hints can be disabled when question sets are used as assignments.

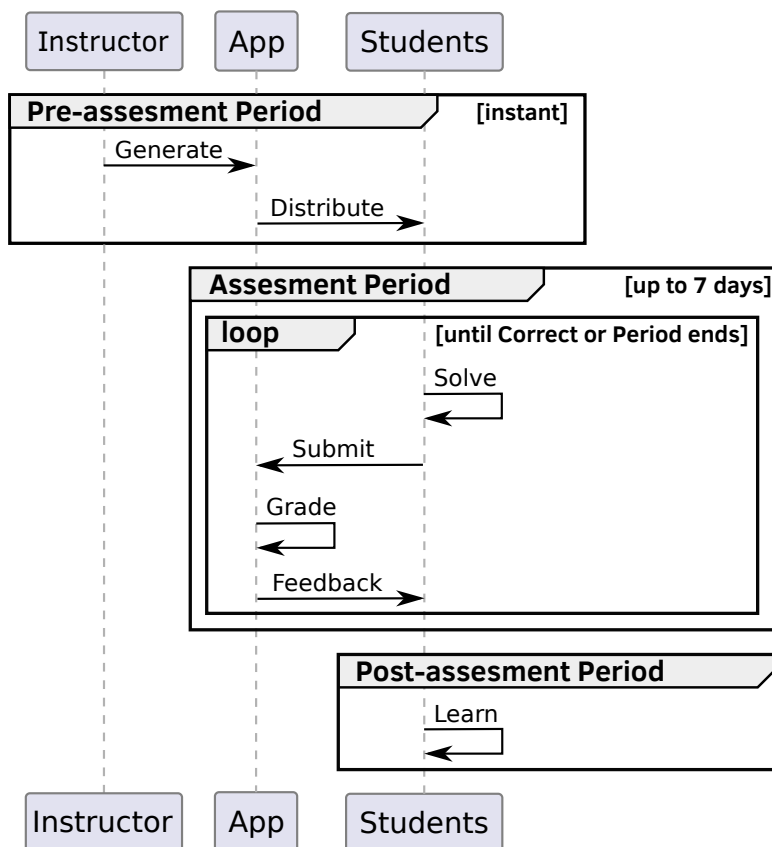


Figure 8: Tool Assessment Process

4.2.3 Grade and Provide Feedback

A standout feature of *AutomaTutor* is its capability to deliver immediate grading and insightful feedback. When students submit their responses, the tool promptly assesses them in comparison to the memorandum solutions. Marks are automatically awarded based on the existence or non-existence of counterexamples in the student solution. This automated evaluation not only benefits students but also significantly advantages instructors.

For instructors, this functionality translates to a substantial reduction in the time and effort traditionally spent on grading assignments. They no longer need to manually check each student’s submission, a process that can be especially cumbersome in large classes. Instead, *AutomaTutors* automated system handles the assessment.

4.2.4 Learn

Immediately after the submission of an assignment via *AutomaTutor* the students receive their marks and, if applicable, counterexamples that illustrate why their solution is incorrect. This instant feedback cycle facilitated by *AutomaTutor* allows students to quickly assimilate and

rectify their mistakes, enhancing the overall learning process. This feature is particularly beneficial in a course with a large number of students, as it ensures timely and personalised feedback for each student, fostering a deeper understanding of automata theory.

4.3 Conclusions of the Enhanced Assessment Process

The integration of *AutomaTutor* into the assessment process of automata theory represents a significant improvement over traditional teaching and assessment methods. The tool's automation of exercise generation and grading not only reduces the instructor's workload but also provides students with an immediate and interactive learning experience. In the next section we present experimental results on how the introduction of *AutomaTutor* impacts student performance, engagement and satisfaction.

5 EVALUATION

In pursuit of understanding the efficacy of digital platforms in teaching automata theory, we conducted an experiment¹ with fourth-year computer science students at our university in South Africa. The experiment compared two distinct teaching methodologies: traditional paper-based assignments and app-based assignments. The objective was to assess how these methods would influence students' performance, their user experience, and the overall effectiveness of learning.

5.1 Methodology

This section provides a detailed guide to how the experiment was conducted. We explore the steps, tools and procedures utilised to maintain transparency.

5.1.1 Participants

The participants comprised of 45 students enrolled in the fourth-year of their computer science programme. Therefore, participants were expected to have a higher level of academic maturity and subject expertise than an ideal test group. However, twenty of the students had recently transferred from other institutions and claimed to have little to no expertise on the subject matter. The remaining twenty five students had originally been introduced to the content being examined two years prior to the experiment. Given the two-year hiatus, the study expected varying degrees of content recall among the participants. Furthermore, it should be noted that participation was voluntary, and the students were briefed about the research goals.

¹ Ethical clearance for the experiment was received

5.1.2 Question Sets

A physical worksheet featuring three question types previously defined in Section 3.2 was used. Mirroring the worksheet, *AutomaTutor* provided an interactive digital counterpart with three questions of the same types and the same level of difficulty. The question sets are depicted in Figure 9.

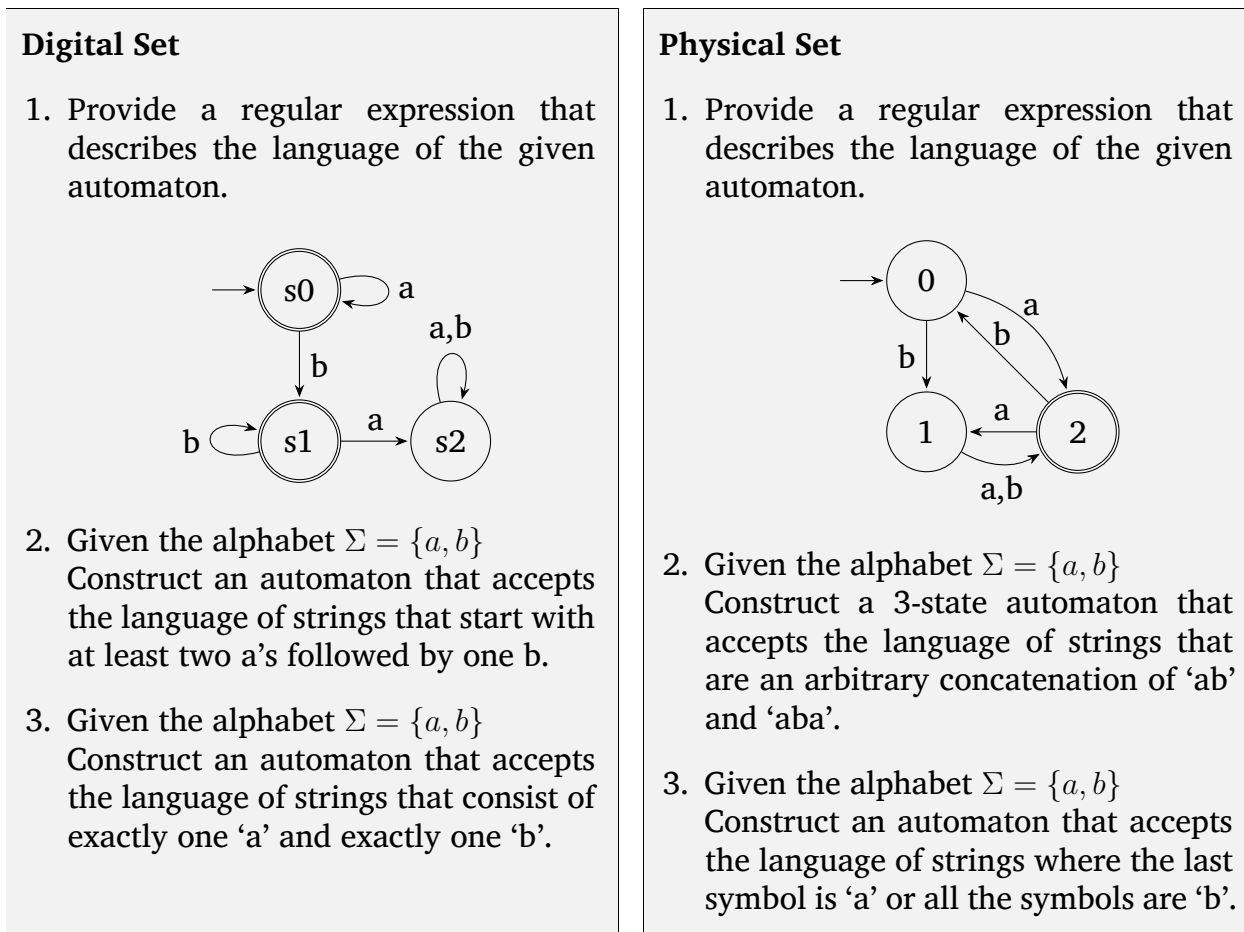


Figure 9: Question sets.

5.1.3 Questionnaire

Post-experiment, a questionnaire was used to gather qualitative data on the participants' experiences. It included various types of questions, from scaled responses to open-ended queries, aimed at understanding user preferences and perceived challenges with both teaching methods. The following questions were included in the questionnaire:

1. Did you complete COS210 at the University of Pretoria?

2. Which exercise did you start with?
3. How would you rate your overall experience using pen and paper for solving exercises?
4. How would you rate your overall experience using the mobile app for solving exercises?
5. Which format did you prefer for problem-solving: pen and paper or the app?
6. Please explain why you preferred the previously mentioned format.
7. Did you encounter any technical issues while using the app? If so, please elaborate.
8. Which questions were you able to complete on the app?
9. How many hints did you use on the app?
10. How many incorrect answers did you submit on the app?
11. What features of the app did you find most beneficial for learning?
12. What improvements could be made to the mobile application to enhance the learning experience?
13. Do you have any additional comments or suggestions regarding this experiment?

5.1.4 Data Collection and Management

The traditional worksheets were manually graded and the data was digitised for analysis, while *AutomaTutor* automatically graded the digital worksheets. For both types of worksheets, the grading scheme was one mark for each correctly solved question and no marks for incorrect solutions. Questionnaire responses were managed through a secure, anonymised platform.

5.1.5 Procedure

The experiment was conducted in a controlled setting to ensure minimal external influence on the outcomes. The process was structured as follows:

1. **Preparation Phase:** A brief content refresher was provided, followed by an overview of the study's objectives.
2. **Execution Phase:** Participants were evenly divided into two diverse groups. The first group initially interacted with the app, followed by a switch to the paper worksheet after a short break. The second group interacted with the two teaching methods in reverse order.
3. **Data Collection Phase:** Worksheets were collected for manual data recording, while the app automatically exposed relevant metrics.

4. **Feedback Phase:** Participants completed a questionnaire to capture their subjective experiences with each teaching method.
5. **Data Management and Analysis:** All data, both from the app and worksheets, were digitised and securely stored for subsequent analysis.

The following section presents the results of this experiment, offering insights into the effectiveness of traditional versus app-based assignments in teaching automata theory.

5.2 Results

This section summarises the experimental results with regard to experiences and performance of participants. The detailed results can be found in [Appendices A and B](#).

5.2.1 Perceived Experiences by Participants

Participants were asked to rate their overall experience with each medium on a scale of one to five, as depicted in [Figure 10](#).

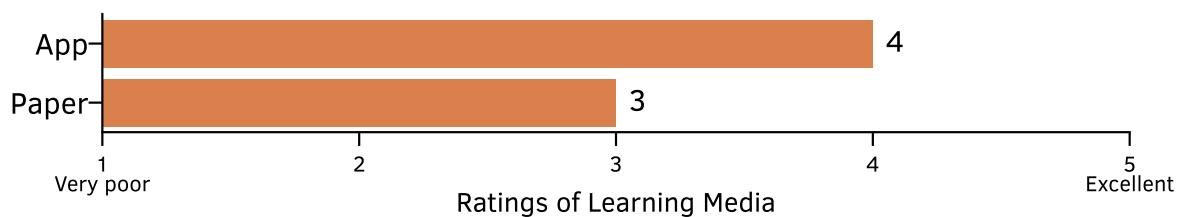


Figure 10: Median ratings of Learning Media

The app-based medium garnered higher ratings, suggesting a more favourable participant perception. Furthermore, when queried about their preferences, as illustrated in [Figure 11](#), a majority (58%) favoured the app over traditional paper worksheets.

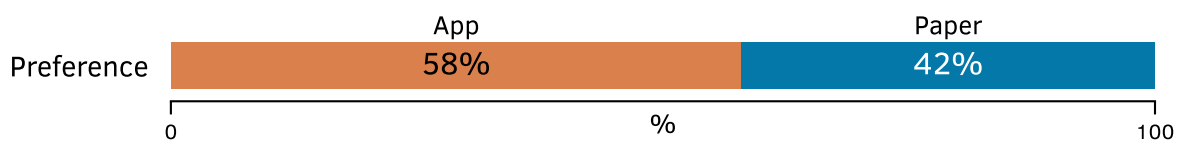


Figure 11: Preferences of Learning Media (%)

When considering the reasons behind these preferences, participants highlighted feeling less pressured and an enhanced freedom to experiment with solutions when using the app. The immediate feedback and interactive nature of the app were seen as key factors that reduced the stress typically associated with an exam-like setting and encouraged a more exploratory approach to problem-solving.

Conversely, a notable proportion of participants (42%) expressed a preference for the traditional paper medium. This group valued the tactile and unrestricted nature of pen-and-paper, finding it more conducive to brainstorming and free-form thinking.

5.2.2 Participant Performance per Medium

The stark contrast in performance between the two mediums, as depicted in Figure 12, necessitates a critical examination. While the data shows a pronounced improvement in participant performance using *AutomaTutor*, this is not solely indicative of the app's ability to enhance cognitive capabilities or learning efficiency. Rather, the key factor contributing to this disparity is the immediate feedback mechanism embedded within the app.

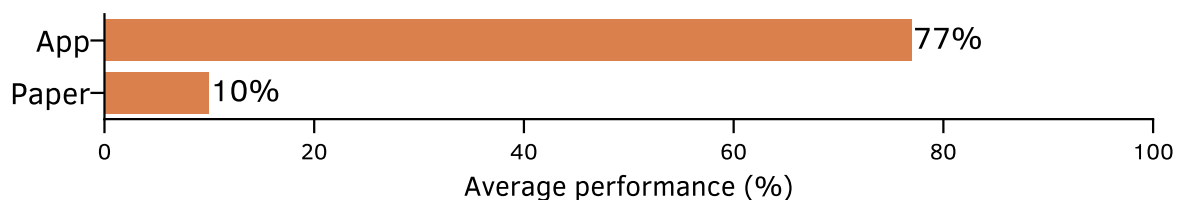


Figure 12: Average Performance by Medium (%)

The design of *AutomaTutor* allows students to receive instant feedback on their submissions, enabling them to quickly identify and correct their errors. This feature is particularly beneficial in a learning environment where understanding the nuances of automata theory is crucial. The ability to immediately rectify mistakes fosters a more iterative and engaging learning process, as opposed to the static nature of paper-based assignments where feedback is delayed.

Furthermore, the app's interactive nature may have contributed to lowering the barrier to entry for students unfamiliar with the content. The app's structured yet flexible learning environment provided these students with a more approachable way to engage with the material, as evidenced by their successful performance in the exercises.

It is also noteworthy that students starting with paper worksheets showed a slight improvement in their final grades. This suggests that while traditional methods have their limitations, they still hold value and can complement digital tools in reinforcing learning.

5.3 Discussion of Findings

The experimental evaluation conducted with *AutomaTutor* provides insights into the effectiveness of digital platforms in enhancing the teaching and learning process, particularly in the context of automata theory. The results from the experiment lend strong support to our initial hypothesis that a digital platform can enhance the learning experience compared to traditional paper-based methods.

The experiment demonstrated that the app's immediate feedback mechanism and interactive interface contributed to a more engaging and effective learning environment. This was evident in the higher performance scores and preference ratings for the app. The ability of students, especially those unfamiliar with the content, to perform well in app-based assignments is indicative of the platform's potential as a self-contained learning tool.

However, the experiment also revealed some limitations of the digital approach. While the app was generally preferred and led to better performance, a notable proportion of participants still found value in the traditional paper-based method. This suggests that the digital platform might be more effective when used as a complement to conventional teaching methods, rather than as a complete replacement.

In light of these findings, future improvements to the digital platform could focus on integrating features that replicate some of the benefits of traditional methods, such as free-form brainstorming and the tactile experience of pen and paper. This enhancement could involve developing a feature set centered around stylus-based input, allowing users to draw solutions freely. This addition not only caters to diverse learning styles but also paves the way for future advancements in computer vision research. It presents an opportunity to train models adept at recognising and interpreting a variety of hand-drawn automata, integrating traditional drawing methods with cutting-edge digital recognition technology.

6 CONCLUSION

This research introduced *AutomaTutor*, a mobile application designed to facilitate the construction, simulation of finite automata, and solving of interactive exercises on automata theory and regular expressions. With a strong focus on usability and feedback features, *AutomaTutor* has been tailored to guide users through their learning journey without necessitating additional intervention from instructors.

The application's capabilities for automatically generating random questions of various types demonstrate its potential for a comprehensive learning experience. So far, the application operates offline on the student's mobile phone and allows them to generate exercises as well as the memorandums. Work on an online version has started which will allow lecturers to create and distribute exercises to all the students as well as track their scores using a leaderboard system.

Our experimental evaluation, involving computer science students at our university, compared traditional pen-and-paper methods with *AutomaTutor* for solving automata theory exercises. The results revealed a strong preference among students for the guided learning approach offered by *AutomaTutor*. This preference was bolstered by the app's immediate feedback mechanisms and interactive interface, which contributed to a more engaging and effective learning environment.

Looking ahead, we plan to integrate *AutomaTutor* into the *Theoretical Computer Science* undergraduate module from 2024. We anticipate that the tool will enhance students' comprehension of theoretical computer science's abstract topics. Moreover, as automata theory forms

a foundational aspect of several formal methods, the introduction of *AutomaTutor* also aims to prepare and motivate students for advanced studies in formal methods at the postgraduate level.

Future developments of *AutomaTutor* will focus on expanding the range of automata types supported, including pushdown automata and Turing machines. Additionally, we intend to incorporate Kripke structures and Büchi automata to facilitate teaching model-checking subjects. In response to student feedback, we will also refine the application's usability, feedback, and question generation features. This will involve integrating elements that replicate the benefits of traditional methods, such as a stylus-input feature for free-form drawing and evaluation of solutions, thereby fusing traditional learning approaches with advanced digital technology. Another possible direction of future work is to have the generated exercises evaluated by subject matter experts.

In conclusion, *AutomaTutor* represents a significant step towards the digitalisation of theoretical computer science education. It not only offers an innovative alternative to traditional teaching methods but also opens up new avenues for research and development in educational technology. As it evolves, *AutomaTutor* has the potential to play a pivotal role in contemporary computer science education, contributing positively to the learning experiences and achievements of both students and educators.

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A DETAILED QUESTIONNAIRE RESPONSES

In this appendix we provide the detailed responses to the questionnaire that was used in the experimental evaluation.

Figure 13 shows the responses to demographic questions.

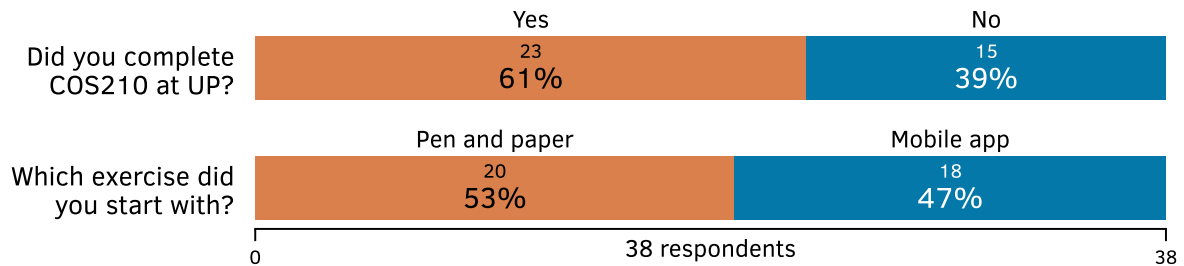


Figure 13: Demographics

Figure 14 shows the responses to user experience questions.

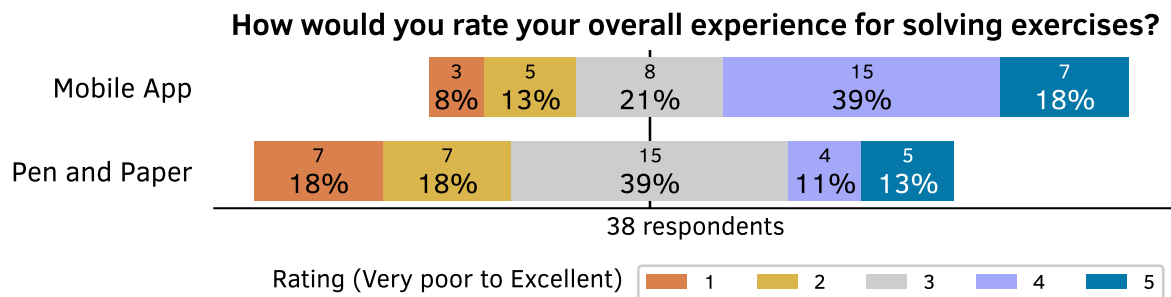


Figure 14: Experiences

Figure 15 shows the responses to the question with regard to preference in terms of the format of solving exercises.

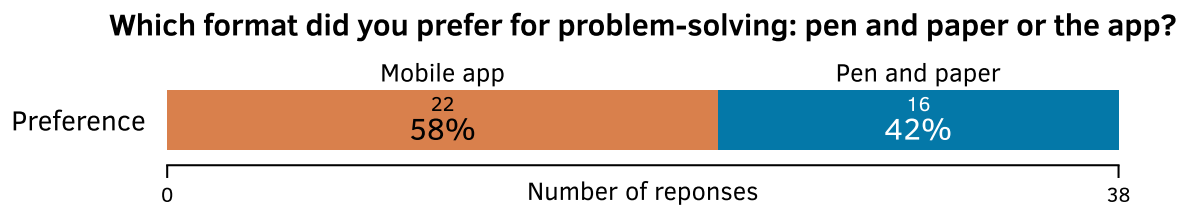
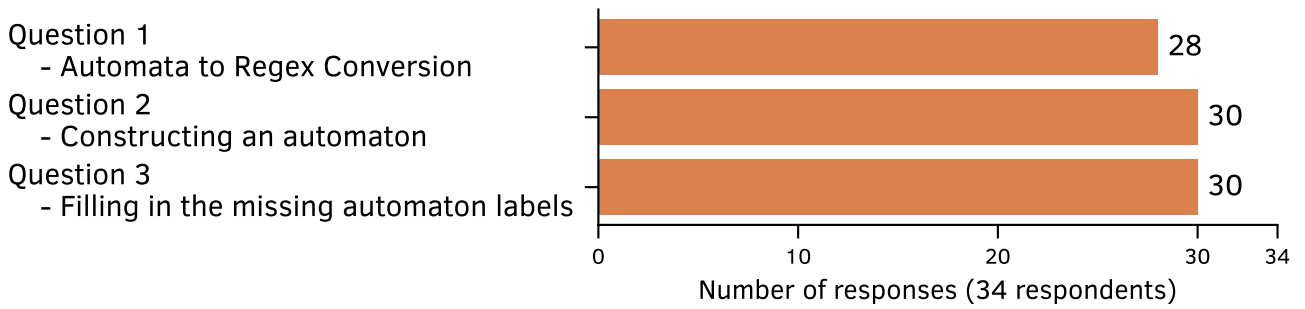


Figure 15: Preference

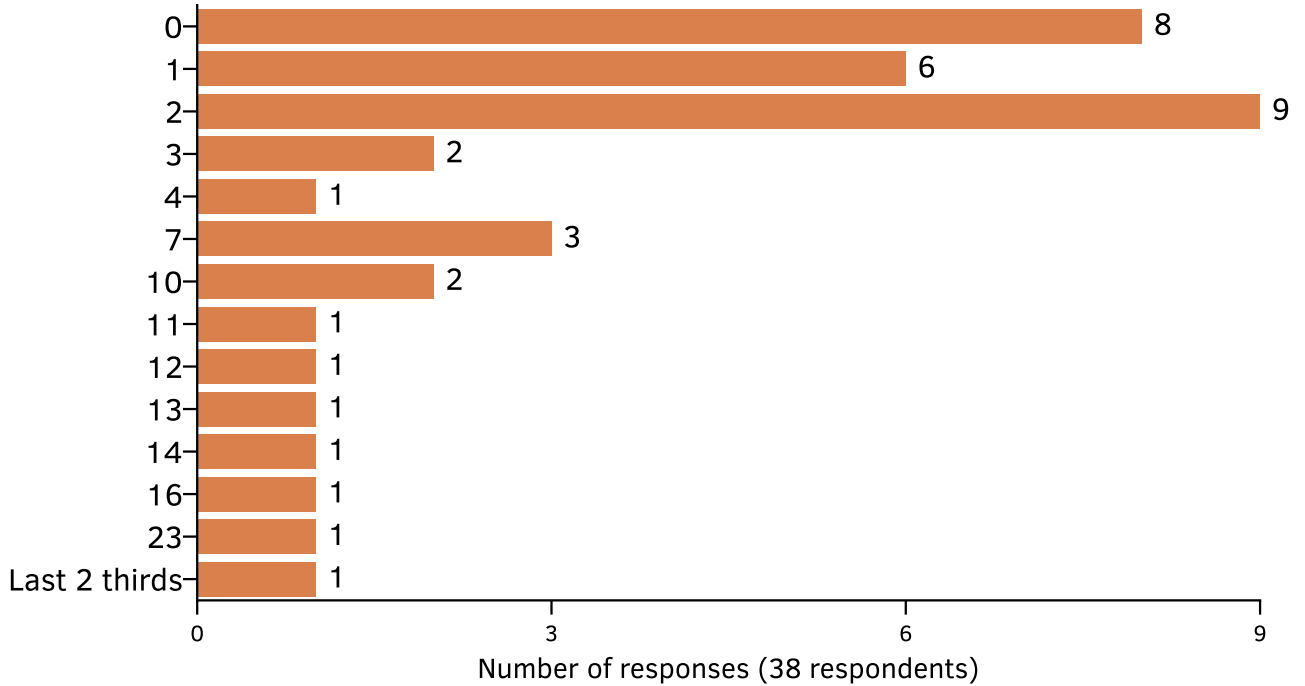
Figure 16 shows comparative results of the experimental evaluation.

Which questions were you able to complete on the app?



(a)

How many incorrect answers did you submit on the app?



(b)

Figure 16: Comparative results

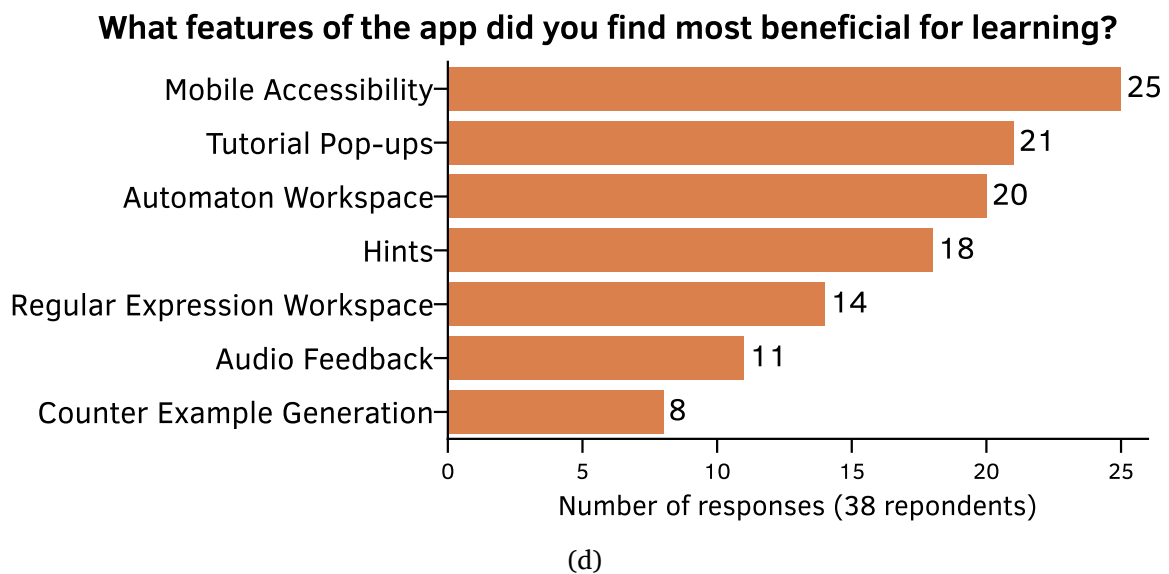
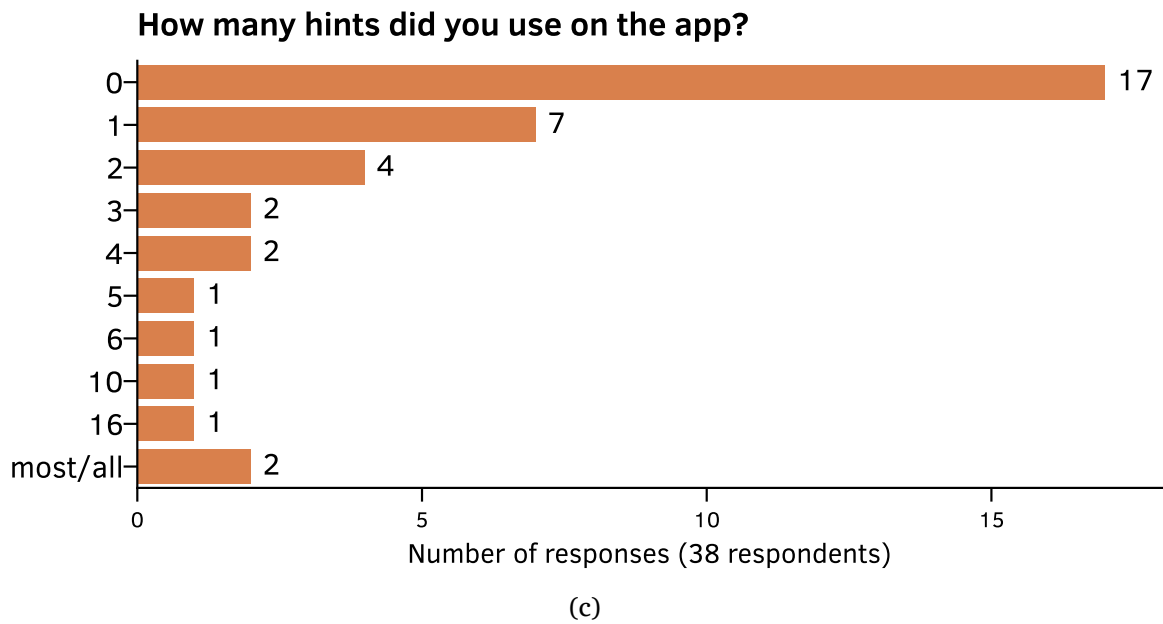


Figure 16: Comparative results (continued)

B ANSWERS TO OPEN-ENDED QUESTIONS

Please explain why you preferred the previously mentioned format.

- Making a mistake was a lot easier to fix since you can just undo the last one or remove a part of it.
- I got have scrap paper and work through it
- First it saves paper, and I can attempt anywhere anytime any assessment is given to me
- The phone wasn't as convenient
- The interface was intuitive and easy to understand after the tutorial. I was not slowed down by writing and erasing-rewriting my answers as much with the app.
- Because it is linked to what I was used to
- Idk man. Pen and paper made me feel like I'm in an exam of sorts.
- Something that I'm used, plus I can jot my working out process before providing my answer
- Guided, provided hints, easier to know what is wrong while learning, less mechanical
- I like the visualization and the simplicity of using the application
- Na
- Prompt feedback made me excited to learn
- Found it simpler
- Easier to draw out the automata to a format I want and understand
- I found it easier to process the question when I had paper
- It was easier to see if i was wrong or not
- Having the feedback of correct vs incorrect helped solve the questions
- Space to scribble and make rough work.
- The feedback (on submit) was great.
- Because is understandable and it has instruction
- It offers a more familiar way of doing things or solving problems
- There was a learning curve drawing the automata on the mobile app
- I could edit at the point of error without undoing all steps before I realized error
- It had tips
- I feel indifferent, pen and paper allows you to work out different options, the mobile app requires you to calculate the options in your head or revert back to pen and paper defeating the purpose of it
- Even though it can also be done when using the mobile app, what I found easier with pen and paper is to jot down your your working outs. Especially with these types of questions that require you to work out a solution. It is quite difficult to do so when using a mobile app.
- I preferred the app as it provided a less permanent mode of solving the task (I could change my answers and problem solve without having to scratch out or use scrap paper) and I was able to easily change answers as I problem solved. The hint functionality is also a great feature for those who need assistance.
- I felt that it was easier to complete the questions and I could try something and erase if it was wrong easily with the push of a button. I also liked the fact that there were hints and feedback provided so that I could immediately see when I was wrong, what I was doing wrong so that I could fix it.
- Helps visualise the solution
- A visual representation of the problem helped me somewhat comprehend what I was supposed to do than the pen and paper
- I prefer the previously mentioned format because I was able to complete correctly 2 questions even though I didn't have enough knowledge on the topic.
- It's easier to use

- Familiarity, the mobile app was a bit confusing to navigate
- The mobile app has instructions with diagram and is more intuitive instead of having to draw out the diagrams for automaton and scratching it out if a mistake was made which cause the answer to illegible at times
- I don't have any idea for this lecture
- The hints were really informative and helpful. The game experience also made it more interesting.
- It felt like a game. Made me want to solve more problems.

Did you encounter any technical issues while using the app? If so, please elaborate.




- No
- No.
- When making a figure some explaining would be nice and the ability to see your language
- It feels like a drag and drop interface would be better
- It kept rejecting my answer
- Nope
- Yeah I had to resubmit wrong solutions to see the example expression due to a timer
- Yes, the pop ups disappeared and I couldn't view them again
- No, maybe the wording was a bit confusing, but that could also be my rusty knowledge
- None.
- no
- It was not ergonomically friendly
- No issue experienced
- No the tutorial was just a bit too long
- Cant navigate to a specific character, you have to backspace all the characters to get to the one you want to change
- Yes I did. I pressed one of the buttons below multiple times and the web site crashed
- None at all
- No I didn't
- Yes. I couldn't figure out the interface.
- No issues
- The button to bring back the hints only worked for the first click.

Do you have any additional comments or suggestions regarding this experiment?

- No
- Nope
- None
- N/A
- Cool idea. Wish it was a thing when I did 210.
- I want to see a much more complex example be rendered on a small mobile device interface.
- Something about popup tutorials urks me
- Nothing made sense for me.
- Well made
- No

- I would make the option to reopen the tutorial pop up a bit more clear
- A gif or example illustrating how things work.
- no
- Its has great potential. Just wondering if it could handle very large automata. At least drawing them
- Allow user to click on point of error and only change that portion as opposed to undoing all steps to get to that point
- None. Great experiment!
- More sounds!
- The experiment worked work actually
- Very well done!

An IT career choice model

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ABSTRACT

Research focusing on students' Information Technology (IT) career choices shows that their decisions were influenced by factors, such as exposure to programming concepts at school level, culture, parents, teachers and role models. Theories relating to career choice have focused on individual characteristics and their environment. In South Africa however, there have been limited studies investigating the factors influencing students' IT career decisions, specifically choosing study programmes in Computer Science (CS), Information Systems (IS) and IT. The aim of this study was to evaluate a proposed IT career choices model. A questionnaire was developed and distributed amongst CS/IS/IT first-year students at the Nelson Mandela University in South Africa and 205 students completed the survey. The data were statistically analysed, including Exploratory Factor Analysis. The study highlighted that students with high academic confidence and exposure to programming concepts at an early age, chose an IT career. The study further showed statistical differences between students speaking different home languages and genders in their perceptions about the IT industry and choosing an IT career. The main contribution of the study is the evaluation of a proposed IT Career Choice Model, based on existing theories, literature and the statistical results obtained from the study.

Keywords IT career choice model, career choice theories, IT career choice factors

Categories • CCS ~ Social and professional topics, Professional topics, Computing profession, Employment issues

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1 INTRODUCTION

The Information Technology (IT) industry is experiencing an IT skills shortage in some countries. IT and computing skills have been identified as one of top three scarce skills by the South African Government and the aim is to increase IT, Computer Science (CS) and Information Systems (IS) enrolments at Higher Education Institutions nationally (Kirlidog et al., 2018).

In South Africa, a limited number of scholars are choosing a career in IT (Kirlidog et al., 2018). First year students who have chosen a career in IT or other computing related fields were generally influenced by people and events in their daily living environment (Vernon & Drane, 2020). Research conducted globally on the factors that influence career choice identified the factors family influence, specifically parents, teachers, passion, values, a sense of

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belonging and self-efficacy (Yoel & Dori, 2023). Social media also has an influence on a student's career choice (Lee et al., 2019). Other interventions, such as computer clubs, gaming and mobile Apps, workshops and IT camps have created IT career awareness amongst scholars (Greyling, 2023; Kapoor & Gardner-McCune, 2019).

Career choice for scholars is a complex process and unique for everyone, depending on cognitive factors and the social structures of the individual's environment (Braza & Guillo Jr., 2015; Mtemeri, 2017). Mtemeri's (2017) research study proposed a career guidance model with the following six components: training career guidance teachers, planning career guidance activities, availing adequate resources, training parents, peer education on career guidance and linking students with industry. Parental education about careers, parental encouragement and advice are critical in students' choices of careers (Mtemeri, 2017).

Socialisers, such as family, parents, teachers and friends are key influencers for scholars' decisions in choosing an IT career (Säde et al., 2019; Stone, 2019). Recent research indicates that exposure to new technologies and being taught programming concepts at school level using mobile technologies can influence a scholar's IT career choice (Mano, 2019).

Students who have chosen a career in IT were influenced by parents, teachers and role models (Siddiky & Akter, 2021; Vernon & Drane, 2020). However, recent research findings in South Africa contradict the literature (Siddiky & Akter, 2021; Vernon & Drane, 2020), which states that parents and teachers, influence a first-year student's IT career choice. Thirty-five percent of the first-year respondents in a study by Cullen et al. (2024) indicated that they did not know their father, 19% did not know their mother and 38% did not know their father's occupation.

The important factors identified by Twani et al. (2020) and included in a proposed IT career choice conceptual model (Figure 3) were socialisers, learning experiences, career perceptions, self-efficacy and career awareness. The study (Twani et al., 2020) was based on the Theory of Planned Behaviour, which suggests that behaviour is determined by a person's intentions, attitudes (beliefs about a behaviour) and subjective norms (beliefs about others' attitudes toward a behaviour). The aim of this study was to empirically evaluate the proposed IT Career Choice Model and to statistically identify the factors that influence scholars' decisions to pursue an IT career.

2 STUDENT CAREER CHOICE

A scholar's career choice often starts with personal interest and curiosity about a certain field. Perceptions of IT careers vary, based on a person's gender, culture and other factors, such as future expected earnings and experience of working with computers (Carrico et al., 2019).

2.1 Theory of Planned Behaviour

The Theory of Planned Behaviour (TPB) (Figure 1) is based on the perceived behavioural control component to account for behaviours that occur without a person's volitional control

and norms (Ajzen (1991), as cited in Joachim et al., 2015). Human planned behaviour is guided by three kinds of considerations: beliefs about the likely consequences of the behaviour (behavioural beliefs), beliefs about the normative expectations of others (normative beliefs) and beliefs about the presence of factors that may facilitate or impede performance of the behaviour (control beliefs).

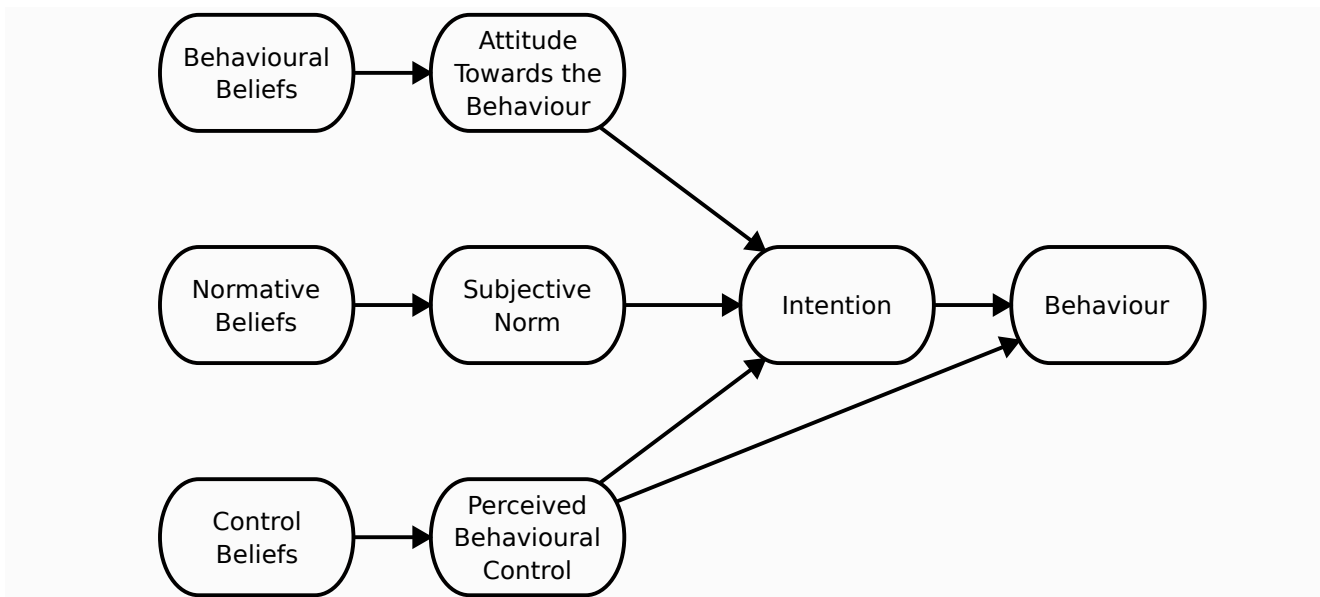


Figure 1: Theory of Planned Behaviour (Ajzen (1991), as cited in Joachim et al., 2015)

Behavioural beliefs produce a favourable or unfavourable attitude towards the behaviour. Normative beliefs result in perceived social pressure or subjective norm and control beliefs give rise to perceived behavioural control. In combination, attitude toward the behaviour, subjective norm and perception lead to the formation of behavioural intention.

2.2 Career choice models

Babin et al. (2010) developed a model, using the concepts from the Theory of Planned Behaviour to provide a structure to assess students' decisions to pursue an IT programme at university (Figure 2). The model consists of attitudes and subjective norms as key influencers in a person's decision making. The model infers that personal interest and academic performance affect the students' decision to enroll for an IT programme after finishing school. Additionally, subjective norms, i.e. teachers, family, peers and career image will influence a student's career decision.

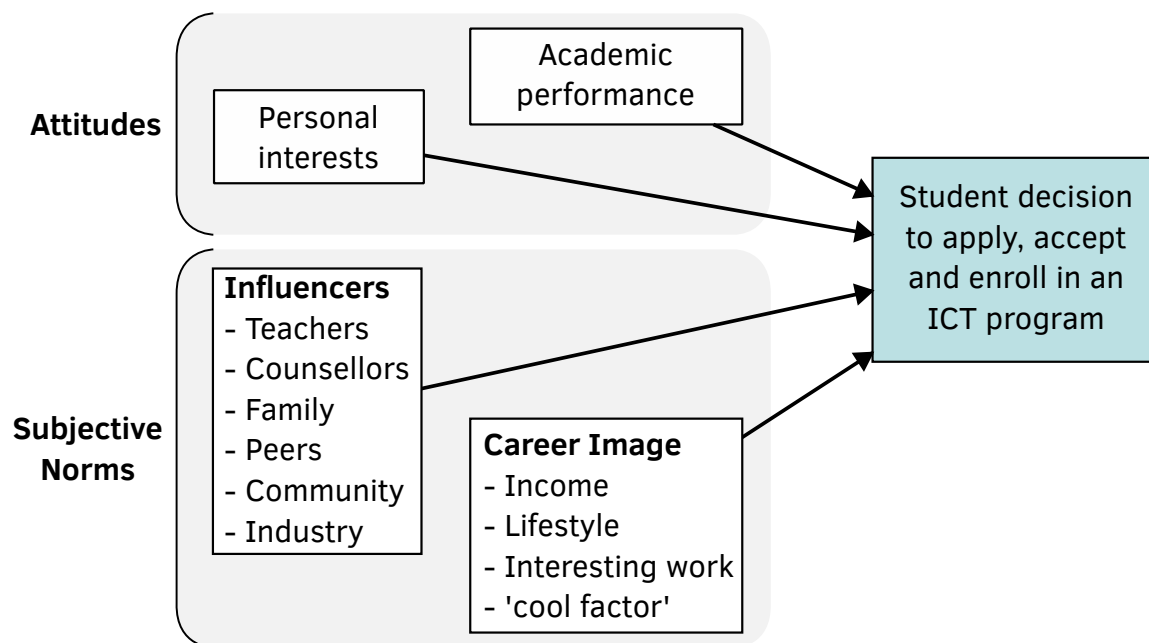


Figure 2: A model of influencers on student decisions to enter university IT programmes (Babin et al., 2010)

2.3 Factors influencing career choice

Different factors influence a scholar's career choice. The factors include gender, culture, influencers or socialisers, role models, computer experiences, self-efficacy, career perceptions and expectations and career awareness (Twani et al., 2020). Career image, career expectations and academic performance are factors Babin et al. (2010) included in their model (Figure 2). Wang et al. (2015) state that household income could be the pressure that may be used as an influencer. Household income and pressure to obtain a university qualification were pressures, specifically amongst African language speakers in South Africa (Twani et al., 2020). A lack of career knowledge by influencers, such as family and friends led to students not choosing to pursue IT studies.

Age, gender (Aivaloglou & Hermans, 2019) and culture affect scholars' career choice (Calitz et al., 2022). Aivaloglou and Hermans (2019) indicated gender differences with the CS career orientation of female students. Culture is defined as the customs and habits that characterise a certain group, society or a nation. Culture includes the way people in society dress, the language they speak, how the family lives, religion, work patterns and leisure pursuits. Culture includes the beliefs, values and material objects that constitute people's way of life (Naik et al., 2023). Culture influences the career choice of a person, how their career paths develop and how they earn a living (Naik et al., 2023). Culture has a major impact on a student's IT career choice (Calitz et al., 2022). Sharif et al. (2019) argue that in the Eastern Culture, the

most powerful influence is making a difference in society and therefore parents pressure their children to choose a particular career.

Socialisers, also called influencers by Babin et al. (2010), include parents, family, teachers, counsellors and the community. Research indicated that a student's career choice is generally influenced by parents, teachers, career counselors and role models (Kirlidog et al., 2018; Vernon & Drane, 2020). The occupation, education and advice of a child's parents are influencers in students' choices of careers (Mtemeri, 2017). Social media also has an influence on a student's career choice (Lee et al., 2019). Positive school-based support from teachers and counsellors plays a positive role in guiding students to STEM fields (Abe & Chikoko, 2020; Twani et al., 2020).

Learning experiences, in school subjects, specifically mathematics and science, are important for a student's career choice (Twani et al., 2020). Learning experiences (interest, programming knowledge, enjoyment) are closely linked with Career Awareness, Self-Efficacy, Career Perceptions and Expectations (Twani et al., 2020). Early exposure to computer clubs and programming is important as interest in IT at school is a key factor for students' decisions (Greyling, 2023). Computer education and problem-solving were key as learning experiences that have influence on students' IT career decisions (Greyling, 2023).

Self-efficacy, including problem solving abilities, grades and enjoyment opportunities are also factors that influence a student's career choice (Aivaloglou & Hermans, 2019). Self-efficacy is defined as belief in one's capability to organise and execute a course of action required to achieve a specific goal. Beliefs are linked to self-perception, which is the same as self-efficacy, according to Wang et al. (2015) and provides internal encouragement for students' ongoing confidence and abilities. High self-perception is key to scholars choosing to study IT courses.

Career perceptions and expectations involve individuals' beliefs about the consequences of actions, which can be social or functional and are shaped by influencers and learning experiences (Carrico et al., 2019). A study in the USA by Hodges and Corley (2016) indicated that some students believe that by choosing IT careers, they would receive a good salary and are guaranteed good job security. In support of their study, Sharif et al. (2019) indicated that future income is a strong influencer of students' career decisions. Learning new skills, job opportunities and career-image were also important career perceptions that influenced students' career choice.

Career awareness is the process of knowing and understanding what various career paths or career options are available to a person, based on their interest. Career awareness assists a scholar to know what knowledge, training and skills they must learn and acquire to achieve success in their chosen career. A child's career awareness and interest vary according to knowledge and interests (Jusoh et al., 2021). Children today are increasingly focused on achieving excellence in education; however, they are uncertain about the career they want to pursue (Jusoh et al., 2021). A South African study on career awareness amongst IT graduates indicated that they too are not aware of the possible IT career opportunities and career tracks available to them. They are uninformed about new IT job titles, careers and IT job

descriptions (Calitz et al., 2011).

Exposure to new technologies and programming concepts at school level creates IT career awareness and influences a scholar’s career choice. Kirlidog et al. (2018) indicate that ignorance and lack of information on IT careers are reasons for students not enrolling in courses in the IT field. Awareness can be increased through exposure and can provide a broader picture of IT being relevant to students’ lives. Even students in their senior years at university, were unaware of IT programmes and their function (Calitz et al., 2011).

Twani et al. (2020) proposed an IT Career Choice model that included the factors socialisers or influencers, learning experiences, self-efficacy, career perceptions and expectations, and career awareness (Figure 3).

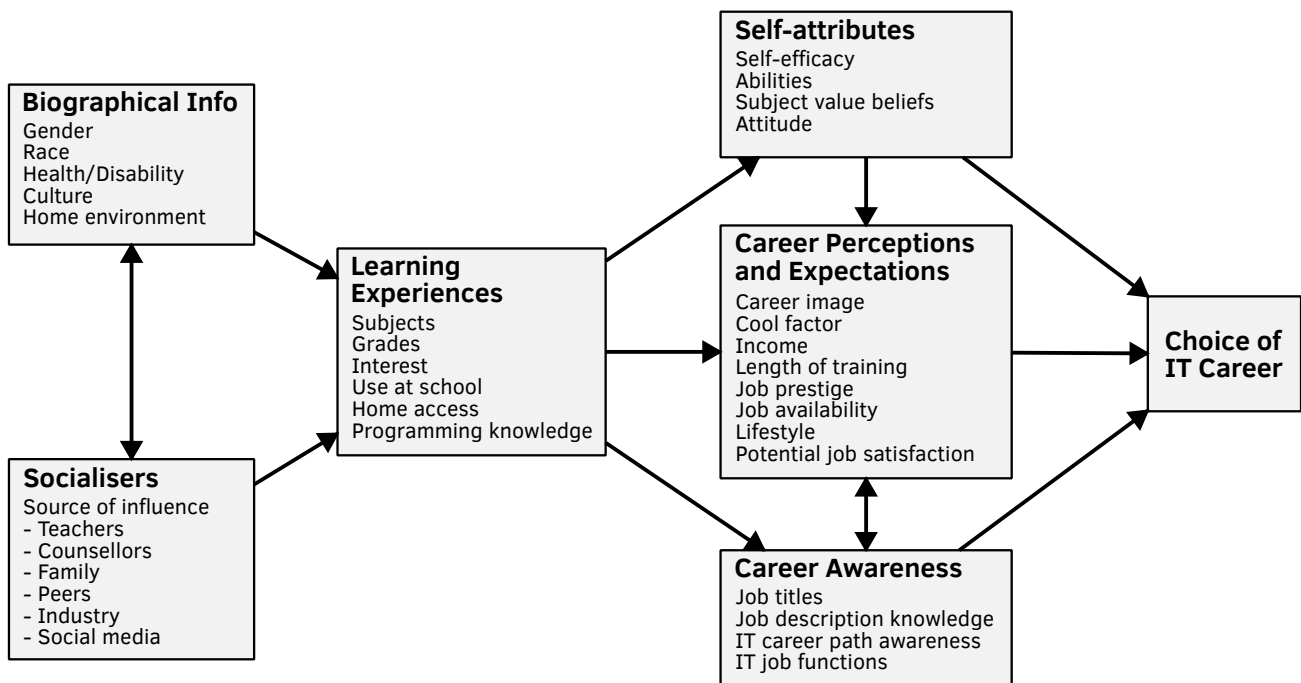


Figure 3: Proposed IT Career Choice Model (Twani et al., 2020)

3 RESEARCH METHODOLOGY

The first-year students have made a career choice to enter the IT profession and an understanding of the factors that influenced CS, IS and IT students’ career decisions is important. A questionnaire for first year students was compiled based on a similar questionnaire used in previous studies (Twani et al., 2020). In order to determine personal perceptions and honest information, it was decided to keep the survey anonymous. The survey was sent to all registered CS, IS and IT first-year students at the Nelson Mandela University, a comprehensive

university in South Africa. Over 1000 students were contacted via email to participate in the study. The first-year questionnaire consisted of the following sections:

- Biographical details;
- Culture and IT role models;
- Sources of influence (Socialisers);
- Learning experiences;
- Personal attributes, including self-efficacy;
- Career perceptions and expectations; and
- Career awareness.

The questionnaire consisted of 5-point Likert scale items and was captured using an on-line survey tool, *QuestionPro*. The data were collected from first year students enrolled for either a *BSc CS*, *BCom IS* or *BIT* programme. The research study focused on these programmes as these students intend to pursue a career in IT. The data were statistically analysed using *Statistica*. Ethics approval was obtained from the University Ethics Committee, #H2020BUSBS15.

4 RESULTS

4.1 Descriptive statistics

The survey was completed by 205 students who were registered for CS, IS, IT degree programmes ($n = 92$, 45%) and IT Diploma programmes ($n = 113$, 55%) in the Department of Computing Sciences and the School of IT at the Nelson Mandela University. **Figure 4** shows that the sample consisted of 154 males and 51 females. The sample included 42% Black, 48% White, 8% Coloured, and 2% Asian students. The citizenship of the total group was mainly South African (90%). A small number of students (10%) were from Botswana, Malawi, Namibia, Zambia and Zimbabwe. The home language spoken was Afrikaans/English (24%), Xhosa (43%), Zulu, including Sesotho, Tswana, etc. (19%) and other languages, such as Sepedi and Xitsonga (14%). The Home languages were finally categorised into two groups, namely Afrikaans/English and African languages.

4.2 Exploratory Factor Analysis (EFA) and Reliability

The EFA was undertaken to keep items and factors that were statistically significant in the model (**Figure 3**). Eigenvalues and Scree plots were used as part of the EFA with the Cronbach Alpha for reliability. The factor loading greater or equal to 0.389 was deemed significant at the $\alpha = 0.05$ level for the sample size $n = 205$. Various one factor and two factor models were evaluated and the Eigenvalues for all the factors were all greater than 1.

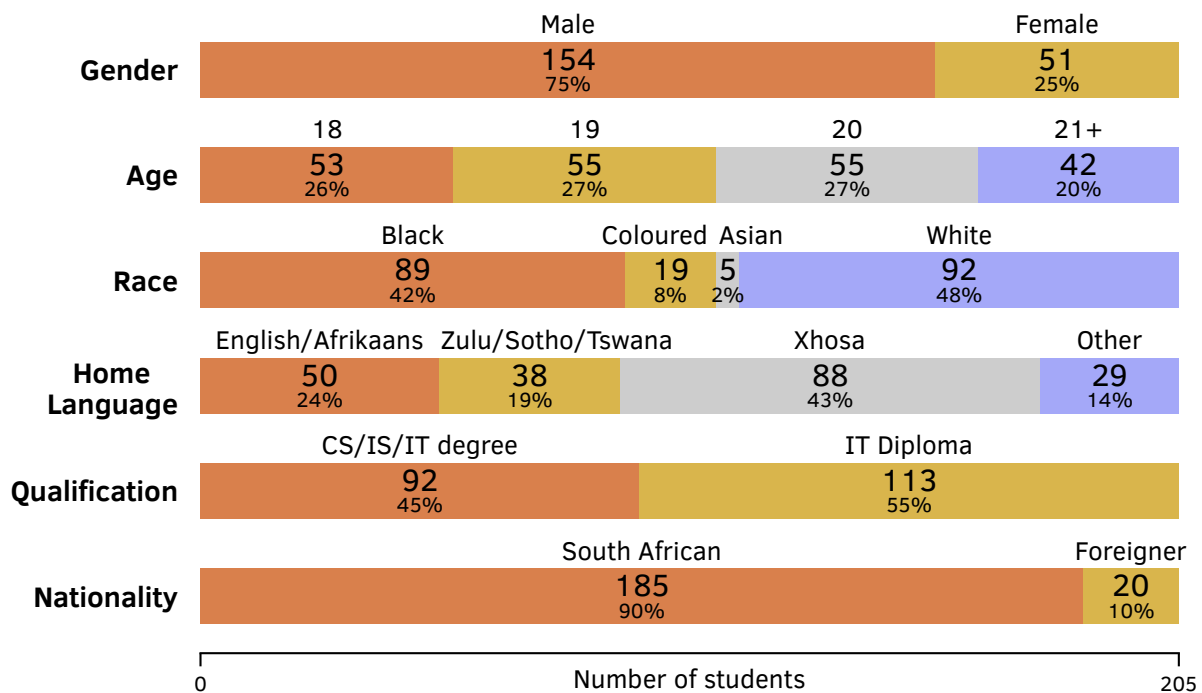


Figure 4: Demographics (n = 205)

The EFA identified new factors, namely Career Choice Influencers (Media and Personal) and Career Awareness (Current and Prior to Study). The Self-Confidence factor name was changed to Academic Confidence. The reliability was ‘Good’ or ‘Excellent’, except for IT Role Models ($\alpha = 0.55$, Poor). Cronbach’s Alpha coefficient results are shown in Table 2. The revised hypotheses and correlations after EFA are presented in Table 1

and the hypothesised model is presented in Figure 5. In the survey, respondents were required to match IT job titles, such as Business Analyst, Database Administrator and Software Developer/programmer with job descriptions for these positions. The factor was named Job Title/Descriptions Knowledge. Table 1 shows that Career Awareness - Prior to Studies, Career Choice Influencers - Personal and IT Role Models did not influence Job Title/Descriptions Knowledge.

An interesting finding was that IT Role models ($r = 0.342, p = 0.005$) and Culture ($r = 0.261, p = 0.005$), positively influence a student’s learning experiences. Culture also influences Academic Confidence ($r = 0.224, p = 0.005$), Career Awareness ($r = 0.083, r = 0.0005$) and IT Career Choice ($r = 0.217, r = 0.005$). Strong correlations were found between Perceptions about the IT Industry ($r = 0.452, p = 0.005$), Personal Attributes ($r = 0.401, p = 0.005$), Academic Confidence ($r = 0.401, p = 0.005$) and IT Career Choice.

Table 2 shows that the five factors; Learning Experiences (0.91), Academic-Confidence (0.89), Perceptions about IT industry (0.86), Career Awareness – Prior to Studies (0.86) and Perceptions about Chosen Career (0.87) recorded excellent Cronbach Alpha reliability as the

Table 1: Hypotheses and correlations

Hypothesis #	Description	Pearson		
		Correlation r	Correlation Strength	p-value
HA ₁	Career Choice Influencers - Media $\overset{+}{\rightarrow}$ Career Choice Influence - Personal	0.384	Strong	< 0.005
HA ₂	Career Choice Influence - Media $\overset{+}{\rightarrow}$ IT Role Models	-0.15	Negative	0.01
HA ₃	Career Choice Influence - Media $\overset{+}{\rightarrow}$ Learning Experiences	-0.261	Negative	< 0.005
HA ₄	Culture $\overset{+}{\rightarrow}$ Career Choice Influencers - Personal	0.2	Medium	< 0.005
HA ₅	Culture $\overset{+}{\rightarrow}$ Learning Experiences	0.26	Medium	< 0.005
HA ₆	IT Role Models $\overset{+}{\rightarrow}$ Learning Experiences	0.342	Strong	< 0.005
HA ₇	Career Awareness - Current $\overset{+}{\rightarrow}$ IT Career Choice	0.418	Strong	< 0.005
HA ₈	Career Awareness - Prior to Studies $\overset{+}{\rightarrow}$ Job Title/Descriptions Knowledge	-	None	0.092
HA ₉	Career Choice Influencers - Media $\overset{+}{\rightarrow}$ Perceptions about the IT industry	0.177	Medium	0.001
HA ₁₀	Career Choice Influencers - Personal $\overset{+}{\rightarrow}$ Career Awareness - Current	0.111	Medium	0.013
HA ₁₁	Career Choice Influencers - Personal $\overset{+}{\rightarrow}$ Job Title/Description Knowledge	-	None	< 0.005
HA ₁₂	Culture $\overset{+}{\rightarrow}$ Academic Confidence	0.224	Medium	< 0.005
HA ₁₃	Culture $\overset{+}{\rightarrow}$ Career Awareness - Current	0.083	Weak	< 0.005
HA ₁₄	Culture $\overset{+}{\rightarrow}$ Career Awareness - Prior to Studies	0.119	Medium	< 0.005
HA ₁₅	Culture $\overset{+}{\rightarrow}$ Perceptions about the IT industry	0.21	Medium	< 0.000
HA ₁₆	Culture $\overset{+}{\rightarrow}$ Personal Attributes	0.199	Medium	< 0.005
HA ₁₇	IT Role Models $\overset{+}{\rightarrow}$ Job Title/Description Knowledge	-	None	0.006
HA ₁₈	Learning Experiences $\overset{+}{\rightarrow}$ Career Awareness - Current	0.028	Weak	0.13
HA ₁₉	Job Title/Description Knowledge $\overset{+}{\rightarrow}$ Perceptions about IT industry	-	None	0.57
HA ₂₀	Learning Experiences $\overset{+}{\rightarrow}$ Career Awareness - Prior to Studies	0.396	Strong	< 0.005
HA ₂₁	Learning Experiences $\overset{+}{\rightarrow}$ Job Title/Description Knowledge	-	None	0.011
HA ₂₂	Perceptions about the IT industry $\overset{+}{\rightarrow}$ IT Career Choice	0.452	Strong	< 0.005
HA ₂₃	Personal Attributes $\overset{+}{\rightarrow}$ IT Career Choice	0.491	Strong	< 0.005
HA ₂₄	Academic Confidence $\overset{+}{\rightarrow}$ IT Career Choice	0.401	Strong	< 0.005
HA ₂₅	Career Awareness - Prior to studies $\overset{+}{\rightarrow}$ IT Career Choice	0.248	Medium	< 0.005

Hypothesis accepted or rejected:

accepted
rejected

$\overset{+}{\rightarrow}$ positively influences

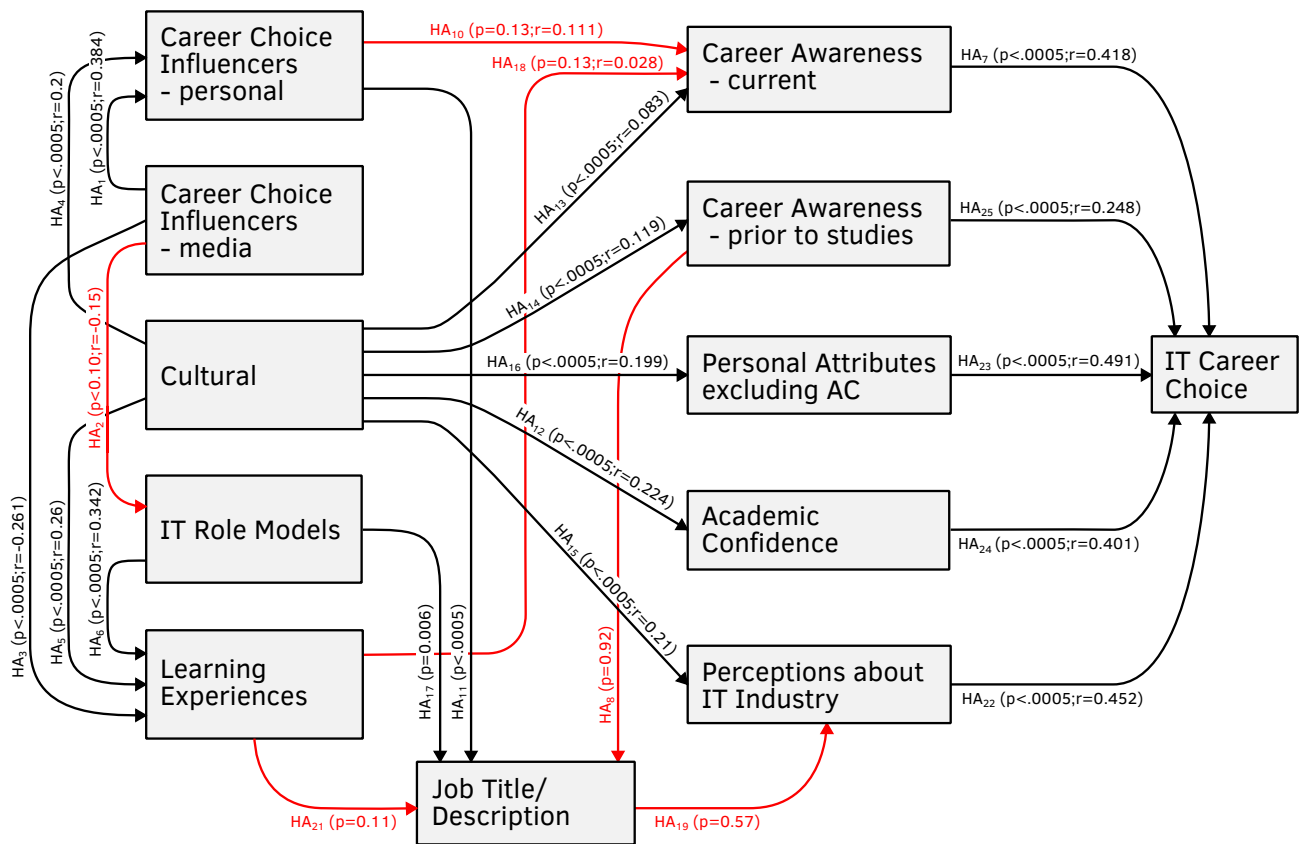


Figure 5: Final Hypothesised Model IT Career Choice Model

coefficients were above 0.80. Furthermore five factors; namely Culture (0.70), Career Choice Influencers – Personal (0.78), Career Choice Influencers – Media (0.74), Personal Attributes (0.75) and Career Awareness – Current (0.74) indicated good Cronbach’s Alpha reliability with a coefficient between 0.70 and 0.79.

The one-sample t-tests are presented in Table 3. The only two factors that were not statistically and practically significant, as indicated by Cohen’s *d*, were Career Choice Influencers – Media and Career Awareness – Current. Statistical analysis (ANOVA) was performed to determine whether any significant relationships were observed between demographic variables and the factors that influence the student’s perceptions of their chosen IT careers. Statistical differences ($p = 0.000$) and practical significant differences (Cohen’s $d = 0.70$, medium) were found between respondents whose home language was one of the African languages ($\mu_1 = 1.22$), compared to those with a home language Afrikaans/English ($\mu_2 = 1.41$) for the factor IT role models. The findings indicate that first-year students speaking African languages did generally not have IT role models. Most of these students lived in townships and in rural areas.

Home language was grouped into African languages (Zulu/Xhosa/Other) and Afrikaans/English (Figure 4). Statistical differences ($p = 0.004$) and practical significant differences (Co-

Table 2: Reliability and EFA

Factors	Coefficient	Reliability	Eigenvalue	Variance explained
Learning Experiences	0.91	Excellent	4.567	65.2
Academic Confidence	0.89	Excellent	4.219	60.3
Perceptions about the IT industry	0.86	Excellent	4.308	47.9
Career Awareness – Prior to Studies	0.86	Excellent	4.315	71.9
Career Awareness – Current	0.74	Good		
Perceptions about Chosen Career	0.87	Excellent	4.189	52.4
Culture	0.70	Good	4.252	53.2
Career Choice Influencers – Personal	0.78	Good	4.574	57.2
Career Choice Influencers – Media	0.74	Good		
Personal Attributes	0.75	Good	2.768	46.1
IT Role Models	0.55	Poor	1.909	47.7

Table 3: t-tests, statistical and practical significance

Variable	Mean	S.D.	H ₁ :μ	t	p (d.f. = 204)	Cohen’s d
IT Role Models	1.26	0.28	≠1.60	-24.19	<.0005	1.20
Career Choice Influencers - Personal	1.81	0.54	≠2.20	-14.49	<.0005	0.72
Career Choice Influencers - Media	2.25	0.70	≠2.20	1.31	.190	n/a
Learning Experiences	2.70	1.17	≠3.40	-11.98	<.0005	0.60
Personal Attributes	4.01	0.54	≠3.40	22.77	<.0005	1.13
Academic Confidence	3.87	0.72	≠3.40	13.10	<.0005	0.65
Perceptions about the IT industry	3.99	0.56	≠3.40	21.36	<.0005	1.06
Career Awareness - Prior to Studies	3.04	0.97	≠3.40	-7.54	<.0005	0.37
Career Awareness - Current	3.42	0.85	≠3.40	0.37	.712	n/a
IT Career choice	4.19	0.55	≠3.40	28.72	<.0005	1.43

Practical significant difference small medium large

hen’s *d* = 0.36 – medium) were found between respondents whose home language was one of the African languages ($\mu_1 = 3.57$), compared to those with a home language for Afrikaans/Eng-

lish ($\mu_2 = 3.77$) speakers for the factor Culture. The findings indicate that Afrikaans/English speaking first-year students' culture influences their IT career choice more than African language speaking first-year students.

The findings ($p = 0.000$, Cohen's $d = 0.39$ – medium) indicate that Career Choice Influencers – Media, specifically social media, indicated gender differences between males ($\mu = 2.10$) and females ($\mu_2 = 2.37$), indicating that social media is an important source of information for female students.

Learning experience showed a statistical ($p = 0.005$) and a large practical significance (Cohen's $d = 1.30$) between Afrikaans/English speaking first-year students ($\mu_1 = 3.71$), compared to those speaking an African home language ($\mu_2 = 2.38$). The findings highlight the discrepancies in the South African schooling system and the tragic state of the governmental schooling system.

The career awareness of the first-year students ages 18–20 years and 21+ years showed a statistical difference ($p = 0.010$) and a medium practical significance (Cohen's $d = 0.36$). Respondents under 21 years currently have a lower perception of IT careers ($\mu_1 = 3.32$) than respondents who are 21 years and older ($\mu_2 = 3.62$).

Finally, regarding the perceptions of their chosen IT career, statistical ($p = 0.019$) and medium practical significant differences (Cohen's $d = 0.27$) were observed between males ($\mu_1 = 4.11$) and females ($\mu_2 = 4.26$). The results indicate that female respondents have positive perceptions about Chosen Careers compared with male respondents.

4.3 IT Career Choice Model

The IT Career Choice Model developed in this study after EFA is presented in **Figure 6**. The model included career choice influences, specifically culture, IT role models and home environment. Scholars growing up in a rural area, as is the situation in South Africa, generally do not have parents and family with the knowledge who can influence their IT career choice. Learning experiences, specifically in rural schools with limited infrastructure, further negatively influence scholar's career decisions.

A two-factor model for the initial Career awareness factor was identified after the EFA. The two new factors were Career awareness prior to university studies and career awareness currently. The factor Self-attributes was renamed Personal attributes and included self-efficacy and present academic confidence. Career perceptions of the IT industry was added as a new factor affecting a first-year students IT career choice.

5 CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

Scholars' career choices are influenced by a combination of internal and external factors, including personalities, interests, experiences and the cultural and societal environment where they grow up. Several factors influence a first-year IT student's career choice, most importantly, IT career awareness, academic confidence and exposure to programming concepts (Grey-

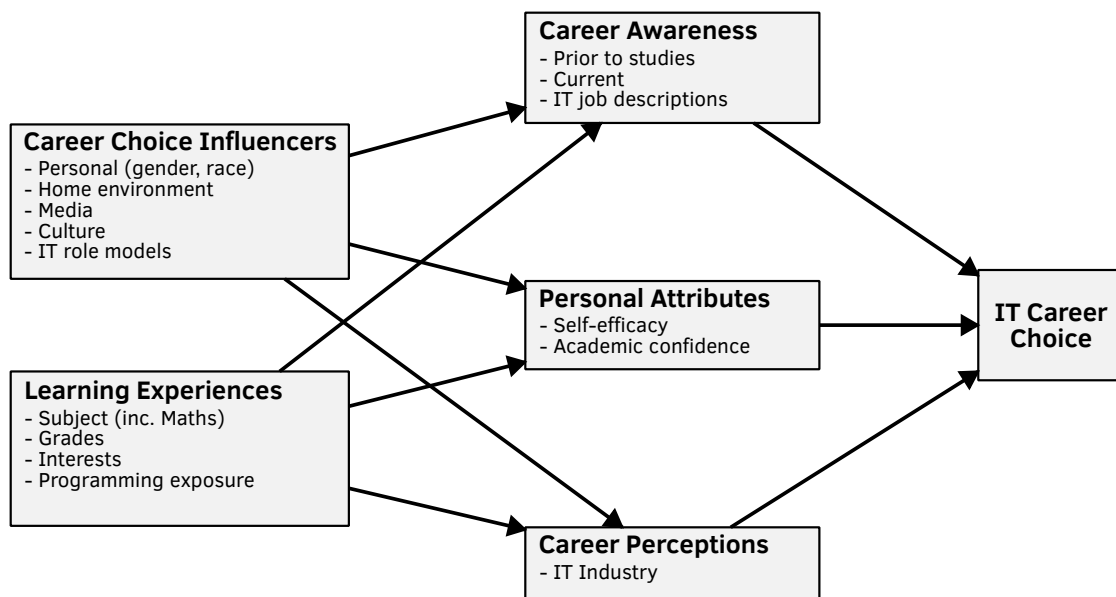


Figure 6: IT Career choice model

ling, 2023). Recent research indicates that exposure to new mobile technologies, understanding programming concepts at school level and teachers and parents can influence a scholar's IT career choice (Aivaloglou & Hermans, 2019; Greyling, 2023; Mano, 2019).

In South Africa, culture has a significant effect on a scholar's IT career choice (Calitz et al., 2022). Social media and having IT role models were shown as important influencers for first-year CS, IS and IT students speaking an African language at home (Cullen et al., 2024). Younger first-year students were less aware of future IT careers than older (21+) first-year students.

The final IT career choice model included factors relating to a scholar's career choice influencers, including their home environment and IT role models. The factors learning experience, career awareness, personal attributes, including self-efficacy and IT industry career perceptions were included in the IT career choice model.

The theoretical contribution of this research study is based on the constructs in the Theory of Planned Behaviour. The factor culture includes items on beliefs and showed statistical and practical significance with the dependent factor, IT Career Choice. The practical contribution is a new IT Career model that can assist academic departments with identifying factors that influence scholars' IT career choice. They can then create activities based on the components, identified by Mtemeri (2017) to create IT career awareness amongst scholars.

The limitations of the study are the sample size and that the study was only undertaken at one university in South Africa. Recommended future research is repeating the study at other universities in South Africa and investigating opportunities to conduct the study internationally, specifically in other developing economies like South Africa. An additional factor that

could be included in future research is the flexible work arrangements, remote work options and opportunities for freelancing or consulting in the IT industry. Scholars may be attracted to IT careers offering work-life balance and flexible remote working conditions.


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Predicting the performance of ORB-SLAM3 on embedded platforms

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ABSTRACT

Simultaneous Localization and Mapping (SLAM) is a crucial component to the push towards full autonomy of robotic systems, yet it is computationally expensive and can rarely achieve real-time execution speeds on embedded platforms. Therefore, a need exists to evaluate the performance of SLAM algorithms in practical embedded environments – this paper addresses this need by creating prediction models to estimate the performance that ORB-SLAM3 can achieve on embedded platforms. The paper uses three embedded platforms: Nvidia Jetson TX2, Raspberry Pi 3B+ and the Raspberry Pi 4B, to generate a dataset that is used in training and testing performance prediction models. The process of profiling ORB-SLAM3 aids in the selection of inputs to the prediction model as well as benchmarking the embedded platforms' performances by using PassMark. The EuRoC micro aerial vehicle (MAV) dataset is used to generate the average tracking time that the embedded platforms can achieve when executing ORB-SLAM3, which is the target of the prediction model. The best-performing model has the following results 2.84%, 3.93%, and 0.95 for MAE, RMSE and R^2 score respectively. The results show the feasibility of predicting the performance that SLAM applications can achieve on embedded platforms.

Keywords Monocular-Inertial SLAM, ORB-SLAM3, Embedded platform, Nvidia Jetson TX2, Raspberry Pi

Categories • Computer system organization ~ Real-time systems ~ Embedded and cyber-physical systems

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1 INTRODUCTION

Simultaneous Localization and Mapping (SLAM) is the process where a robot or vehicle concurrently creates a representation of its environment while determining its position within the environment. SLAM presents two primary challenges: To create an accurate map of the environment, the robot needs to have an accurate localisation; and to accurately localise a robot in an environment, an accurate representation of the environment is needed (Kumiawan et al.,

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2016). SLAM implementations consist of four major algorithmic components: landmark extraction, data association, state estimation, and state and landmark update. Each component has multiple solutions, depending on the environment, sensors used, and the platform it is implemented on; thus, SLAM is a diverse topic which is often associated with high computational expense. There are algorithms (Oriented FAST and Rotated BRIEF (ORB) (Rublee et al., 2011), Scale-Invariant Feature Transform (SIFT) (Lowe, 2004), Speeded-up Robust Features (SURF) (Bay et al., 2008)) that extract features from the environment to be used with other algorithms, such as pose (position and orientation) graph optimisation or bundle adjustment (BA) to estimate the pose and generate a map of the environment.

Eyvazpour et al. (2022) and Barros et al. (2022) illustrate the extensive variety of approaches to SLAM, reflecting the complexity and diversity of solutions in the field. Barros et al. (2022) highlight that the main challenges with current SLAM techniques include algorithmic robustness, computational resource usage, and the ability to understand real-world dynamic environments. In contrast, Eyvazpour et al. (2022) focus on the performance differences among various SLAM techniques across embedded platforms, emphasising that selecting an appropriate hardware platform for SLAM implementation requires careful consideration of factors such as cost, power consumption, computational power, and the specific application.

There is a practical need for SLAM to be implemented on mobile platforms for real-world scenarios such as search-and-rescue operations, military reconnaissance and attack, and automatic exploration of areas. All these endeavours can be autonomously performed by SLAM. The building blocks needed to implement SLAM are: sensors, actuators, processors, and algorithms. The processors and algorithms control the flow of information between the sensors and the actuators. Different sensors can be used in SLAM implementations such as: sonar (Kleeman, 2003), LiDAR (Kohlbrecher et al., 2011), and various types of camera configurations. The type of robotic platform that is used highly influences the choice of sensors. The most significant contributors in deciding what system and sensors to use in SLAM are the cost and the computational load of the required calculations. Sensors such as LiDAR provide accurate results, but an inexpensive camera can achieve similar results depending on the environment.

Visual SLAM (VSLAM) has gained popularity over the past years as it can provide a very detailed representation of the environment in a 3D space, with the disadvantage of being more computationally expensive due to a large amount of information within an image (Chen et al., 2018). However, due to the high level of detail, VSLAM can be used for autonomous navigation and mapping applications. VSLAM can be divided into three categories: monocular, stereo, and RGB-d, according to the camera types used (Taketomi et al., 2017). Monocular SLAM uses a single camera as input, thus being the least computationally and physically expensive VSLAM method. However, monocular SLAM has the disadvantage of the scale ambiguity problem, as scale cannot be determined from a single camera. Therefore, VSLAM has been expanded into visual-inertial SLAM (VISLAM), where visual and inertial data are used to obtain more stable estimation results or, in the case of monocular SLAM, to remove the scale ambiguity problem (Taketomi et al., 2017).

Abouzahir et al. (2017) showed that there is a large performance difference when executing certain SLAM algorithms on an embedded platform versus a high-end desktop computer. The execution performance achieved by the desktop is 1.8, 6.4 and 2.2 times faster for FastSLAM2.0 (Montemerlo et al., 2003), ORBSLAM (Mur-Artal et al., 2015) and RatSLAM (Milford et al., 2004) respectively. Nardi et al. (2015) created SLAMBench 1.0, which provided a portable but untuned KinectFusion (Newcombe et al., 2011) implementation of SLAM in C++ OpenMP, Cuda, and OpenCL. From a performance comparison of KinectFusion on a high-end computer and embedded devices, it is found that the high-end machine can achieve a frame rate of 135 frames per second (FPS), while the best performing embedded device is the Nvidia TK1 with a frame rate of 22 FPS. The TK1's performance is considerably lower than that of the high-end device, but the authors asserted that this performance could almost be classified as real-time. Peng et al. (2020) evaluated two popular visual SLAM techniques, ORBSLAM2 (Mur-Artal & Tardós, 2017) and OpenVSLAM (Sumikura et al., 2019), on the 3 Nvidia Jetson platforms. It is found that the Nvidia Jetson TX2 could run both visual SLAM algorithms within their real-time constraints. An alternative ORB-SLAM2 algorithm that is modified to use the power of a GPU is also investigated. The GPU-accelerated ORB-SLAM2 algorithm increased the performance by 10 FPS while consuming less power than the original algorithm. This shows that although satisfactory results can be obtained using SLAM on high-end machines, there is still a performance gap when using them on embedded devices due to their hardware constraints.

There are three notable benchmarking tools for SLAM: SLAM Hive (Liu et al., 2024), GSLAM (Zhao et al., 2019), and SLAMBench 3.0 (Bujanca et al., 2019). These software frameworks enable researchers and developers to evaluate a wide range of SLAM techniques across various datasets. They focus on critical performance metrics such as accuracy and speed, providing a consistent basis for comparing the robustness and efficiency of different SLAM algorithms in diverse environments. However, these benchmarking tools are not capable of estimating the performance of SLAM algorithms on specific hardware platforms.

This paper makes a two-fold contribution: Profiling ORB-SLAM3 on the Nvidia Jetson TX2 to identify the execution bottlenecks, and creating a model capable of estimating the performance that ORB-SLAM3 can achieve on embedded platforms.

The paper is organised as follows: **Section 2** details the hardware and software used within the study, along with the initial implementation. **Section 3** profiles the software to identify its bottleneck impact on the hardware. **Section 4** discusses the experimental design used to create a model that can estimate the performance of ORB-SLAM3 on embedded platforms. **Section 5** provides and discusses the results of the modelling process. **Section 6** concludes the study.

2 HARDWARE AND SOFTWARE IMPLEMENTATION

2.1 Hardware - Embedded platforms

Three embedded platforms were selected for experimentation: the Nvidia Jetson TX2, Raspberry Pi 3B+, and Raspberry Pi 4B. The Jetson TX2 features a heterogeneous multi-processing environment with two CPU clusters: a dual-core Nvidia Denver 2, optimised for single-threaded performance, and a quad-core ARM Cortex-A57, suited for multi-threaded tasks. In contrast, the Raspberry Pi 3B+ and 4B are equipped with quad-core ARM Cortex-A53 and Cortex-A72 CPUs, respectively.

Table 1 compares these CPUs. The Denver 2, with its superscalar width of seven in Dynamic Code Optimization (DCO) mode, offers the highest potential instruction execution per cycle, surpassing the Cortex-A53, A57, and A72. While the A72 and A57 are “out-of-order” processors that handle code dependencies more effectively, the “in-order” Denver 2 addresses these challenges through DCO.

Additionally, the Denver 2’s larger L1 cache and higher associativity reduce miss rates but increase access times, whereas the Cortex-A53 experiences more conflict misses with quicker access times. Overall, the Denver 2 provides a balance of lower miss rates with a higher miss penalty.

The hardware listed in **Table 1** was selected for this study due to their status as some of the most powerful and widely used embedded platforms available today. Each platform features multi-core CPUs, facilitating parallel processing. Additionally, the Jetson TX2 includes a robust GPU that can be leveraged for enhanced performance. ORB-SLAM3 was executed on all three platforms, and performance metrics captured from which the performance of ORB-SLAM3 on similar embedded systems could be estimated.

Table 1: Comparison between embedded platform CPUs

	Cortex-A57	Denver 2	Cortex-A53	Cortex-A72
ISA	ARMv8	ARMv8	ARMv8	ARMv8
Superscalar	3	7 with DCO (2 without)	2	3
Execution order	Out-of-order	In-order	In-order	Out-of-order
L1 instruction cache (set-associative)	48 KB 3-way	128 KB 4-way	2 KB 2-way	48 KB 3-way
L1 data cache (set-associative)	32 KB 2-way	64 KB 4-way	16 KB 4-way	32 KB 2-way
L2 shared cache (set-associative)	2 MB 16-way	2 MB 16-way	512 KB 16-way	512 KB 16-way
Operating frequency	2 GHz	2 GHz	1.2 GHz	1.5 GHz

2.2 Software - ORB-SLAM3

ORB-SLAM is a highly robust feature-based monocular SLAM system that can operate in real-time in small and large indoor and outdoor environments (Mur-Artal et al., 2015). It also includes loop closing, relocalisation, and complete automatic initialisation. ORB-SLAM uses the same features for all SLAM tasks such as tracking, mapping, relocalisation, and loop closing. The point and keyframes of ORB-SLAM are selected using survival of the fittest, leading to reconstruction with excellent robustness and compact map generation that only grows if the scene changes. ORB-SLAM uses ORB features as a feature extractor, which allows for real-time performance while providing good invariance to changes in viewpoints and illumination differences (Ruble et al., 2011).

ORB-SLAM is written to use three threads that run in parallel: tracking, local mapping, and loop closing. The tracking thread is responsible for localising the camera with every frame and deciding when to insert a new keyframe. The local mapping thread is responsible for processing any new keyframes and performs local BA to achieve optimal reconstruction of the camera pose. The loop closing thread searches for loops with every new keyframe.

ORB-SLAM2 (Mur-Artal & Tardós, 2017) was released two years after ORB-SLAM, and expanded functionality beyond monocular SLAM into stereo and RGB-D SLAM. Another two years later, ORB-SLAM3 (Campos et al., 2021) was released, which is the first system to perform visual, visual-inertial, and multi-map SLAM with monocular, stereo, and RGB-D cameras, using the pin-hole and fisheye lens models. The fact that ORB-SLAM3 allows the user to use different SLAM types, with different sensor input types and various camera models, makes it an ideal SLAM algorithm to investigate. ORB-SLAM3 is a state-of-the-art algorithm extensively used in the research community for visual SLAM tasks (Abouzahir et al., 2017; Barros et al., 2022; Eyvazpour et al., 2022; Peng et al., 2020; Ragot et al., 2019). It is known for its robust performance and versatility across various applications. ORB-SLAM3 leverages ORB (Oriented FAST and Rotated BRIEF) features to deliver accurate and efficient SLAM capabilities, making it a popular choice for research and practical implementations in the field.

The primary objective of this study is to predict the performance of ORB-SLAM3 on an embedded platform, with a specific focus on execution time. In mission-critical applications such as search and rescue, reconnaissance, and attack missions, SLAM applications are only valuable if they can operate in real time.

The way ORB-SLAM3 is written, the tracking thread is the main thread of execution, and if the main thread is stalled or slow, the overall performance of ORB-SLAM3 will be slow. The important performance metric, therefore, is the tracking thread execution time. The objective of the model created in this study is therefore to predict the mean tracking time of ORB-SLAM3 on an embedded platform.

2.3 Implementation

Ubuntu 18.04 was installed on all embedded platforms, along with Docker (Docker, 2018) and Passmark (PassMark, 2024). Passmark was utilised to benchmark CPU performance, provid-

ing input for the estimation models. Docker enabled the execution of a containerised version of ORB-SLAM3 on these platforms. The results from Passmark benchmarking and the containerised ORB-SLAM3 were used to develop a performance estimation model. Figure 1 illustrates the software setup on the embedded platforms and how the software was used to generate training and testing data for the performance estimation model.

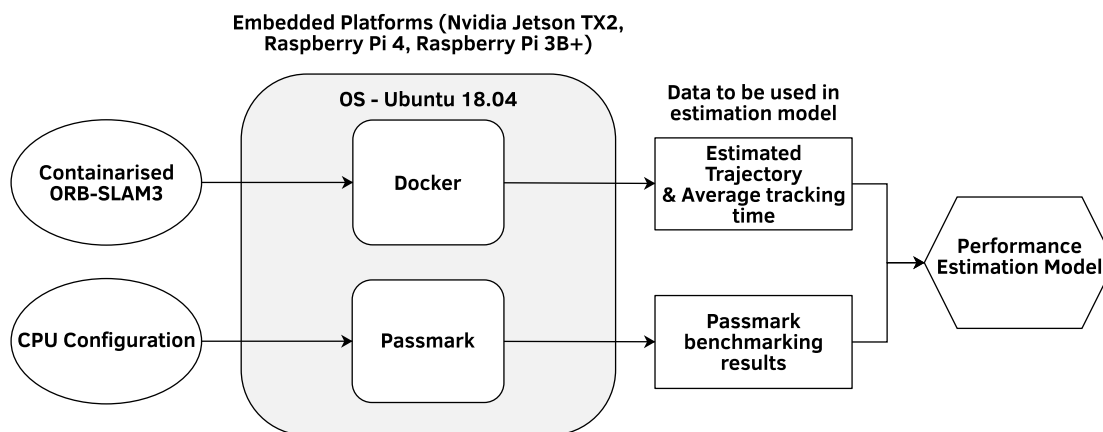


Figure 1: ORB-SLAM3 embedded implementation illustration

3 PERFORMANCE PROFILING

3.1 ORB-SLAM3 profiling

ARM MAP (ARM, 2024b), which was employed in this study, can expose performance problems and bottlenecks by measuring the computation over the time of an application, showing the thread activity, and providing access to the CPU performance measuring unit (PMU) to count the performance events. Due to licensing constraints, profiling was only done on the ARM Cortex A57 CPU of the Nvidia Jetson TX2.

Profiling aims to identify bottlenecks in ORB-SLAM3 on the Nvidia Jetson TX2 and to determine program characteristics such as total instructions executed, instruction mix, and cache performance. The total instructions executed show how many instructions were completed during program execution. Instructions are commonly divided into four groups: arithmetic, load, store, and branch. The combination of instruction types is called instruction mix and indicates what type of instructions are dominant in the program. Cache performance indicates how many times the cache was accessed and what the cache miss ratio was. These program characteristics can be used to aid in the selection of inputs into the prediction model.

Since the ARM A57 CPU has only 6 hardware counters available, the events were measured in four different sets as listed in Table 2 during four separate executions of ORB-SLAM3. Each group was linked to a specific instruction type, such as arithmetic instructions, load and store

instructions, cache performance, and branch performance for sets 1–4 listed in Table 2. For the event description, please refer to ARM (2024a).

Table 2: The set of A57 counted performance events

Set	Performance events
1	CPU-Cycles, Instructions, ASE_SPEC, DP_SPEC, VFP_SPEC
2	LD_SPEC, ST_SPEC, Cache-misses, MEM_ACCESS_RD, MEM_ACCESS_WR
3	L1D_CACHE_RD, L1_CACHE_WR, L2D_CACHE_RD, L2D_CACHE_WR, Cache-misses, Cache-references
4	Branch-misses, BR_IMMED_SPEC, BR_INDIRECT_SPEC, BR_RETURN_SPEC

Using ARM MAP to profile ORB-SLAM3, it was identified that the CPU is constantly working and not waiting for any other input, indicating that ORB-SLAM3 is compute intensive on the Nvidia Jetson TX2.

By analysing the function call stack in Figure 2, the FAST function of the OpenCV library was found to be the most time-consuming. This function is called within ORB-SLAM3's *ComputeKeypointsOctTree* function, which forms part of the *ORBextractorOperator*.

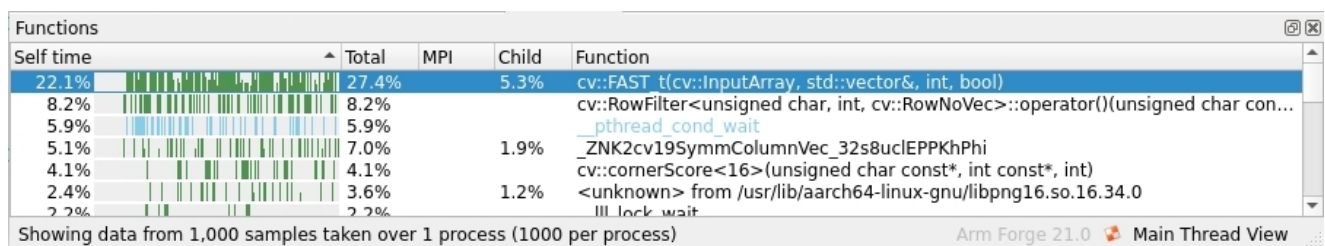


Figure 2: Snippet of ARM Map output of the ORB-SLAM3 function call stack

Figure 3(a) shows that ORB-SLAM3 is dominated by arithmetic logic unit (ALU) instructions, followed by load instructions. Figure 3(b) shows that the ALU instructions were dominated by data processing and integer math instructions with relatively few SIMD instructions, which indicates that ORB-SLAM3 was poorly optimised to use single instruction multiple data SIMD instructions on the Nvidia Jetson TX2. The high amount of load instructions was due to the sequence images loaded into the cache hierarchy, for processing by the CPU.

No modifications were made to the ORB-SLAM3 source code to enhance efficiency. However, there was potential for performance improvement on the Nvidia Jetson TX2 by modifying the source code to utilise the GPU's CUDA cores.

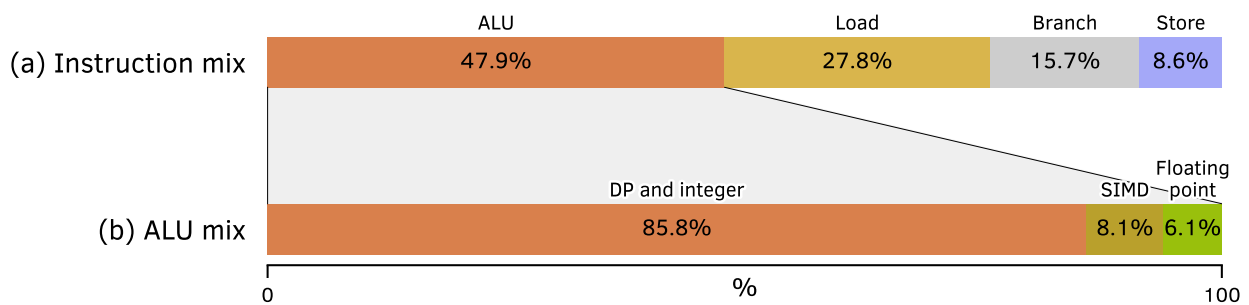


Figure 3: Initial ORB-SLAM3 profiling results

4 EXPERIMENTAL DESIGN

The previous sections described the hardware characteristics of the embedded platforms used in the study and how software such as ORB-SLAM3 executed on them. This section describes the creation of a prediction model to estimate the performance of ORB-SLAM3 on embedded platforms.

4.1 Model inputs and outputs

Since ORB-SLAM3 is CPU-Bounded on embedded platforms, the CPU characteristics were used as inputs to the model. One method to characterise a CPU is using a benchmark program such as PassMark which is a collection of CPU stress tests that executes on the CPU to determine its performance. Table 3 shows the categories that are tested by the PassMark benchmark. The CPU mark is an overall score that combines all the other categories. The rest of the categories are individual benchmark test scores where specific programs are executed to test the CPU performance in a specific category. All tests were done with multi-threading except for the CPU single-threaded test. These benchmark scores were investigated and reduced to be used as inputs to the prediction model.

Table 3: PassMark benchmark elements

PassMark benchmark elements									
CPU Mark	Integer Math	FP Math	Prime Numbers	Sorting	Encrypt	Comp	Single Threaded	Physics	NEON

Since the FAST algorithm forms part of the tracking thread and is the bottleneck of ORB-SLAM3, the maximum performance that ORB-SLAM3 can achieve on an embedded platform is determined by the speed at which the platform can execute the tracking thread. Thus the prediction model predicts the average tracking time that ORB-SLAM3 can achieve on a given platform.

4.2 Dataset generation for modelling

With the inputs and output defined, data had to be gathered to train and test the model. The model output was generated by executing the 11 EuRoC MAV sequences on the embedded platforms. The study had access to three embedded platforms with a total of four different CPUs: the Nvidia Jetson TX2 (Denver 2 and A57 CPUs), the Raspberry Pi 3B+ (A53) and the Raspberry Pi 4B (A72). If all 11 sequences were executed on the four different CPUs, the dataset would only contain 44 data pairs, which could limit the prediction model's performance. Thus the number of available CPUs was artificially increased by setting up different CPU configurations to generate enough data pairs for the model creation.

Generating the different CPU configurations was achieved through over-clocking and under-clocking the different CPU cores and limiting the number of available CPU cores.

Table 4 shows the 39 CPU configurations that were used to generate the prediction model dataset, by varying the number of CPU cores and CPU core frequencies.

Table 4: List of CPU configurations to be used to generate dataset

CPU	Number of cores	Core frequencies (GHz)	Number of CPU configs
A57	2, 4	1.0, 1.2, 1.4, 1.6, 1.8, 2.0	12
A72	2, 4	1.0, 1.2, 1.4, 1.6, 1.8, 2.0	12
A53	4	1.0, 1.2, 1.3	3
Denver 2	2	1.0, 1.2, 1.4, 1.6, 1.8, 2.0	6
TX2	6	1.0, 1.2, 1.4, 1.6, 1.8, 2.0	6

By executing the 11 EuRoC MAV sequences on the 39 available CPU configurations, the data set will have 429 data pairs. The prediction model training data comprises 15 parameters as described in Table 5. It constitutes the CPU name, clock frequency, PassMark benchmarking results, the executed sequence as 14 model inputs and the average tracking time that the specific CPU configuration achieved while executing ORB-SLAM3 as model output.

Table 5: Prediction model training data description

Input Parameter	Description	Input Parameter	Description
CPU	CPU Name	Cores	Amount of CPU cores
Frequency	CPU clock frequency	Mark	PassMark CPU score
Int	PassMark integer score	Float	PassMark float score
Prime	PassMark prime score	Sort	PassMark sort score
Encrypt	PassMark Encrypt score	Comp	PassMark comp score
Single	PassMark single CPU score	Phys	PassMark physics score
NEON	PassMark NEON score	Sequence	EuRoC MAV sequence
Output Parameter	Description		
Tracking	Average tracking time		

4.3 Data collection and pre-processing

Two separate steps were followed in collecting data: benchmarking the CPU configuration and executing ORB-SLAM3 with the 11 EuRoC MAV sequences. Once the CPU frequency was set, the PassMark benchmark was executed to characterise the performance of the CPU configuration. Afterwards, the 11 EuRoC MAV sequences were executed on the platform using a created Docker container that containerised ORB-SLAM3 for the embedded platforms. The results of the PassMark benchmarking and ORB-SLAM3 execution are combined in a table format shown in Table 5. Figure 4 shows the procedure that was followed to generate the necessary dataset. The data used for training the models can be accessed at <https://figshare.com/s/ec2a3faca0f1311ed7dd>.

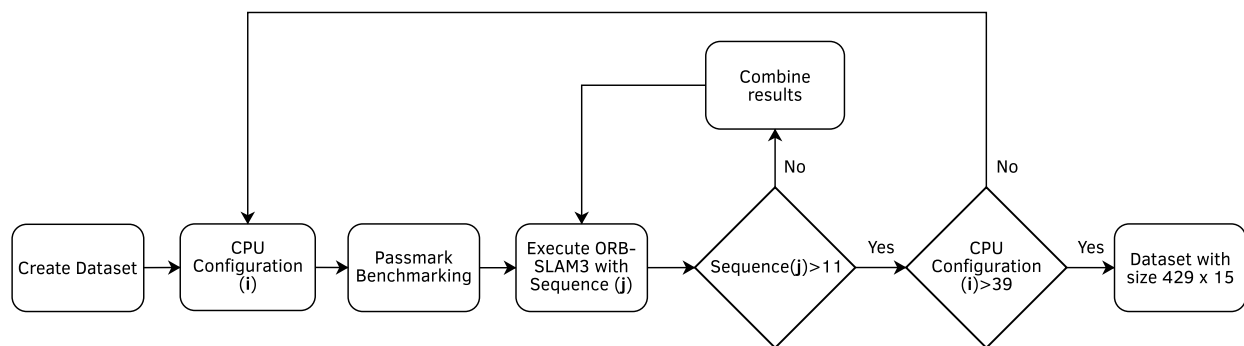


Figure 4: Training data composition procedure

Out of the 15 parameters in the dataset, 14 are chosen as inputs, and the last parameter was designated output of the model, i.e. the average tracking time that ORB-SLAM3 achieved for the different EuRoC MAV sequences on the different CPU configurations. It is important to note that the 14 parameters were immediately reduced to 13, as it was decided to always include the EuRoC MAV sequence as an input to ensure that the model would have 429 unique data pairs. If the EuRoC MAV sequence had been left out, there would have been only 39 unique entries in the dataset. To further reduce the complexity of the prediction model, two feature selection methods were used: the correlation between the target value and the remaining inputs and a user-selection method guided by profiling as described in the previous sections.

4.4 Model creation

After the dataset has been generated, the prediction models could be created. Different prediction models were created and evaluated to determine which one performed the best. With the dataset created, feature selection was applied to it to select the inputs that have a performance impact on the average tracking time on embedded platforms. The feature selection process was guided by calculating the correlation between the target and all the inputs and by the knowledge gained through the literature study and the profiling of ORB-SLAM3. After the

feature selection process, the dataset was standardised using Python's *StandardScaler* module to ensure that the dataset has zero mean and unit variance.

Two experiments were conducted, *Experiment 1* for verification and *Experiment 2* for validation. The only difference between the two experiments was the data pairs used to train and test the models. *Experiment 1* used the entire dataset with a ratio of 75:25 split ratio for training and testing. *Experiment 2* was trained on only a subset of the dataset to see how the models perform on an unseen embedded platform. The subset of training data included the data pairs of the A72, A53, and Denver 2 CPUs, with the test data being the data from the A57 CPU. The data from the TX2 CPU were removed as it combined the A72 and A57 CPUs performances. This dataset constituted 363 data pairs, of which 231 pairs were used for training and 132 for testing, effectively creating a training test set with a 63:37 split ratio. If the model could achieve adequate performance for an unseen embedded platform, the model would be validated.

Three modelling techniques were used: a simple Linear Regression model, an ExtraTrees Regressor, and a multi-layer perceptron model, MLP. Linear Regression offers a straightforward and interpretable baseline, which allowed the assessing of whether a simple modelling technique could address the problem. The ExtraTrees Regressor was selected for its robustness and accuracy, combining multiple decision trees to mitigate overfitting and improve generalisation. The Multi-Layer Perceptron (MLP) was chosen for its capability to capture complex, non-linear patterns. These models were created using *sklearn.linear_model.LinearRegression*, *sklearn.ensemble.ExtraTreesRegressor*, and *sklearn.neural_network.MLPRegressor*. The Linear Regression and ExtraTrees models used default settings, while the MLP model was configured with *random_state = 42*, *hidden_layer_sizes = 200*, and *max_iter = 10000*. Together, these models provided a comprehensive evaluation, ranging from basic to advanced approaches. The last step in the model creation process was to compare the performances of the different models.

Figure 5 shows the steps of the experimental design.

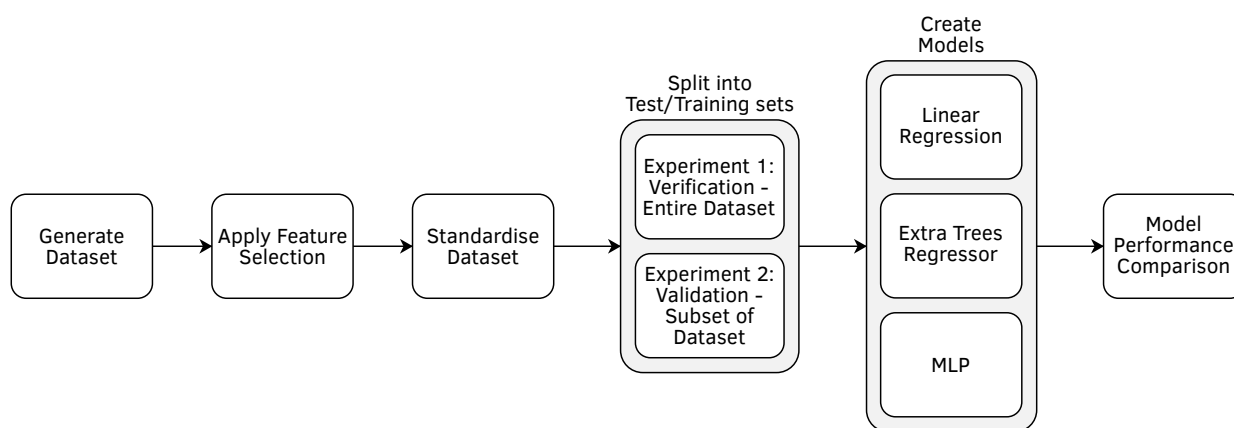


Figure 5: Experimental design method

The performance metrics measured included the mean absolute error (MAE), root mean

square error (RMSE), and the coefficient of determination, R^2 .

Table 6 shows the performance metrics criteria that the models had to achieve for verification and validation.

Table 6: Performance metrics for prediction models

MAE %	RMSE %	R^2
less than 10%	less than 10%	greater than 0.9

Table 7 summarises the two experiments with their names and their performance criteria.

Table 7: Summary of experiments

Experiment	Name	Dataset	MAE %	RMSE %	R^2
1	Verification	Entire Dataset	< 10%	< 10%	> 0.9
2	Validation	Subset	< 10%	< 10%	> 0.9

5 RESULTS AND DISCUSSION

For verification, the entire dataset was used for training and testing, whereas for validation, a CPU was removed from the dataset to see how the models would perform for unseen CPUs.

5.1 Experiment 1: Verification

With the dataset created, the feature selection method had to be applied to the data to determine what data fields would be used as input for the prediction models. Firstly, the correlation between all the inputs of the dataset were correlated to the target of the model, which was the average tracking time that the embedded platforms achieved during the execution of ORB-SLAM3. The inputs with the highest correlation to the target were selected as inputs to the model. Table 8 shows the top five correlation scores with respect to average tracking time for different model parameters.

Table 8: Correlation coefficient with respect to average tracking time for model parameters: Experiment 1

Parameter	CPU frequency	Single thread	Float score	NEON	Sorting
Correlation	-0.73	-0.71	-0.64	-0.57	-0.56

As expected, the most significant correlation coefficient belongs to the CPU frequency, as higher clock frequencies usually mean applications can execute at faster speeds. The second most significant contributor is the Single Threaded CPU score of PassMark.

The appropriate inputs of the models were determined by combining the results from the correlation coefficients and the knowledge gained during [Experiment 3.1](#). From the PassMark category results, the following inputs were chosen: Single CPU score, Neon Score and integer score. The Single CPU score was chosen as the tracking thread only executes on a single core and has the second-highest correlation coefficient. The Neon score was also selected as the FAST algorithm executes with NEON instructions and contains 19.93% NEON instructions. The correlation coefficient also showed that the NEON score strongly correlated with the model's target. The integer score was the last input, as it is the largest portion of executed instructions during the FAST algorithm, with 3.71%. [Table 9](#) summarises the inputs that were used to create the models.

Table 9: Prediction model inputs: Experiment 1

Input	CPU frequency	Single thread	NEON	Integer math	EuRoC MAV sequence
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Python is used to create the prediction models. The data were first standardised using Python's *StandardScalar* module to ensure that the dataset has zero mean and unit variance. The dataset was also split into a training and test set with a ratio of 75:25 to be used for the models' verification.

Different models were created to see what model would provide the best results. Modelling techniques such as linear regression, *ExtraTrees* and a simple MLP regressor were used to create the models. All the models were used from the *Scikit-learn* library, including *LinearRegression* from the linear model module (Scikit-learn, [2024b](#)), *ExtraTreesRegressor* from the ensemble module (Scikit-learn, [2024a](#)), and the *MLPRegressor* from the neural network module (Scikit-learn, [2024c](#)).

The linear regression model is an ordinary least squares linear regression model with all the default Python settings. This model was chosen for its simplicity. The *ExtraTrees* ensemble methods were chosen as they provide better performance. They are typically made up of more than one model, and the models learn from each other and they are known for their robustness (Brownlee, [2020](#)), the default settings were also used. The MLP regressor neural network was chosen as it has the ability to learn non-linear relationships in the dataset. The hidden layer size was increased from 100 to 200, and the max iterations to 20000 to allow for convergence.

[Table 10](#) shows the performance of the prediction models.

Table 10: Prediction model performance: Experiment 1

Modelling technique	MAE (ms)	MAE %	RMSE (ms)	RMSE %	R^2
Linear Regression	27.48	10.62	32.76	12.66	0.51
ExtraTrees	7.34	2.84	10.15	3.93	0.95
MLP	9.49	3.67	12.86	4.97	0.93

The *ExtraTrees* model is the best performing model with an MAE and RMSE percentage of

2.84% and 3.93% and a R^2 score of 0.95. The low MAE and RMSE percentages indicate that the model can make accurate predictions with a small relative error. Both the MAE and RMSE percentages were calculated by dividing their respective values by the range of the target training data multiplied by 100. The high R^2 score shows that the input variables are good predictors for the target variable. The linear regression model has the worst performance, and the MLP regressor has a comparable performance to the ExtraTrees model.

Figures 6(a) to 6(c) show scatter plots for the three prediction models plotting the actual vs. the predicted values. Figure 6(a) shows that the linear regression model is loosely clustered around the diagonal line and cannot make accurate predictions. It should also be noted that it struggles to predict targets with a longer average tracking time accurately. Figures 6(b) and 6(c) are more tightly clustered around the diagonal line, showing their strength in accuracy.

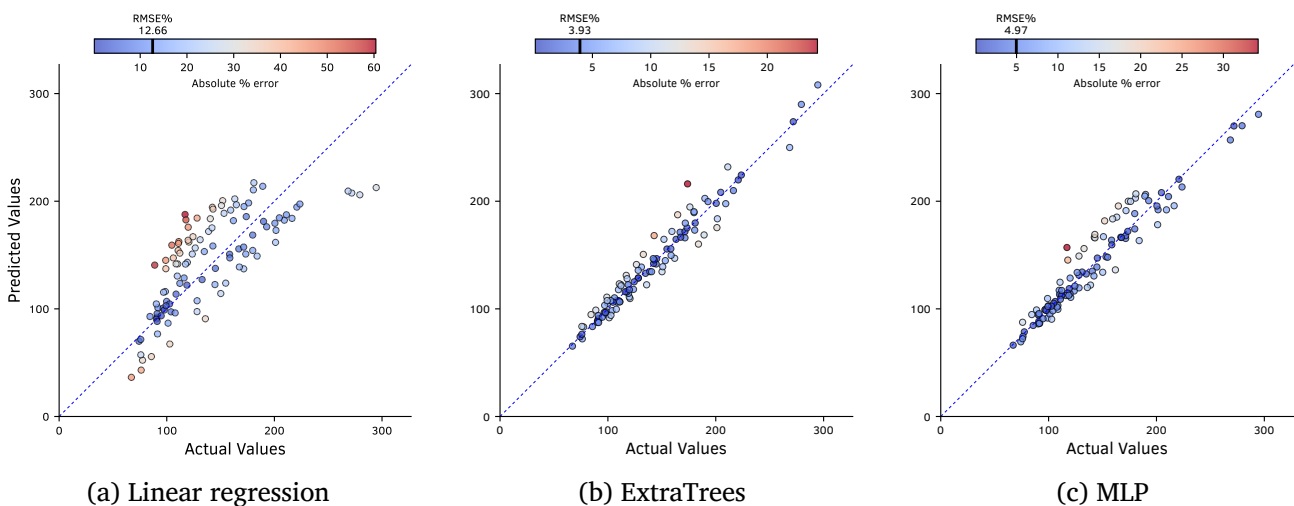


Figure 6: Scatter plots of prediction results for Experiment 1

The performance that the ExtraTrees model achieved verified the model, and confirms the robustness and performance capabilities of ExtraTrees models. However, the models were still trained and tested with all of the embedded platforms. In the next section, the models are validated with some of the embedded platform data not included in the training.

5.2 Experiment 2: Validation

This section validates the models by predicting the average tracking time of ORB-SLAM3 for an embedded platform that is not present in the training set. To achieve this, the dataset had been reduced to only include the data gathered from the Denver 2 CPU, A72 CPU and the A53 CPU. The unknown CPU that was used for testing is the A57 CPU. The TX2 CPU data was removed as it was a combination of the A57 and Denver 2 CPU and could have skewed the results.

The correlation coefficients were also recalculated, and the results are provided in [Table 11](#). The same top five inputs are present in this training set as with the entire dataset. Since the correlation table did not change, the same inputs were used to create the validation models as used for verification.

Table 11: Correlation coefficient with respect to average tracking time for model parameters: Experiment 2

Parameter	CPU frequency	Single thread	Float score	NEON	Sorting
Correlation	-0.72	-0.66	-0.56	-0.48	-0.46

The same three modelling techniques were used, and the performance of the models is displayed in [Table 12](#). The best-performing model is still the ExtraTrees model, with the lowest MAE and RMSE percentages of 9.12% and 13.14%, respectively and a coefficient of determination score of 0.78. [Table 12](#) shows that the linear regression model now performs better than the MLP model. Neither the linear regression nor the MLP model achieved the performance criteria listed in [Table 6](#). Only the ExtraTrees model was able to achieve a MAE% of below 10%. However, it does not meet the RMSE or R^2 criteria. The RMSE performance is 3.14% over the specified value. The R^2 score of 0.78 is well below the required value of 0.9. The model accuracy can be improved by increasing the training and test set data size by profiling more embedded platforms.

Table 12: Prediction model performance: Experiment 2

Modelling technique	MAE (ms)	MAE %	RMSE (ms)	RMSE %	R^2
Linear Regression	29.39	13.72	36.89	17.22	0.61
ExtraTrees	19.55	9.12	28.16	13.14	0.78
MLP	40.25	18.79	53.40	24.92	0.19

[Figures 7\(a\) to 7\(c\)](#) show the scatter plots for the three prediction models, plotting the actual vs. the predicted values for *Experiment 2*. [Figure 7\(a\)](#) reveals that the linear regression model shows poor performance. As with *Experiment 1*, it predicts longer than actual tracking times. The ExtraTrees model, [Figure 7\(b\)](#), shows the best performance. It can accurately predict the performance of the average tracking time if below 150 ms. Above the latter the error increases. This could mean that the model is over-fitted to that portion of the dataset as there is a denser representation of data in that range. [Figure 7\(c\)](#) shows that the MLP model could accurately predict only a portion of the dataset, with the rest of the predictions forming another distinct pattern.

Changing the training data influenced the model's results. A contributor to the decrease in performance can be caused by the decrease in training data from 321 data pairs down to 231 to train the model with. The MLP had a drastic performance decrease. On the other hand, the

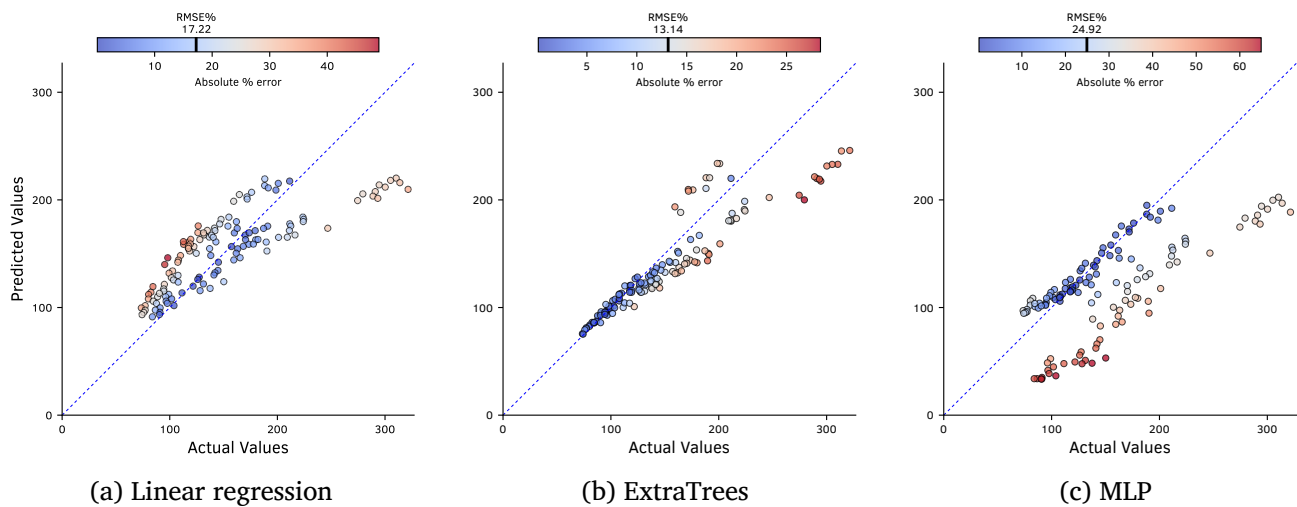


Figure 7: Scatter plots of prediction results for Experiment 2

linear regression had a similar performance to that of the entire dataset. ExtraTrees is still the best performing model. The experiment validated the approach by creating a model that can predict the performance of ORB-SLAM3 on embedded platforms. However, the models were not able to achieve the required performance, with the ExtraTrees model missing the RMSE criteria with 3.14% and the R^2 score with 0.12.

6 CONCLUSION

The paper showed that the performance that ORB-SLAM3 can achieve on embedded platforms can be predicted. Through profiling and investigation into the execution of the code, different models were created to estimate the performance of ORB-SLAM3 on embedded platforms. The predictive models' target was the average tracking time of ORB-SLAM3, and the inputs to the models were a selection of the PassMark benchmarking results. The models could predict the performance of ORB-SLAM3 with satisfactory results. The ExtraTrees model for *Experiment 1*, verification, had the best results with 2.84%, 3.93%, 0.95 for the MAE, RMSE and the R^2 score, respectively. For *Experiment 2*, validation, the ExtraTrees model was also the best model with the MAE, RMSE, and R^2 scores 9.12%, 13.14%, 0.78. The paper showed the feasibility of creating a model in estimating the performance of ORB-SLAM3 on embedded platforms. One of the limitations is the number of available embedded platforms to generate the training data, along with the use of only the EuRoC MAV dataset. It should also be noted that the models were trained on CPU architectures of the ARMv8a architecture, so the models will perform poorly on other architectures.


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Big data analytics capabilities and the organisational performance of South African retailers

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ABSTRACT

Big data analytics provides a competitive advantage and growth opportunities for organisations. Recent studies identify the resources required to build big data analytics capability (BDAC) and its correlation with firm performance. This study extends this exploration by investigating the nexus between specific dimensions of big data analytics capabilities namely, Big Data Analytics Tangible Capabilities (BDATC), Big Data Analytics Human Capabilities (BDAH), and Big Data Analytics Intangible Capabilities (BDAIC) and the organisational performance of South African retailers. Employing a descriptive research design, this study applied a quantitative survey administered to members of the Business Intelligence (BI) teams within selected South African retailers. The study's findings affirm a positive and significant impact of BDA capabilities (BDATC, BDAH, and BDAIC) on the organisational performance of South African retailers, thereby supporting the three proposed hypotheses. In essence, this research underscores the indispensable nature of all primary dimensions of BDAC in optimising the organisational performance of retailers. The outcomes of this study indicate that cultivating these capabilities empowers retailers to enhance productivity, elevate sales revenue, improve profit margins, foster customer retention, and augment return on investment.

Keywords big data, big data analytics, organisational performance, retailers

Categories • Information systems ~ Information systems applications ~ Decision support systems ~ Data analytics

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1 INTRODUCTION

In an era characterised by a surge in data generation from diverse sources (Su et al., 2022), organisations find themselves navigating an increasingly complex landscape. From social media and government records to personal computers, mobile phones, and healthcare records, the volume and complexity of data are growing exponentially (Jha et al., 2020). Recognising the indispensable role of big data (BD), organisations are investing strategically to leverage

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its potential, considering it a crucial resource for enhancing performance and gaining a competitive edge (Akhtar et al., 2019). Furthermore, BD empowers organisations to decipher the intricacies of large datasets, marked by the five Vs of volume, velocity, variety, variability, and value to extract the insights essential for shaping effective business strategies (Alwan & Ku-Mahamud, 2020). Uncovering concealed patterns within extensive datasets requires the robust implementation of big data analytics, facilitating the extraction of high-quality information.

Big Data Analytics Capability (BDAC), enables the storing, processing, and analysing of extensive datasets to provide meaningful information to users (Sabharwal & Miah, 2021). Despite previous studies on BDAC and firm performance, a noticeable gap exists in understanding how BDAC specifically influences the organisational performance of South African retailers (Ridge et al., 2015; van Dyk & Belle, 2020). This study aims to address this gap, offering crucial insights for retailers seeking to maximise their performance in an increasingly data-driven landscape.

Organisational performance (OP) stands at the core of industrial enterprises' existence (Babelová et al., 2020). Defined as the ability of a firm to use its resources effectively and achieve results consistent with its objectives and goals (Ogbo et al., 2015), OP encompasses product market performance, financial performance, and shareholder return (Bhasin, 2020). As the retail industry expands into diverse markets (Ying et al., 2021), retailers play a pivotal role in providing access to a wide range of products. This study specifically delves into the South African retail landscape, where the growing economy sees retail groceries and supermarkets as key niches for growth. However, this growth is threatened by macroeconomic instability, geopolitical uncertainties, and the fast-paced evolution of technology (BDOSA, 2024). The study seeks to answer what the impact of big data analytics capabilities is on the organisational performance of selected South African retailers. To answer the research question, the impact of tangible, human and intangible capabilities and their significance on the organisational performance of retailers were tested using Spearman coefficient correlation.

The discussion commences with a review of the literature to provide an overview of BDA and BDAC and the impact thereof on firm performance. Thereafter the BDA capability resources are discussed to situate the research methodology and hypotheses followed by a discussion of the findings.

2 LITERATURE REVIEW

2.1 Overview of big data analytics (BDA)

Big data analytics is increasingly shaping the way organisations manage their decision-making processes, create new services and products, and gain competitive advantage (Mikalef et al., 2017). According to Najafabadi et al. (2015), big data analytics requires technologies and techniques that disclose hidden values from large and complex datasets through advanced analytics that involve complex applications. The main aim of BDA is to extract useful information from

a large data set and convert it into comprehensive structures for further use (Balachandran & Prasad, 2017). There are mainly four types of analytics (predictive, prescriptive, diagnostic, and descriptive) which are often used for different types of data (Pathak, 2021).

Retailers can use big data analytics to gain new insights about their customers to inform decision-making around pricing and marketing (Najafabadi et al., 2015). Several studies have provided empirical evidence that there is a link between big data analytics and firm performance (Sekli & Vega, 2021; Shabbir & Gardezi, 2020). They identify various key factors that impact the adoption of big data analytics and enhance firm performance. These factors include individual aspects, organisational aspects, big data analytics capability, data-related aspects, business analytics capability, absorptive capacity, open innovation, and market orientation. Furthermore, BDA will allow organisations to navigate the challenges and opportunities faced by the expanded applications of artificial intelligence (AI) and machine learning to contribute to front-end offerings impacting the interface with customers, as well as back-end technologies that facilitate retail operations (Grewal et al., 2021).

2.2 Big data analytics capability (BDAC)

Big data analytics capability is the ability of an organisation to mobilise, deploy and utilise big data analytics resources effectively to enhance its performance (Sekli & Vega, 2021). It encompasses various elements such as human resources, technical skills, advanced technologies, and mathematical techniques to process large datasets for generating analytical reports and actionable insights (Akhtar et al., 2019; Munir et al., 2022). It is generally concerned with the ability of firms to leverage BDA to attain strategic objectives.

Furthermore, Akter et al. (2016) note that BDAC is often categorised into three primary dimensions i.e. BDA management capability, BDA technology capability, and BDA talent capability. BDA management capability involves making sound business decisions within a proper management framework, while BDA technology capability focuses on developing and deploying IT infrastructures. BDA talent capability refers to the ability of analytics professionals to perform tasks in the big data environment (Akter et al., 2016).

Several studies focused on investigating and understanding the concept of BDA capability. For instance, Garmaki et al. (2016) aimed to understand the impact of BDA capability on a firm's financial and market performance. They derive four BDA capability dimensions (infrastructure, management, relational, and personnel capabilities) from IT capability to better understand the current firm's abilities and their influence on performance. These four dimensions are further explained by eleven constructs: investment, BDA planning, coordination, connectivity, control, compatibility, modularity, relational knowledge, technical knowledge, business knowledge, and technology management knowledge.

Similar to the BDA capability model created by Gupta and George (2016), others (Huang et al., 2022; Mikalef et al., 2017) draw on the resource-based theory of the firm (RBT) to identify the various resources needed to create a firm's BDA capability and to test the relationship between BDA capability and firm performance. Three types of resources are proposed in-

cluding tangible resources (data, technology, and other basic resources), intangible resources (data-driven culture and organisational learning), and human resources (managerial and technical big data skills). The empirical results of these studies provide evidence that BDAC leads to high firm performance. This study adopts the BDA capability constructs from Gupta and George (2016) to test the research question and hypotheses.

2.3 Big data analytics capability and firm performance

Numerous studies have investigated the relationship between BDAC and firm performance, consistently finding a positive association. Gupta and George (2016) demonstrated that BDAC positively impacts both operational and market performance based on the resource-based theory of the firm. Similarly, Shabbir and Gardezi (2020) identified a positive influence of BDAC on OP in small and medium enterprises, with knowledge management practices partially mediating this relationship.

Wamba et al. (2017) and Akhtar et al. (2019) confirmed a positive relationship between BDAC and firm performance, with dynamic capabilities and the alignment of analytics capability with business strategy serving as mediating factors, respectively. Garmaki et al. (2016) found that BDAC, assessed through an IT capability model, positively impacts finance and market performance, with operational performance acting as a mediator. Anwar et al. (2018) revealed that big data capabilities significantly influence firm performance, with competitive advantage mediating this relationship. Wang et al. (2018) demonstrated the positive impact of BDAC on business value creation in healthcare industries. Additionally, Amankwah-Amoah and Adomako (2019) introduced a framework illustrating how different approaches to BDA adoption and implementation can affect firm performance across various domains.

The specific benefits to retailers include inter alia, greater customisation, personalised products, services and pricing models (Akhtar et al., 2019; Maheshwari et al., 2021), improved customer satisfaction and increased sales (Cuenca et al., 2021), price optimisation (Akter et al., 2016) and inventory management (Grewal et al., 2021). Predictive analytics also bring additional benefits like fraud minimisation and overall supply chain management (Maheshwari et al., 2021). Therefore, several studies proved that BDA capability and firm performance are positively related to different moderating and mediating variables.

To compete effectively, South African retailers must leverage BDA to differentiate themselves. This involves creating unique value propositions, offering localised products and providing personalised customer experiences. By embracing innovation and change through BDA, retailers can navigate evolving consumer trends and industry dynamics, ensuring their survival and success in this challenging environment (BDOSA, 2024).

2.4 BDA capability resources

Nowadays, organisations need to possess several resources to fully obtain the benefits that big data offers (Grewal et al., 2021). Even though limited research was conducted on BDA

capability, some studies focused on understanding the resources needed to develop such a capability (Gupta & George, 2016; Huang et al., 2022; Mikalef et al., 2017; Munir et al., 2022; Su et al., 2022). Mikalef et al. (2017), note that an organisation needs a combination of tangible, intangible and human resources to build a big data analytics capability. These resources are fundamental in the formation of an organisation’s overall BDA capability.

To date, most studies have discussed the processes and resources needed to deploy BDA but have provided little insight into how organisations can create a strong BDA capability (Gupta & George, 2016). Building on the foundations of the resource-based theory of the firm and several information technologies (IT) work, the main resources necessary to build a strong BDAC were identified. These resources are divided into three main groups: tangible resources (data, technology and basic resources), intangible resources (data-driven culture and organisational learning), and human resources (technical skills and managerial skills). Also, this study adopted the BDAC constructs proposed by (Gupta & George, 2016) to test the research questions and hypotheses. These constructs include seven resources drawn from the resource-based theory of the firm see Figure 1.

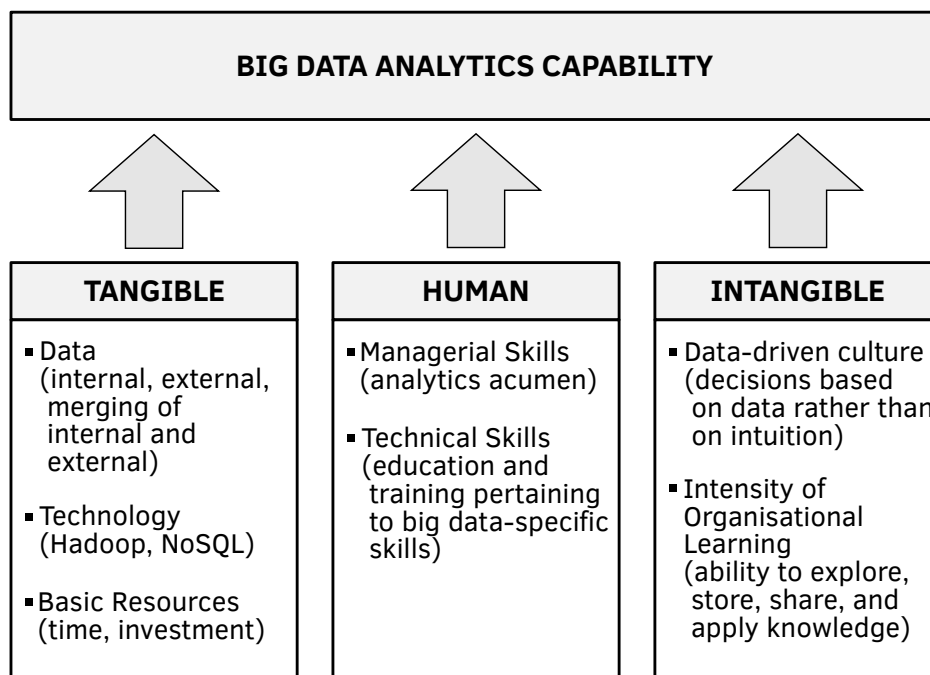


Figure 1: BDA capability resources Gupta and George (2016).

Tangible resources encompass organisational structures, physical assets, and financial resources, facilitating the rapid development, installation and support of necessary system components for big data analytics (Gupta & George, 2016). These resources include data, technology and basic resources, all vital for big data success (Mikalef et al., 2017). Data, as a crucial factor of production, can be categorised into internal and external sources, each contributing

to organisational insights and decision-making (Gupta & George, 2016). A technological infrastructure capable of analysing, sharing and storing data is essential for handling massive and fast-moving datasets, with relational database management systems and extract, transform, and load (ETL) methods being common tools (Mikalef et al., 2017). Basic resources, such as investments and time allocation, are necessary for the persistence and success of big data initiatives (Gupta & George, 2016).

Human resources encompass the knowledge, experience and skills of employees, with managerial and technical skills being fundamental for big data analytics (Mikalef et al., 2017; Su et al., 2022). Technical skills, including competencies in data extraction, machine learning and statistical analysis, are acquired through formal education, training programs and practical experience (Gupta & George, 2016). Managerial skills, on the other hand, are developed over time within the organisation and involve interpreting and utilising insights extracted from big data for decision-making (Mikalef et al., 2017).

Intangible resources, such as data-driven culture and organisational learning, play a critical role in building BDAC (Mikalef et al., 2017). Organisational learning enables continuous improvement through knowledge and insights gained from big data analysis (Gupta & George, 2016). A data-driven culture emphasises data-based decision-making and experimentation, fostering an environment where insights outweigh opinions and failure leads to learning (Berndtsson et al., 2018). Such a culture is essential for successful big data implementation and organisational performance (Cao et al., 2015).

The review of the literature reveals that most of the studies on BDAC and organisational performance were conducted in Europe, the USA and Asia with a few exceptions in Africa. In addition, the above studies mostly focused on sectors such as banks, telecommunications, health care and automotive (Akhtar et al., 2019; Anwar et al., 2018; Garmaki et al., 2016; Mikalef et al., 2017; Wamba et al., 2017). This study is among the few studies that consider the retail sector of South Africa (Ridge et al., 2015; Sabharwal & Miah, 2021). This can serve as a framework for South African retailers utilising BDA to maximise their organisational performance.

3 RESEARCH MODEL AND RESEARCH HYPOTHESES

3.1 Research model

Drawing on BDA capabilities literature, this study proposes a research model as depicted in [Figure 2](#). This model shows a pictorial description of the relationship between the independent variables (BDA tangible, human and intangible resources) and the dependent variable (organisational performance).

3.2 Research hypotheses

The proposed hypotheses for this study were:

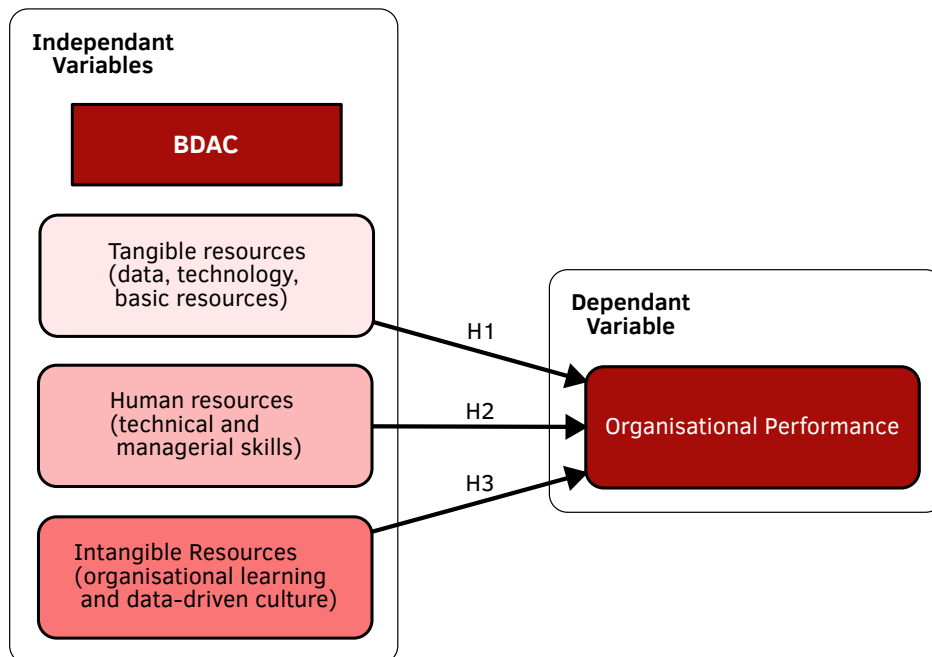


Figure 2: Research model

Hypothesis 1 (H1) There is a positive and significant relationship between BDA’s *tangible capabilities* and the organisational performance of selected South African retailers.

Hypothesis 2 (H2) There is a positive and significant relationship between BDA’s *human capabilities* and the organisational performance of selected South African retailers.

Hypothesis 3 (H3) There is a positive and significant relationship between BDA’s *intangible capabilities* and the organisational performance of selected South African retailers.

4 METHODOLOGY

This study adopted a descriptive research design through a quantitative approach to determine the relationship between the independent variables and the dependent variable (Ragab & Arisha, 2017). A questionnaire adopted from (Gupta & George, 2016) was used to collect the data.

The population included employees of selected South African retailers. The target population was limited to the BI team members of the selected retailers. To reduce the size of the population, only retailers in Cape Town were targeted. The sample size was estimated to be 109 employees. There are various statistical methods for calculating sample size. The study

used the formula developed by (Yamane, 1967) to calculate the sample size:

$$n = \frac{N}{1 + N \cdot e^2}$$

where:

$$\begin{aligned} N &= \text{target population} \\ e &= \text{acceptable sampling error} \end{aligned}$$

In calculating the estimated sample size, a 95% confidence interval and a 5% sampling error were used by the researcher. Therefore, using the above formula the sample size was obtained as:

$$n = \frac{150}{1 + 150 \cdot (0.05)^2} = 109$$

The data analysis of this study consisted of two main parts: summarising the collected data (descriptive statistics) and determining the relationship between the dependent and the independent variable (Spearman Correlation). This was done using Excel and Statistical Package for Social Science (SPSS). Descriptive statistics are generally used to make research data summaries. Additionally, a correlation test was run to determine the relationship between the variables. According to Ali and Al-Hameed (2022), Spearman coefficient correlation is a coefficient that expresses the strength and direction of the relationship between two phenomena only. This type of correlation is generally used when the variables are measured on an ordinal scale, not normally distributed and when the sample size is small. Therefore, Spearman coefficient correlation was the appropriate correlation analysis for the study because it had a small sample size and discrete ordinal data (Likert scale data).

5 RESULTS AND FINDINGS

This section presents the analysed data and overall findings of the study. It is divided into findings on the response rate and the demographic characteristics of all the respondents followed by the reliability and validity of the statistics and lastly the descriptive statistics and the Spearman correlation results of the independent and dependent variables.

5.1 Response rate and demographic profile

The study targeted 109 participants and received responses from 68 participants resulting in a 62.4% response rate which was satisfactory for the analysis according to (Yamane, 1967) who state that a 70% response rate is very good, 60% good and 50% adequate. The response rate of the study is presented in Figure 3.

The results (as shown in Figure 4) revealed that (47%, $n = 32$) of the participants were female and (53%, $n = 36$) were male. It was promising to achieve a good distribution between male and female participants. The majority of the participants (32%) were in the younger age

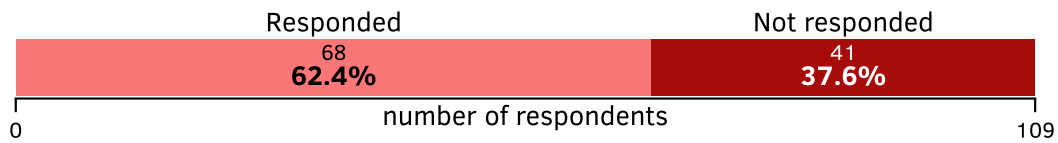


Figure 3: Response rate

brackets (22–29 years). They were followed by those aged between 38–45 years (27%, $n = 18$) and 46+ (22%, $n = 15$). Lastly, those aged between 30–37 years represented a minority of 19.1%. The results revealed that the majority of the participants of this study were Honours degree holders (33.8%, $n = 23$) and Bachelor’s degree holders (33.8%, $n = 23$). Holders of Master’s degrees were represented by 22%. Lastly, secondary school holders represented a minority of 10%. Therefore, the above results show that most of the participants were well-educated.

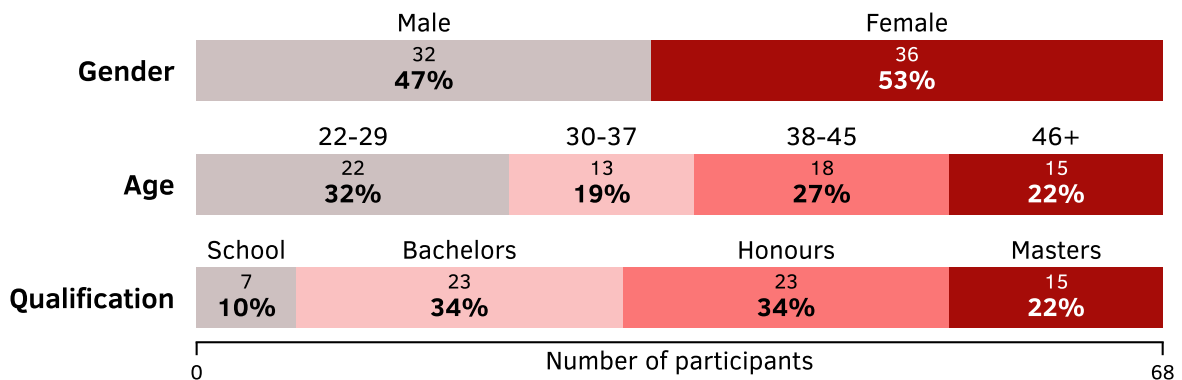


Figure 4: Demographics

5.2 Reliability and validity statistics

Reliability often refers to the consistency of study constructs to ensure the stability of the measuring instrument used and its consistency over time (Sürücü & Maslakçi, 2020). In this study, construct reliability was assessed using Cronbach’s alpha. According to Taber (2018) Cronbach alpha is used to measure the consistency or reliability between several items, measurements or ratings. It is frequently used to test the stability of the assessment instrument of the study. Moreover, a construct is generally considered reliable when the alpha value is greater than 0.70 (Taherdoost, 2016). See Table 1 for a depiction of the reliability statistics for BDA capabilities.

Table 1 indicates that all BDA tangible capability constructs have a reliability score of 0.7 and above (high reliability). The findings revealed that data, technology and basic resources had a reliability score of .719, .838 and .924 respectively. Furthermore, the findings indicate

Table 1: Reliability statistics for BDA capabilities

BDATC constructs	#items	Cronbach alpha	Comments
Data (D)	3	.719	High reliability
Technology (T)	10	.838	High reliability
Basic resources (BR)	2	.924	High reliability
BDAHIC constructs	#items	Cronbach alpha	Comments
Technical skills (TS)	10	.875	High reliability
Managerial skills (MS)	5	.950	High reliability
BDAIC constructs	#items	Cronbach alpha	Comments
Data-driven culture (DDC)	10	.839	High reliability
Organisational learning (OL)	5	.950	High reliability

that all BDA human capability constructs have a reliability score of 0.7 and above (high reliability). It revealed that technical skills and managerial skills had a reliability score of .875 and .950 respectively. Moreover, results revealed that data-driven culture had a Cronbach alpha of .839 and organisational learning had a Cronbach alpha of .909. This implies that all BDA intangible capability constructs were reliable.

Validity is often concerned with the meaningfulness and accuracy of study constructs. When research is highly valid, it implies that its results are consistent with reality (Bahariniya et al., 2021). There are mainly four types of validity namely, content validity, face validity construct validity and criterion validity (Taherdoost, 2016). This study adopted construct validity which is often defined as “*the extent to which a research instrument (or tool) measures the intended construct*” (Heale & Twycross, 2015, p. 66). According to Bahariniya et al. (2021), this type of validity is often evaluated by factor analysis. Factor analysis is usually considered a data reduction technique. It is often associated with factor loading which is defined as the correlation between the variable and the factor (Tavakol & Wetzal, 2020). According to Shrestha (2021), the variables with large loadings values >0.40 indicate that they are representative of the factor.

Summarised results in Table 2 indicate that the factor loads used in measuring BDA tangible capabilities ranged from 0.706 to 0.807. The results revealed that technology had the highest factor loading (.801) and basic resources had the lowest factor loading (.706). Additionally, results reveal that both technical skills and managerial skills had a factor loading of .888. Moreover, Table 2 reveals that both data-driven culture and organisational learning had a

Table 2: Factor analysis of BDA tangible capabilities

BDATC	Factor loadings
Data(D)	.801
Technology (T)	.807
Basics resources (BR)	.706

BDAHc	Factor loadings
Technical skills (TS)	.888
Managerial skills (MS)	.888

BDAIC	Factor loadings
Data-driven culture (DDC)	.901
Organisational learning (OL)	.901

factor loading of .901.

Therefore, the analysis revealed that all the variables used to measure BDATC, BDAHc and BDAIC had a coefficient greater than 0.4. This implies that all the BDATC, BDAHc and BDAIC variables were feasible and significant to be used in data collection.

5.3 Spearman coefficient correlation between BDA capabilities and organisational performance

Spearman correlation was used to determine the relationship that exists between big data analytics tangible capabilities (BDATC), data analytics human capabilities (BDAHc), data analytics intangible capabilities (BDAIC) and the organisational performance (OP) of South African retailers.

H1 assesses whether BDATC is positively and significantly related to the organisational performance of South African retailers. The relationship between BDATC and OP is displayed in **Table 3**. The results reveal a Spearman correlation of .306 and a probability sig. (2-tailed) of .011. This implies that there is a moderate positive correlation between BDATC and the organisational performance of South African retailers, which is statistically significant. Additionally, it indicates that as retailers increase their BDA tangible capabilities, their organisational performance increases as well. Therefore, **H1** was supported.

H2 evaluates whether BDAHc is positively and significantly related to the organisational performance of South African retailers. The relationship between BDAHc and OP is displayed

Table 3: Correlation between BDATC and organisational performance

			BDATC	OP
Spearman's rho	BDATC	Correlation Coefficient	1.000	.306*
		Sig. (2-tailed)	–	.011
		N	68	68
	OP	Correlation Coefficient	.306*	1.000
		Sig. (2-tailed)	.011	–
		N	68	68

* Correlation is significant at the 0.05 level (2-tailed)

in Table 4. The results reveal a Spearman correlation of .225 and a probability sig. (2-tailed) of .035. This implies that there is a significant positive correlation between BDATC and the organisational performance of South African retailers. In addition, results indicate that as retailers increase their BDA human capabilities, their organisational performance increases as well. Hence, **H2** was supported.

Table 4: Correlation between BDAHIC and organisational performance

			BDAHIC	OP
Spearman's rho	BDAHIC	Correlation Coefficient	1.000	.225*
		Sig. (2-tailed)	–	.035
		N	68	68
	OP	Correlation Coefficient	.225*	1.000
		Sig. (2-tailed)	.035	–
		N	68	68

* Correlation is significant at the 0.05 level (2-tailed)

H3 assesses whether BDAIC is positively and significantly related to the organisational performance of South African retailers. The relationship between BDAIC and OP is displayed in Table 5. The results reveal that BDAIC is positively and significantly related to the organisational performance of South African retailers ($r = .627, p = .001$). This implies that there is a strong relationship between both, suggesting that an increase in the BDAIC of retailers will lead to an increase in their Organisational performance. Consequently, **H3** was supported.

Table 5: Correlation between BDAIC and organisational performance

			BDAIC	OP
Spearman's rho	BDAIC	Correlation Coefficient	1.000	.627*
		Sig. (2-tailed)	–	.001
		N	68	68
	OP	Correlation Coefficient	.627*	1.000
		Sig. (2-tailed)	.001	–
		N	68	68

* Correlation is significant at the 0.01 level (2-tailed)

6 DISCUSSION

Several researchers have been working toward understanding BDA capability and examining its relationship with firm performance (Akhtar et al., 2019; Garmaki et al., 2016; Sekli & Vega, 2021; Wamba et al., 2017). Prior studies on this topic confirmed a positive relationship between BDAC and firm performance (Akhtar et al., 2019; Anwar et al., 2018; Gupta & George, 2016; Su et al., 2022). However, few studies have focused on understanding this relationship in retail sectors. Thus, this study aimed to fill this gap by examining the impact of BDA capabilities on the organisational performance of retailers. Empirical research was conducted and insights were provided on the relationship between BDAC and the organisational performance of South African retailers. Based on the findings from prior studies, three hypotheses were proposed.

Hypothesis 1 There is a positive and significant relationship between BDA's *tangible capabilities* and the organisational performance of selected South African retailers.

Firstly, it was assumed that BDA's tangible capabilities positively and significantly impact the organisational performance of South African retailers. The findings from the analyses revealed that there is a positive and significant relation between BDATC and the organisational performance of South African retailers ($r = .306, p = .011$). Hence, **H1** was supported. This significant relationship shows that South African retailers should deploy BDA tangible resources to maximise their organisational performance. The above findings correspond to a study conducted by Su et al. (2022) whose results revealed that BDA tangible resources have a positive impact on organisational performance. Similarly, other studies confirmed a positive relationship between BDATC and organisational performance (Akhtar et al., 2019; Anwar et al., 2018; Ong & Chen, 2013). Moreover, the findings of the study revealed a positive impact of BDA's tangible capabilities (data, technology and basic resources) on selected South African retailers. Hence, all South African retailers should consider employing BDA tangible capabilities to enhance their organisational performance and competitive advantage and save their money

and time. In addition, retailers should reinforce the performance of their BD analytics platforms in terms of compatibility, connectivity and modularity to maximise their organisational performance.

Hypothesis 2 There is a positive and significant relationship between BDA's *human capabilities* and the organisational performance of selected South African retailers.

Secondly, it was hypothesised that BDA's human capabilities have a positive and significant impact on the organisational performance of South African retailers. The results reveal that the relationship between BDA human capabilities and organisational performance was positive and significant ($r = .225$, $p = .035$). Consequently, **H2** was supported. The above result is consistent with previous studies that found that BDA human capabilities enhance organisational performance (Tambe, 2014). For instance, Anwar et al. (2018) reported that BDA human capabilities significantly and positively impact the performance of an organisation. Similarly, Su et al. (2022) concluded that BDA human resources positively impact organisational performance.

Furthermore, the findings of the study revealed a positive impact of BDA human capabilities (technical skills and managerial skills) on selected South African retailers. Consequently, all South African retailers should consider deploying BDA human capabilities as this has a direct impact on organisational performance. Moreover, to maximise organisational performance through this capability, retailers should consider investing in the training of their staff to have a well-trained BDA team that is eager to be efficient, attentive and creative. Additionally, retailers should consider recruiting more technically trained senior managers with real BDA experience. Managers who understand how BDA works and hire people with the right knowledge and skills.

Hypothesis 3 There is a positive and significant relationship between BDA's *intangible capabilities* and the organisational performance of selected South African retailers.

Thirdly, it was hypothesised that BDA's intangible capabilities positively and significantly impact the organisational performance of South African retailers. The findings from the analyses reveal that BDAIC is positively and significantly correlated to the organisational performance of South African retailers ($r = .627$, $p = .001$). Thus, **H3** was supported. The finding of this study corresponds to prior studies that examined the relationship between BDA intangible capabilities and organisational performance (Kamasak, 2017; Rua & França, 2017; Su et al., 2022). Additionally, Gupta and George (2016) provided evidence that BDA intangible resources significantly impact organisational performance.

Moreover, the findings of the study revealed a positive impact of BDA tangible capabilities (technical Skills and managerial skills) on selected South African retailers. Hence, South African retailers should consider employing BDA human capabilities to enhance their organisational performance. Furthermore, to maximise organisational performance through this capability, retailers should consider building a data-driven culture, enhancing data management skills, developing decision-making capabilities and expanding the various data-driven

decision-making that combine intuition and analytical insights. In addition, retailers should encourage organisational learning to understand the dynamic and complex environment.

Therefore, the study concludes that all the BDAC primary dimensions (BDA tangible, BDA human, and BDA intangible capabilities) have a positive and significant impact on the organisational performance of South African retailers. This implies that the high market and operational performance of South African retailers is a result of well-deployed BDA tangible, intangible and human resources. In addition, this study provides retailers with evidence that the deployment of BDAC is essential for the improvement of organisational performance.

7 RECOMMENDATIONS

The essential resources for improving organisational performance include data, technology, basic resources, technical skills, managerial skills, data-driven culture and organisational learning. To maximise organisational performance through these capabilities, the following recommendations should be taken into consideration:

Integration of BDA into Operations Retailers should recognise the critical role of BDA in their operations, as it directly impacts organisational performance. This integration can enhance competitive advantage, streamline processes and result in significant cost and time savings. Furthermore, changing customer behaviour and the importance of customer orientation need to drive the integration of BDA in the SA retail sector, also cited by (Ridge et al., 2015). The global trends of e-commerce growth, omnichannel retailing and personalisation underscore this shift in customer behaviour (Deloitte, 2024).

Enhancement of Human Resources The study reveals that tangible and intangible capabilities are more strongly related to the organisational performance of South African retailers than human capabilities. This indicates a need to enhance human resources. Retailers should continuously assess and upgrade their BDA human skills by hiring individuals with the right expertise and investing in ongoing training and development. This needs to be underscored by a focused change management strategy to combat resistance to change.

Optimisation of BDA Platforms To maximise the benefit of BDA tangible capabilities, retailers should focus on improving their analytics platforms in terms of compatibility, connectivity and modularity. This ensures seamless integration and efficient data processing, essential for the digital infrastructure.

Investment in Training and Development Retailers should consistently invest in the training of their BDA teams to enhance their knowledge and skills. A well-trained team is essential for extracting meaningful insights from data and making informed business decisions.

Improvement of Intangible Capabilities Retailers should enhance the quality of investment, planning and coordination to fully leverage BDA intangible capabilities. This improvement

will lead to better service quality and product innovation, contributing to overall organisational performance. Tailoring these strategies to South Africa's unique economic and cultural landscape will provide a competitive edge.

Real-Time Monitoring Retailers should implement real-time monitoring systems to keep track of competitors and customer behaviours. This proactive approach helps identify operational bottlenecks and deficiencies, allowing retailers to adapt to changes in the business and economic environment quickly.

8 CONCLUSION

The goal of this study was to determine the impact of BDA capabilities on the organisational performance of South African retailers. The study was guided by two main objectives. Firstly, a literature review was conducted to understand the impact of BDA capabilities on organisational performance. Secondly, empirical research was conducted to determine the impact of BDA tangible, intangible and human capabilities on the organisational performance of South African retailers.

Data were collected from South African retailers through an online questionnaire to measure the level to which BDA capabilities impact the improvement of their organisational performance. The collected data was then analysed through SPSS and a correlation test was conducted to determine whether the proposed hypotheses of the study were accepted or rejected. The study proposed three hypotheses.

Firstly, it was hypothesised that BDA tangible capabilities and the organisational performance of South African retailers are positively and significantly related. The findings of the study validate this hypothesis thus the research concludes that BDATC impacts the organisational performance of South African retailers. Additionally, this implies that the more retailers deploy BDA tangible resources, the higher their organisational performance.

Furthermore, the study proposed that a positive and significant association exists between BDA human capabilities and the organisational performance of South African retailers. The findings of the study provide evidence that this hypothesis is true thus the research concludes that BDAHHC impacts the organisational performance of South African retailers. This implies that BDAHHC is a key factor that should be considered by all retailers as they adopt big data analytics. It is evident that the use of BDA human resources is essential for increasing productivity, sales revenue, profit rate and return on investment.

Moreover, the study predicted that BDA intangible capabilities and the organisational performance of South African retailers are positively and significantly related. The results of the study provide validation of this relationship. Thus, the research concludes that BDAIC impacts the organisational performance of South African retailers. This implies that the more retailers deploy BDA intangible resources, the higher their organisational performance. In addition, this shows that BDAIC is of importance to South African retailers.

Overall, the study attempted to examine the impact of BDA capabilities on the organisational performance of retail industries in South Africa and the findings stated that these capabilities have a positive and significant impact on organisational performance. This study provides retailers with a deeper understanding of the various BDA capabilities and the key role they play in maximising organisational performance.

9 LIMITATIONS AND FURTHER RESEARCH

As with any other research, the study had a series of limitations. Firstly, this research was limited only to South African retailers. It is difficult to apply the results of this study to other industries such as manufacturing, banking, automobile, etc. Thus, future researchers can focus on different countries and different sectors using the same study model.

Secondly, the study targeted 109 respondents to take part in the research survey, only 68 responses were collected and deemed satisfactory for analysis. The sample was selected from the BI teams of the three largest retailers in South Africa as they were deemed to be the most knowledgeable, however, this can pose a potentially biased view. Hence, future researchers can target larger sample sizes and other stakeholders from retail organisations to obtain a higher response rate which may lead to more pertinent results. Additionally, the study adopted a quantitative approach to analyse the collected data. Future researchers can adopt a mixed-method (quantitative-qualitative approach) to validate the proposed findings.

Thirdly, this study focused on investigating the impact of BDAC on the overall organisational performance and not a specific area. Hence, future researchers can investigate the impact of BDA capability within a specific department such as supply chain management, etc. Moreover, since most organisations are in the adoption and development process of BDAC, future researchers should consider improving this research by including other dimensions such as how BDAC relates to improved capabilities to implement and use Big Data Algorithmic Systems.

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Exploring adoption dynamics: Mobile technology in agricultural information dissemination among smallholder farmers in Gokwe South District, Zimbabwe

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ABSTRACT

There is a lack of acceptance, adoption and sustained use of mobile phones for agricultural purposes by smallholder farmers in Zimbabwe, but the reasons for this have not been critically explored. In this study, the authors used a naturalistic methodology to help uncover the nuances of adoption dynamics among smallholder farmers in Gokwe South District, Zimbabwe. Data was gathered from in-depth interviews and focus groups. The findings suggest that gender, age, land ownership size, farming experience, mobile device ownership, and the period of owning a mobile device are critical precursors to adoption and use. Furthermore, digital proficiency and literacy, affluence, mobile technology services cost and telecommunication infrastructure availability are vital in achieving continuous, sustainable use of mobile technology in the Zimbabwean agricultural sector. This research has practical implications for policy and practice and may inform national legislation encouraging the increased use and affordability of mobile devices in the local agricultural sector. The research also makes a theoretical contribution in terms of unpacking the key factors that inhibit the adoption of mobile technology in marginalised settings.

Keywords Mobile phones, Information and Communication Technology (ICT), smallholder farmers, information dissemination, adoption, Zimbabwe

Categories • Human-centered computing ~ Ubiquitous and mobile computing, Empirical studies in ubiquitous and mobile computing

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1 INTRODUCTION

Information and communication technologies (ICTs) have great potential to facilitate global socio-economic development, mainly in emerging economies, since the inception of the Mil-

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lennium Development Goals (MDGs) and subsequent development that ensued (Heeks, 2014). The successes achieved under the MDGs led to the conception of the United Nations 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs). The SDGs are an overarching framework premised on harnessing ICTs for sustainable development. The framework suggests that to create the world we envision, we must place the ICTs at the center of all socio-economic and development activities (Jones et al., 2017). In sub-Saharan Africa (SSA), mobile phone technologies are fashioning inimitable ways of communication and engagement among people from different social strata (Alnes, 2017). ICTs are a universal gateway to valuable public information and other essential basic services to the marginalised people in the Global South, as it is the only digital technology found in the hands of many people, including smallholder farmers. In particular, mobile phone technologies now straddle different socio-economic activities like agriculture (Awuor et al., 2019) and other areas of life (Porter et al., 2020). According to Dunjana et al. (2018), the significant role of agriculture in the Zimbabwean economy in the future will largely depend on the productivity of smallholder agriculture in Zimbabwe. Importantly, agriculture is an information-driven sector.

To boost the significance of agriculture as the primary source of livelihood for many people in the Zimbabwean economy, smallholder farmers need to benefit from information on complementary services in real time. Research has constantly linked mobile phones with development prospects in the developing world (Quandt et al., 2020). Mobile phones can afford smallholder farmers an avenue to obtain novel actionable agricultural information, input prices, and agricultural product market prices in real-time, as reported in the literature (Heeks & Ospina, 2019; Quandt et al., 2020). However, in the last five years, a large body of research has documented the low adoption and usage levels of mobile technologies for agricultural purposes (Issahaku et al., 2018; Musungwini, 2018; Van Greunen & Fosu, 2022; Wyche & Steinfield, 2016). Indeed, information and communication technology for development (ICT4D) is founded on comprehending ICTs' contributory role in the development process in any socio-economic area of life (Msendema & Nyirenda, 2019).

This paper attempts to broaden the understanding of adoption dynamics among smallholder farmers in Zimbabwe. This understanding may lead to crafting recommendations that may result in many smallholder farmers in Zimbabwe fully adopting mobile phones in their agricultural information dissemination activities. Research by Quandt et al. (2020), Lokeswari (2016), and Barakabitze et al. (2017) finds that even though mobile phones are widespread among the populace, including marginalised smallholder farmers, there is a lack of acceptance, adoption, and sustained usage by adopters. Hence, there has been a subsequent failure to scale up adoption and usage to non-adopters among smallholder farmers for agricultural purposes in SSA, including Zimbabwe. Studies have demonstrated that technology cannot impact any socio-economic activity until it has been adopted and used effectively by the intended beneficiaries (Barakabitze et al., 2017; Musungwini et al., 2023). Therefore, it remains challenging to offer crucial recommendations to address Zimbabwe's adoption, acceptance, and usage issues unless the country's context-specific elements hindering their adoption

and usage are established.

1.1 Theoretical development

Many studies on mobile phones and smallholder agriculture have compared adoption to non-adoption; hence, they are dichotomous in nature (Emeana et al., 2020; Issahaku et al., 2018; Kikulwe et al., 2014; Masuka et al., 2016; Palmer, 2012). There is, however, a need to explore the dynamic and subjective reasons behind non- or ill-adoption for agricultural purposes. According to Whetten (1989), theoretical advancement aims not to reproduce the same phenomena but to look for new knowledge that could amend current knowledge with sound reasoning. This study aims to explore smallholder farmers' adoption of mobile phones in their agricultural activities, which required the creation of a conceptual framework to serve as a roadmap for gathering and analysing data. Developing such a (fluid) conceptual framework aligns with Mishra et al. (2021), who suggested that rigidly applying pre-existing theories might limit researchers' ability to find novel, context-specific elements. Because of this, researchers may need to go beyond the traditional adoption theories and the broad theoretical frameworks commonly employed in IS research to uncover new information.

To achieve this endeavour, they could use exploratory, inductive approaches. However, the application of a conceptual framework is aligned with deductive studies, as a result, it followed that this research applied an abductive approach to satisfy the bottom-up data analysis. Abduction is the process of coming up with novel theories, conceptions, and explanations based on the discovery of unexpected events, data, or phenomena that do not conform to explanations provided by prior knowledge (Kennedy & Thornberg, 2017). This approach is particularly valuable in fields where established theories may be insufficient like in this research or where the research aims to explore uncharted territories (Timmermans & Tavory, 2012). This enabled researchers to develop a more nuanced and contextual understanding of the non-adoption of mobile phones for agricultural purposes by smallholder farmers (Cronholm et al., 2023).

Accordingly, in this research, an eclectic model was developed from the critical tenets of adoption models like the technology acceptance model (TAM) (Yousafzai et al., 2007), theory of reasoned action (TRA) (Loken, 1983), theory of planned behaviour (TPB) (Weigel et al., 2014) and diffusion of innovation theory (DOI) (Rogers et al., 2019). The researchers designed a nine-construct eclectic model to provide research boundaries and assist in formulating research questions. The model constructs are as follows: Perceived Expressiveness (PE), Perceived Mobility (PM), Perceived Support of Service Provider (PSoS), Perceived Compatibility (PComp), Perceived Ease of Use (PEOU), Perceived Costs (PC), Perceived Usefulness (PU), Perceived Subjective Norms (PSN) and Perceived Behavioural Control (PBC). **Figure 1** depicts the eclectic model.

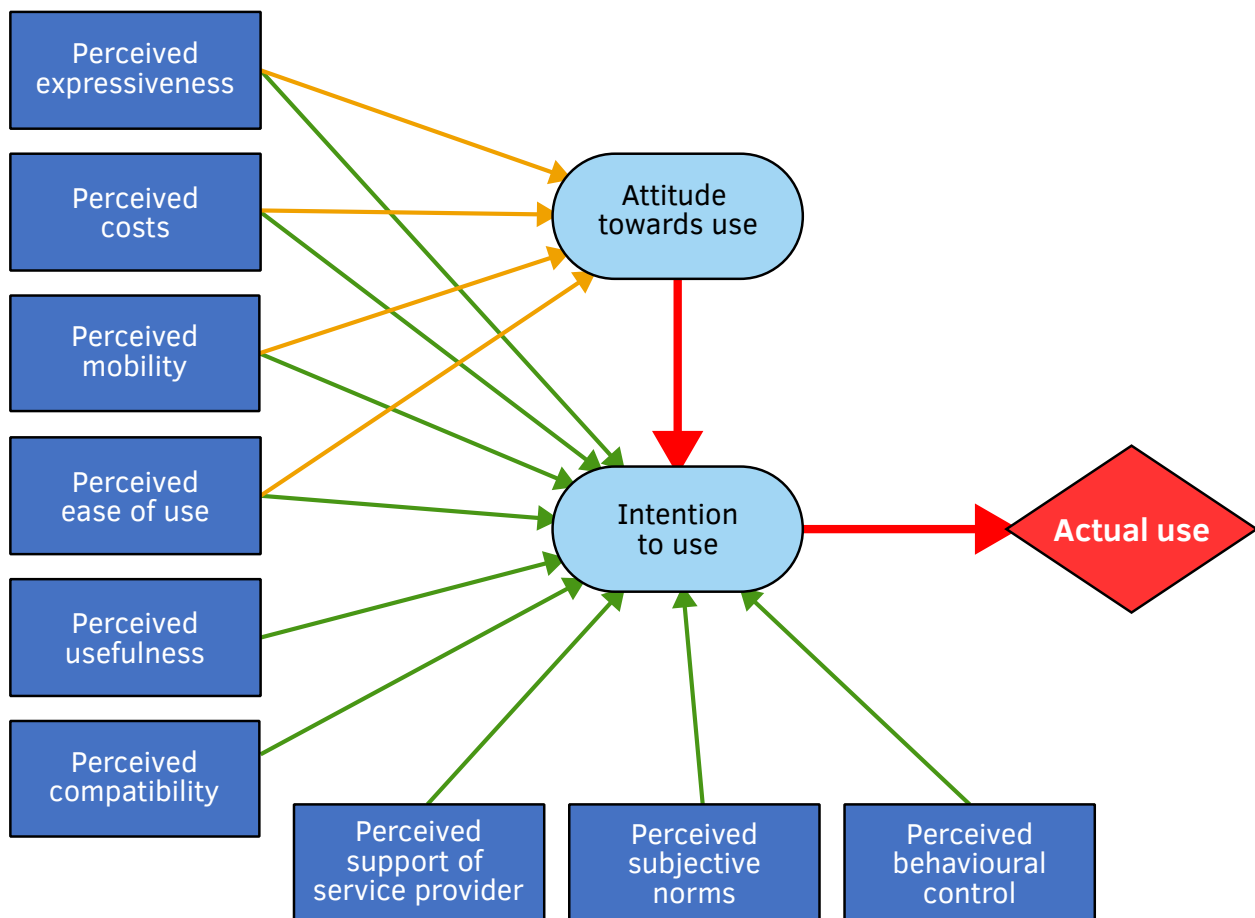


Figure 1: The eclectic model guiding this research (authors' construction).

As stated by Whetten (1989), four main objectives of theory have been identified, which include a theory of analysing and describing, which offers a description of an investigation of the linkages between those concepts and the degree of generalisability in the associations and concepts, the boundaries that hold linkages and discoveries, and the analysis of a phenomenon of interest. The theory of explanation uses different theories of causation and reasoning techniques to explain why and how something happens; hence, the research uses the constructs of the eclectic model to describe the non-adoption of mobile phones by smallholder farmers. Usually, this explanation aims to encourage others to gain deeper comprehension or new perspectives on the phenomenon of interest.

1.2 Research connection to national and international development agendas

This research directly addresses three SDGs, namely SDG1: “End poverty in all its forms everywhere in the world”, SDG2: “End hunger, achieve food security and improved nutrition and promote

sustainable agriculture”, and SDG3: “*Ensure healthy lives and promote well-being for all at all ages.*” Agriculture is an information-intensive sector, and various studies like Gregor (2006), Etwire et al. (2017), Freeman and Mubichi (2017), Krell et al. (2020), Isaya et al. (2018), and Musungwini (2016) have shown that ICTs may play a pivotal role in transmitting and transferring agricultural knowledge. The SDG goals are also in sync with the African Union’s Agenda 2063, adopted in January 2015 at the 24th Ordinary Assembly of the Heads of State and Governments of the continental body in Addis Ababa, Ethiopia (Dunjana et al., 2018; Ndizera & Muzee, 2018; Oguntuase, 2021). It is a twenty-goal continental strategic blueprint for transmuting Africa into a global powerhouse by 2063.

The research is also directly in line with Agenda 2063, Goal 1: *A high standard of living, quality of life, and well-being for all citizens*; Goal 3: *Healthy and well-nourished citizens*; Goal 4: *Transformed economies*; and Goal 5: *Modern agriculture for increased productivity and production* (Quandt et al., 2020). The government of Zimbabwe also developed its national strategic plan titled Vision 2030 and the National Development Strategy 1 (NDS1) to enhance Zimbabwe’s food self-sufficiency status (Government of Zimbabwe, 2020). The macroeconomic measures crafted under this strategy also aim to raise smallholder farmers’ agricultural output and productivity, among other things, provide adequate nutrition and food for their families, higher earnings, an increased likelihood for value addition, and the creation of value chains for the agro-business industry (Heeks & Ospina, 2019). Table 1 links the SDGs, Agenda 2063, and Zimbabwe’s national development strategic plan [Vision 2030].

Table 1: The alignment between the United Nations Sustainable Development Goals 1, 2, and 3, the African Union’s Agenda 2063 Goals 1, 3, and 5, and the Zimbabwe national development strategy [Vision 2030].

United Nations Sustainable Development Goals	African Union’s Agenda 2063	Zimbabwe’s Vision 2030
<i>SDG1</i> : End poverty in all its forms everywhere in the world.	<i>Goal 1</i> : A high standard of living, quality of life, and well-being for all citizens.	The objective is to improve food self-sufficiency and retain the country’s regional breadbasket status.
<i>SDG2</i> : End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	<i>Goal 5</i> : Modern agriculture for increased productivity and production.	It seeks to increase self-sufficiency from the top 100% and reduce food insecurity from 59% in 2020 to less than 10% by 2025.
<i>SDG3</i> : Ensure healthy lives and promote well-being for all at all ages.	<i>Goal 3</i> : Healthy and well-nourished citizens.	

2 RESEARCH QUESTIONS

The key research questions in this enquiry are stated as follows:

- a) *Why are most smallholder farmers in Zimbabwe not effectively using mobile phones for their agricultural activities when they successfully use them daily?*
- b) *What can be done to ensure that smallholder farmers in Zimbabwe can adopt and use mobile phone technologies in their agricultural activities effectively?*

To achieve the research aim, the researchers began by exploring literature to establish why many smallholder farmers in Zimbabwe are not productively using mobile phone technologies in their agricultural information-seeking and sharing activities. The research started with a literature review of articles on Google Scholar covering mobile phone acceptance, adoption, and ultimate usage by smallholder farmers in the developing world. Priority was given to articles on mobile phones and smallholder agriculture in developing countries, especially SSA. After establishing the reasons why most smallholder farmers in Zimbabwe are not fully utilising their mobile phone technologies in their agricultural activities, the research makes suggestions that may be implemented to improve the acceptance, adoption, and eventual usage of mobile phone technologies for agricultural information-seeking and sharing by smallholder farmers in Zimbabwe. The first author then collected empirical data using 16 individual semi-structured interviews with smallholder farmers at farmers' markets in Zimbabwe and a ten-member focus group discussion (FGD) with several stakeholders in the agricultural value chain. The following section looks at the background and context of the study.

3 BACKGROUND AND CONTEXT

Agriculture has historically been a vital sector in the Zimbabwean economy, and due to its vibrance, the country was once lauded as the breadbasket of Africa, dating back to colonial times (Moyo, 2000). So vital is agriculture to the Zimbabwean economy that its current sorry state has a ripple effect across many areas of the country's economy. However, the Fast Track Land Reform Program (FTLRP) of the year 2000 marked a radical change in Zimbabwe's agricultural landscape as agricultural land was transferred from approximately 4 500 white commercial farmers to 130 000 smallholder farmers (Shonhe, 2019). The sudden transfer of land had a detrimental effect on the agricultural and economic fortunes of the country as this faced resistance from the commercial farmers and attracted strong opposition from the international economic powerhouses (USA, UK, among others), as posited by Mazwi et al. (2019). This conflict culminated in the departure of private financial support from financial institutions, resulting in underproduction as crop output significantly declined (Cliffe et al., 2011). This decline continued such that, in comparison with 1990s production levels, maize production had decreased by 65.8%, while wheat had declined by 69.8%, minor grains by 44.2%,

and tobacco output had reduced by 64.7% by the 2007–2008 agricultural season as reported by Moyo (2011).

However, over the years, the government has introduced a raft of heterodox economic and agricultural policy measures like the Command Agriculture Policy, which required farmers to be registered under the scheme and get provided with inputs but were compelled to sell the produce to the grain marketing board (GMB) (Mhaka & Runganga, 2023). The output has remained low, and one of the critical issues cited is the sustainability of these programs. The GMB has been accused of taking time to pay farmers, paying them low prices and, in some cases, below the cost of production. The rapid decline has continued, and as the evolving climate change has introduced frequent droughts in recent years, the agricultural sector has continued to be underproductive. As a result, smallholder farmers in Zimbabwe have remained very poor, and their agricultural production is unsustainable (Tatsvarei et al., 2018). In this context, digital information-seeking in agriculture has become vital.

Smallholder farmers in emerging economies, especially SSA, typically experience the same kinds of issues apart from contextual factors that may be country-specific. ICTs are critical to the socio-economic revolution in SSA and other developing regions. These nations' gross domestic product (GDP) is boosted due to this development. Because of the adoption of mobile technologies (among others), poverty can be eradicated, rural livelihoods – especially smallholder agriculture – can be strengthened, and overall citizen welfare can be raised in any given nation as reported in research by Msendema and Nyirenda (2019), Freeman and Mubichi (2017), Mthoko and Khene (2017), Nyajeka and Duncombe (2022), Govender (2023), and Musungwini et al. (2022), among others. Communication is a precursor to human development, and thus, it is vital to have an efficient information flow for agricultural productivity and improved food security in the developing world, as reported by Tongia and Subrahmanian (2006).

Thus, smallholder farmers must have access to all novel and ground-breaking context-specific agricultural research information relevant to their localities. More smallholder farmers now own mobile phones thanks to Zimbabwe's increasing mobile phone penetration rate, culminating in the falling prices of mobile handsets and the abundant availability of subscriber identity module (SIM) cards (Kemp, 2021). Smallholder farmers in the developing world, especially SSA, provide the bulk of the foodstuffs in their countries, and agriculture is the backbone of those nations' economies. These farmers make up a higher proportion of the population in developing nations, making them crucial (Bisht et al., 2020). Increased access to the most recent agricultural knowledge provides a chance for the growth of smallholder agriculture. In Zimbabwe, a developing country, the mobile phone is the ICT variant in the hands of almost everyone, including marginalised communities like smallholder farmers. Still, its use is intermittent, erratic and flawed.

4 LITERATURE REVIEW

The focus of the literature review is on the acceptance, usage and constraints of mobile phone technology among smallholder farmers in SSA in their agricultural information dissemination and sharing activities.

4.1 Characteristics, challenges and information needs of smallholder farmers

Smallholder farmers mainly grow crops for subsistence purposes. However, research has shown that some have progressed to the extent that they can now grow cash crops but practically rely on family labour. They characteristically have minimal land to farm, do not have entitlement to that land and have limited access to capital, are highly exposed to risk and input technologies, and have limited market orientation (Etwire et al., 2017; Gregor, 2006). Research by Mthoko and Khene (2017) established several characteristics of smallholder farmers in developing nations. Most of these smallholder farmer traits hinder the development of their agriculture outcomes.

Contrary to their counterparts in the developed world, smallholder farmers are among the most marginalised and vulnerable people in the Global South (Kirsten & Van Zyl, 1998; Nkomoki et al., 2019; Van Zyl et al., 2014). Three-quarters of malnourished children found in SSA's rural areas belong to smallholder farmers (Krell et al., 2020). Despite this poverty-stricken tag, smallholder farmers in the developing world have a crucial role in attaining food security and driving agricultural growth to reduce poverty in their nations and on the continent. Studies such as Masuka et al. (2016), Ayanwale et al. (2013), and Kwapong et al. (2020) show that smallholder farmers seem to be more effective and resilient when they have improved access to information, valuable technologies, appropriate marketplaces, reasonable loans, good prices and insurance facilities.

The significant variance in information preferences among rural smallholder farmers can be ascribed to differences in agricultural operations and geographical location. Such variance results in disparities in information demands; however, information needs are generally similar since they revolve around weather, animal and crop farming, pest and disease management, and agricultural markets for agricultural output (Isaya et al., 2018). Researchers have determined that adequately addressing these smallholder farmers' informational demand is essential to the long-term sustainability of smallholder farming across developing nations. There have been calls to solve the looming food crises caused by the growing world population, and smallholder farmers are essential in this matrix.

4.2 Factors affecting mobile phone adoption and use in smallholder agriculture

According to research by Abraham and Pingali (2020) and Masimba et al. (2019), mobile technology adoption by smallholder farmers offers a basis for improving agricultural performance and the potential to achieve SDGs. Adoption strengthens farmer operations and activities and facilitates information dissemination in the field (Batchelor et al., 2014; Kabbiri et al., 2018; Mwantimwa, 2019). However, research has also shown that perceptual issues like usefulness and ease of use significantly impact users' adoption of mobile technology (Barakabitze et al., 2017; Emeana et al., 2020; Wyche & Steinfield, 2016). For this reason, smallholder farmers' perspectives of the role played by mobile phone technology in agricultural activities and the possible benefits perceived should be investigated.

A study by Quandt et al. (2020) established that factors like duration of ownership and digital competency level play a significant role in mobile phone acceptance, adoption and use in agriculture. This finding suggests that farmers who have had a mobile phone for a substantial amount of time are naturally better equipped to operate the device in other activities such as making voice calls, SMS messaging, and internet and other related applications. According to research by Ayim et al. (2022), Kacharo et al. (2018), and Eagle and Saleh (2020), socio-demographic variables also affect farmers' adoption and use of mobile technology to acquire agricultural information on climate and weather conditions, as well as adoption measures. Socio-demographic traits such as age, gender, marital status, family size, size of land held, level of farming experience and ownership of mobile phones are essential to their use of mobile technologies in agriculture. The studies above show that young, married, land-owning male farmers with sufficient farming experience and who own a mobile device are likelier to adopt and use their mobile phone technologies for farming.

Ultimately, ICT4D research attempts to establish the role of ICTs and associated technologies in the development process (Noruwana et al., 2018). ICT4D is premised on harnessing ICTs in poverty eradication, socioeconomic development, human rights and international development, among other domains. That is why policymakers, academia, non-governmental organisations (NGOs), politicians and government agencies have all developed a particular interest in the issue of smallholder farmers' successful acceptance and actual usage of mobile phone technology in agriculture in recent years, at least theoretically. However, in various regions of the globe, ICT4D policies have been developed and implemented, with variable results. What works in one instance does not necessarily work in another.

Theoretical attempts to comprehend local contexts have been at the heart of the challenge. However, studies agree that technology adoption and continual optimal usage occur rapidly and extensively when there is a reasonable knowledge of causal, local and circumstantial factors. Therefore, if ICTs are conceptualised, established and deployed in locally meaningful ways, and if the users embrace them, these ICTs can afford a platform for fostering development agendas in scalable, sustainable and long-term ways.

5 METHODOLOGY

The researchers employed a qualitative approach to explore the challenges confronting smallholder farmers in their quest to adopt mobile phones for agricultural purposes, as posited by Merriam and Grenier (2019). Most technology adoption research like Van Greunen and Fosu (2022), Masuka et al. (2016), Mwantimwa (2019), Kabbiri et al. (2018) and Kacharo et al. (2018) have used quantitative methods, mainly structured surveys. Qualitative research methodology is highly valued when researching the complexities of human behaviour. The research is premised on a 'why' question, typical of qualitative research. Hence a naturalistic methodology has been adopted in the study to help illuminate some key nuances about the mobile phone adoption dynamics among smallholder farmers. The second research question is a what question but builds on the first question. Hence, the qualitative research approach enabled the researchers to explore the participants' underlying motivations, values and beliefs. This research requires cross-sectional data as it explores smallholder farmers' perspectives on the acceptability, adoption and usage of mobile phone technologies across the spectrum rather than their impressions throughout time.

The research study's internal validity is reinforced when the interview guide and focus group discussion guide closely match the constructs and relationships described in the conceptual framework. This alignment guarantees that the techniques for gathering data are intended to gather pertinent information required to answer the research questions and evaluate the suggested theoretical connections. The researchers guaranteed the internal validity of the study by ensuring that the data gathered appropriately represents the theoretical concepts under investigation by creating questions and probes that directly map to the major constructs, see Section C of the interview guide (Appendix A) and Section B of the focus group discussion guide (Appendix B).

Data was mainly collected from smallholder farmers, while agricultural extension service staff and other vital informants in the value chain were also chosen as relevant populations. All 16 interviewees were smallholder farmers and the focus group participants included smallholder farmers, agricultural extension officers and other key stakeholders in the agriculture value chain. Participants were purposefully chosen to meet a variety of variables like their age, gender, level of education, family size, and farming experience to ensure a representative sample. Focus groups allow participants to build on each other's ideas. They can lead to more discussion than individual interviews since they allow for greater closeness and depth of information (Krueger & Casey, 2014). Participants may feel more at ease in a focus group. Still, it may be preferable to conduct individual interviews if the subject matter is sensitive (such as poverty or a lack of understanding of mobile phone use). Focus groups and interviews produce data with the same level of detail. This research used 16 interviews and one focus group to complement one another and ensure that multiple data sets were gathered. The focus group discussion was necessary to validate and amend the data obtained from the 16 individual interviews, thus leading to data saturation.

Observations were carried out in the three markets before the interviews were carried out. These markets have different capacities and clientele. Mbare Farmers' Market, located in Harare is the biggest and most active market in Zimbabwe. Kombayi Farmers' Market is located in Gweru, the third largest city, while the Gokwe Farmers' Market is more of a local market for the Gokwe South District. The first author observed smallholder farmers in the early morning hours as they interacted naturally with vendors in buying and selling agricultural products at each farmers' market (Armstrong, 2010). Naturalistic observation was applied in the initial observation at each market. However, as observation was a continuous process, participant observation ensued – as the first author carried out interviews, he also continued to observe the actions, activities and interactions. Seven participants were purposefully selected at the Mbare farmers' marketplace, five were chosen at the Kombayi farmers' marketplace, and four were selected at the Gokwe South District farmers' marketplace. Farmers were very busy, and some could not agree to set aside up to 40 minutes of their time for the interview as the interviews ranged from 27 minutes to 40 minutes in duration. The data from the 16 in-depth interviews, bolstered with the ten-member focus group discussion, provided valuable information for our research.

The interview participants were given code identities as Smallholder Farmer Number SHF [1-16] for anonymity purposes (Saunders et al., 2015). The 16 interviewees were rich cases; hence, they became critical informants as they possessed vital traits that the researchers desired for this study (Dworkin, 2012). Our sample number falls within the range of sample populations (15 to 25) in line with Marshall et al. (2013), Sandelowski (1995), and Vasileiou et al. (2018) and has been used by most previous researchers; see Kirsten and Van Zyl (1998), Nkomoki et al. (2019), and Van Zyl et al. (2014). The focus group discussion participants were given code identities as Focus Group Discussion Participant Number FGDP[1-10] for anonymity purposes. The details of participants to the FGD are shown in Table 2, summarising their life responsibilities, gender and the number of years that each has owned a mobile phone.

Table 2: Focus group discussion participants

Participant	Code	Mobile phone	Type of handset	Gender	Period of mobile phone ownership
Cotton Company of Zimbabwe representative for the Gokwe South District area	FGDP1	Yes	Smartphone	Female	8
Smallholder farmer	FGDP2	Yes	Smartphone	Male	11
Smallholder farmer	FGDP3	Yes	Smartphone	Male	10
Agricultural extension services officer	FGDP4	Yes	Smartphone	Female	7
Agricultural extension services officer	FGDP5	Yes	Smartphone	Female	6
Net One representative at Gokwe South District centre	FGDP6	Yes	Smartphone	Female	5
Econet representative at Gokwe South District centre	FGDP7	Yes	Smartphone	Male	9
Village head 1	FGDP8	Yes	Smartphone	Male	12
Village head 2	FGDP9	Yes	Smartphone	Male	15
eMkambo employee	FGDP10	Yes	Smartphone	Male	7

Qualitative methods enabled the researchers to explore the complexities of smallholder farmers and the social and cultural reasons that stimulate their adoption and use of mobile phones (Erlingsson & Brysiewicz, 2013). A qualitative approach is anchored on an inductive technique, and thematic patterns emerge from the data as a precondition for the study to align with the recommendations (Williams, 2000). However, this research applied an abductive technique as it fused tenets of deductive and inductive reasoning.

The transcription and coding process of the FGD and interview data resulted in coded data grouped according to the collective factors unveiled among FGD participants and interview participants. The data analysis approach, rooted in a bottom-up or abductive methodology, aimed to capture the nuanced perspectives of smallholder farmers regarding their adoption and use of mobile technologies in agricultural activities. The researchers followed the process for thematic analysis outlined by Braun and Clarke (2006). This involved familiarisation with the data corpus, categorisation and generation of initial codes, pattern identification, and critical theme evaluation and refinement. The researchers finally developed a thematic table to categorise and illustrate the relationships between themes and their associated codes, clearly representing the findings.

6 FINDINGS

Observational studies were carried out in the three markets before the interviews in this study. The first author observed smallholder farmers interacting with vendors without interference or manipulation at each farmers' market. The goal of this process was to gain an understanding of the relationships and interactions between smallholder farmers and vendors without directly manipulating them. Demographic data, such as the educational background of research participants, was used to evaluate the overall literacy level and gauge the potential knowledge level of participants when analysing the findings. The researchers wanted the smallholder farmers' overall farming experience to provide perspective into farmers' tenure as crucial because experience is a key factor influencing the acquisition of technological developments.

Of the 16 research participants chosen for the interview, nine were male, and the other seven were female, making 56.3% male and 43.7% female participants. Participants were between the ages of 38 and 54 at the time of the empirical fieldwork. The first author interviewed farmers with agricultural experience ranging from ten to more than 20 years at farmers' markets. Farmers in this study had a high degree of basic literacy as they had all completed at least an ordinary level of education schooling. Most children go through two years of early childhood learning after age four. They enrol in primary education for seven years at age six, culminating in a Grade 7 Certificate. At 13, the learners enrol in secondary education, which lasts six years and consists of lower and upper secondary education. The lower secondary educational level is the Ordinary (O) level, taking a four-year cycle (from Form 1 to Form 4), which leads to the awarding of the 'O' Level Certificate of which one is required to have attained an A, B or C symbol in at least five subjects including English language and Mathematics for one to be awarded a complete 'O' level certificate.

However, it was not within the scope of this study to determine whether these participants had completed and passed the 'O' level examination. A high school education is sufficient for someone to read, write and comprehend things, which is necessary for a mobile phone to be used competently. Figure 2 summarises demographic profile data for the research interviewees in this research.

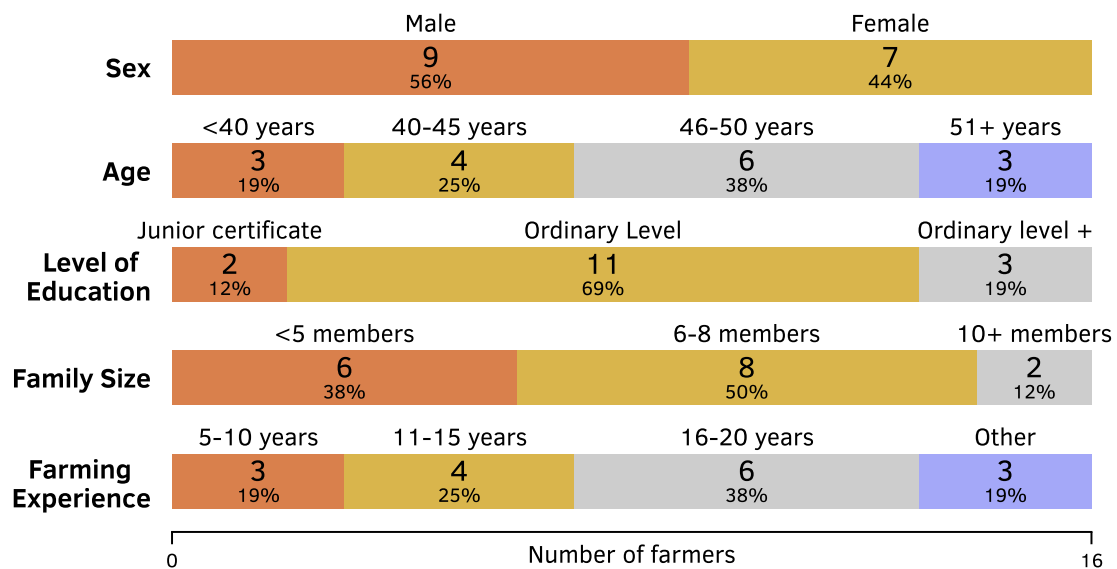


Figure 2: Summary of demographic data of interviewed smallholder farmers

Focus group participants boast a great deal of experience using mobile phone technologies. They are all directly involved in smallholder agriculture, as some were established smallholder farmers. General findings indicate that farmers mainly produce field crops, followed by horticulture, livestock, and poultry. The crops vary, but there is a convergence on cereals, with maize being identified as the major product because it is the primary food source for most Zimbabweans.

Smallholder farmers face myriad challenges in carrying out their agricultural activities, including lack of capital, high costs of inputs, late delivery of inputs from the government, drought, pests and diseases and lack of lucrative markets for their produce. Rudimentary and uncoordinated infrastructure like roads and bridges result in steep transport costs. Several measures proposed include delivering government input schemes on time, contract farming partnerships between organisations like the Cotton Company of Zimbabwe and farmers, input loan schemes and cattle loan schemes. Suggestions also included organising farmers into groups and providing them with loans for farming supplies or cattle collectively, rather than individually. FGD participants indicated that while agricultural extension service officers are mandated to supply all agricultural information and knowledge to smallholder farmers in their areas of supervision, it is now practically difficult for these officers because they are now limited by the lack of resources, such as motorbikes, for use in their everyday operations. How-

ever, these general findings are not directly relevant to our research question. The following sections present more nuanced findings relating to our research questions.

6.1 Factors having an impact on the acceptance, adoption, and sustainable use of mobile phones by smallholder farmers

According to research participants, using mobile phone technologies for agricultural information dissemination is very beneficial to farmers. Farmers demonstrated that they obtain meteorological information through their mobile phones in part. Some farmers indicated that they call or message (SMS or WhatsApp) their customers and arrange for them to pick up their items, which are delivered by buses to different towns. Some farmers band together and create a club, taking turns accompanying their products to marketplaces. Some farmers have developed ties with many vendors in various marketplaces, and they constantly enquire about prices before deciding to sell to specific markets. The research suggests that deciding which market to sell their products in will be based on comparing pricing in the various markets. One interviewee at the Mbare Farmers' Market had this to say:

I am from Mutoko village and have been a farmer for the past 23 years. My phone was purchased in 2003. I am on my sixth phone, a Smartphone ... I switch between Econet and Net One lines [SIM cards]. [Econet] Buddy Econet is quite helpful since I get money from several customers via Ecocash ... I brought several things from my club members for their consumers. Customers arrived, got their products, and then contacted farmers from my area to confirm receipt of goods. Depending on their arrangement with the farmers, some merchants will transfer the money to the farmers' phones via Ecocash, while others will hand me the cash. [SHF3]

Other farmers interviewed at farmers' markets confirmed this. The interviewees utilised their mobile phones to call/WhatsApp/SMS the various markets at various times, and some joined WhatsApp groups with farmers and merchants as members. They talk about anything related to agricultural produce and pricing. Farmers demonstrate that mobile phones are assisting them because after calling different markets, they discover slight variations in prices in different markets; however, considering all factors, such as transportation costs and inconveniences, as well as the time spent travelling, they often settle for markets close to them. Another interviewee had this to say:

In my farming routines, I rely heavily on my cell phone, which is highly handy for exchanging agricultural information with other farmers and traders. Econet is more beneficial for me since the other networks are not available in Gokwe. [SHF2]

Another interviewee weighed in on this:

Buddie is a treasurable asset for the transfer of money from clients via Ecocash. The Smartphone cost me US\$150, and the feature phone cost me US\$25. I buy data for Z\$10 per

week (Z\$40 per month) for my Buddie and Z\$10 for my NetOne for phone calls and SMS.
[SHF6]

According to the respondents, high internet costs, voice calling, and handsets influence their intentions to use mobile phones. Except for four smallholder farmers questioned at the Gokwe South District Market, 12 farmers interviewed in Mbare and Kombayi farmers' markets possessed smartphones. Although there was much talk about most farmers buying used smartphones, three demonstrated that they purchased their mobile phones as new. Farmers interviewed at Gokwe market claimed they could not afford a smartphone because the costs were too exorbitant compared to their earnings from their produce, which were already low given their obligations to provide for their large families. The respondents demonstrated that they could use mobile phones and found them highly beneficial.

My phone helps me a lot ... but acquiring it was difficult ... I bought this smartphone by chance, and it was pre-used. I am not knowledgeable about using it as well. It requires data to be more useful, but it is very expensive to buy data.
[SHF12]

Another farmer had this to say:

However, to make my data last longer, I disable all other programs from updating and checking WhatsApp messages as frequently as possible, but I must turn off the data connection for it to last longer.
[SHF7]

According to the women farmers interviewed, society has no prejudice about their usage. The farmers showed that mobile phones are very compatible with their activities as they move around; when they receive new valuable information when travelling to other places, they change their destination. However, the farmers indicated that not all smallholder farmers use mobile phone technologies in their everyday agricultural activities for various reasons. Some reasons include the erratic network, which results in most farmers facing network blackouts in their areas or when travelling, thereby missing some crucial messages. Some missed messages would contain crucial actionable information, which they would have failed to take. Rural farmers typically only have access to the Econet network in the rural areas where they originate from, which limits their options for network subscriptions. Mobile phone handsets are a challenge for most farmers. Still, the major challenge is a low level of technical know-how among most farmers, and this limits their inclination to acquire (new) mobile phones.

In Zimbabwe, a sizeable segment of the populace, especially the disadvantaged, owns a mobile phone. Nevertheless, the challenge was using phones for agricultural purposes. Mobile phones can deliver actionable, ground-breaking, and context-specific information to farmers in actual time. This can reduce arbitrages as farmers communicate in real-time, saving them time and energy and consequently boosting production. FGDP1 had this to say:

I feel that the mobile phone is useful in the everyday life of a farmer as agriculture is information-centric. It requires information actionable in actual time at the point in time. Cottco occasionally provides information to cotton farmers ... it is not as frequent.

Mobile phones enable farmers to access services, lucrative agricultural markets for their produce, and nascent farming technologies.

I am using a smartphone, but the cost of data is very high for a farmer. My sister in Botswana bought the phone for me. The mobile phone is handy in the work of a farmer because the market for farm produce is very volatile, and the prices can change in any instance. You can get the information that tomatoes are selling for Z\$250-00 a bucket at Mbare and Z\$300-00 in Bulawayo, but when you travel there, you will not find customers buying for that price.
[SHF14]

Participants in the FGD agreed as a group that Gokwe South District had a high percentage of mobile phone penetration as suggested by FGDP7, a representative of Econet in the area:

There is a high level of mobile phone ownership in Gokwe, particularly from an Econet perspective. Given the statistics of mobile phone users of our services, I would like to believe a good number of people in the area have mobile phones if they are farmers.

Not every farmer has a mobile phone, but almost every household has at least some kind of mobile phone. Some households have two or more mobile phones. Other households have a smartphone, while most households have feature phones. The FGD also pointed out that farmers may have a SIM but no handset in some situations. These farmers usually seek to use their colleagues' handsets. FGD participants indicated that a few farmers get information on agricultural issues through their mobile phones, and FGDP7 pointed out:

Econet has a mobile phone service called EcoFarmer where all registered farmers receive agriculture information, however, only those who would have subscribed to the services.

However, this position was said to be very limited as many farmers are not subscribers of the service in Gokwe South District. Below is an extract of the statement by one FGD member, an agricultural extension officer in Gokwe South District.

... all agriculture information about crops, inputs, pests, and diseases, whether broadcasted on the radio ... but it is general and not geographically specific and not actionable by farmers. ... Agricultural extension officers are always on the ground relaying any critical and ground-breaking information to farmers. ... if [I] get anything critical that should be communicated to farmers, even if it is broadcasted on the radio. It is my responsibility to ensure that the information has reached all farmers in the area which I preside over. However, given the challenges of transport and the area size that I should cover ... I have now turned to the mobile phone. Most households have mobile phones and I have their mobile phone numbers ... I buy bulk SMSs from the telecommunication services provider. I then broadcast one message to all farmers advising them of a meeting at a viable position and time ... There are five meeting points in my area and each meeting point has two farmers that I appointed to lead. I then record myself explaining everything and then send the recording to each of the farmers leading at the meeting points. There are different times for distinct meeting points

... when it is time for the meeting, the audio is played, and everyone will listen. If there are questions from any farmer, they are noted down. One of the meeting leaders will then call me and give me the questions ... I will then advise the person who called to put the phone on the loudspeaker. ... I will then address every question raised at that meeting. ... This happens to all groups. [FGDP5]

Some farmers receive agricultural information, especially from the agricultural extension officers, using their mobile phones, but very few directly access, enquire or search for information for themselves. FGDP4 said this:

I have some farmers who have been so enthusiastic about using mobile phones ... these farmers have created WhatsApp groups where they discuss and interrogate issues ... I am a member of such groups.

Base station infrastructure is lacking, which causes the availability of the network to fluctuate as pointed out by FGDP7: *“Infrastructure is a real challenge and I agree”*. The proliferation of cheap, poorly manufactured nameless handsets of poor quality is problematic as these phones malfunction in a brief period after their acquisition. As one participant suggested:

Farmers are also exposed to dealers who sell counterfeit handsets; these are phones that would appear reasonably priced and affordable for their appearance, and unsuspecting farmers are attracted by that. [FGDP10]

Perhaps this is a result of the steep price of authentic mobile devices considering the farmers' incomes. Participants also talked about the cost of general mobile phone services and specific agricultural services and applications. FGDP3 pointed out that:

... the cost of mobile phone agriculture applications and services is very high and is not affordable for many ... erratic network availability, only Econet is found in many places.

The other challenges identified by the FGD participants include illiteracy (as some farmers may not be digitally skilled to operate mobile phones), old age, gender dynamics and the socioeconomic status of some farmers. FGDP4 suggested that *“education and training of farmers are critical.”* POTRAZ, which is the regulatory authority, should gazette affordable prices for telecommunication services and lobby companies that provide mobile agricultural applications and services like EcoFarmer, eMkambo, Mubatsiri and ESOKO, among others, to reduce their current prices for the use of their services. It was also noted that agricultural extension officers must be trained about any mobile phone agricultural service. They should teach farmers as they greatly influence the farmers; farmers listen to them and have hero worship for them.

The mobile telecommunication operators and other application developers should engage agricultural extension officers in the area where they want to deploy their applications and services before launching them ... an educated farmer is informed and empowered to act and put into practice what they know. [FGDP5]

The research participants highlighted the need for smallholder farmers to be trained and empowered on effective ways of using mobile phone applications in agriculture.

The agriculture department should disseminate all agricultural information about crops, inputs, pests and diseases, and the weather by broadcasting through mobile phones. [FGDP9]

Econet has embarked on an exercise to push the adoption of its mobile phone service called EcoFarmer through its network of agents, where all EcoCash agents in farming areas encourage farmers to register on the EcoFarmer platform. It then involves the farmers in some promotional activities where they win prizes.

... They are also given promotional regalia ... We have just registered farmers in Gokwe, and I think bit by bit we will get there with the support of other stakeholders like agricultural extension and chiefs and village headman we will get there. [FGDP7]

An organisation like Econet could also look at its capacity and develop contingent measures for farmers' handsets, contracting a vendor to supply mobile phones for farmers at concessionary rates.

The researchers tabulated the themes that emerged from the in-depth interviews and FGD data with thematic information on the prospects of mobile phone technology, the challenges associated with using it, and possible solutions. **Table 3** presents the thematic analysis data from the 16 individual interviews and the focus group discussion.

Table 3: Thematic analysis of mobile phone capabilities, challenges faced by smallholder farmers using them for agriculture and proposed solutions.

Statement	Codes	Themes
<ul style="list-style-type: none"> - I feel that the mobile phone is very useful in the everyday life of a farmer as agriculture is information-centric. - Cotteco occasionally provides information to cotton farmers. - I bought my phone 12 years ago. - I am using a smartphone and I can say this is my fifth handset. - Econet is very useful because I receive money from many customers through EcoCash. - The mobile phone is precious to me in my farming activities. It is useful for agriculture information sharing with other farmers and vendors. 	<p>Mobile phone capabilities</p> <ul style="list-style-type: none"> - It is a means of learning. - It is a communication gadget. - It can significantly reduce information acquisition costs. - It can ease information asymmetry. - The mobile phone can be a conduit for agricultural information like climatic circumstances, weather, input prices, the market price for products, diseases, and other cataclysms in real-time. - It can reduce losses of perishable agricultural produce. - It is capable of accelerating knowledge-sharing. - It can facilitate financial service options and money transfers between buyers and sellers. 	<ul style="list-style-type: none"> - Tool for communication, learning and banking services. - Payment facility

[Continued ...]

Table 3: [...continued]

Statement	Codes	Themes
<ul style="list-style-type: none"> - Infrastructure is a real challenge. - Farmers are exposed to dealers who sell counterfeit handsets, at low prices that are not durable. - The cost of mobile phone agriculture applications and services is very high and is not affordable for many. - There is the problem of an erratic network. - I alternate [between] Econet and NetOne lines. - I use a smartphone, but the cost of data is very high for a farmer. 	<p>Challenges of using mobile phones</p> <ul style="list-style-type: none"> - There is a lack of infrastructure. - There are counterfeit mobile phone handsets. - Mobile handsets are costly. - There is an erratic network. - There is low ownership of mobile phone handsets. - There is a high cost of mobile phone technology services like data. - There is a lack of digital skills. - Mobile phone technology applications are complex. 	<ul style="list-style-type: none"> - Poor infrastructure - Costly mobile phone services
<ul style="list-style-type: none"> - Education and training of farmers are critical. - Mobile telecommunication operators and other application developers should engage agricultural extension officers in the area where they want to deploy their applications and services before launching them. - The government should educate and train all farmers about using mobile phone applications in their agricultural activities. - At the time of carrying out this research, Econet was registering farmers and giving promotional regalia like t-shirts and caps to wear. 	<p>Suggestions to address the challenges of using mobile phones.</p> <ul style="list-style-type: none"> - There is a need for the training of farmers. - There is a need to engage an Agritex officer to deploy mobile phone technologies before launching them. - The government should facilitate the training of farmers by equipping Agritex officers. - There is a need for private sector involvement. - There is a need for the erection of base stations in most rural areas. - POTRAZ should regulate the prices of mobile phone technology services. 	<ul style="list-style-type: none"> - Training empowerment - Partnerships

7 DISCUSSION

7.1 Why many smallholder farmers do not effectively use mobile phones for agricultural activities

The research found a high level of mobile phone ownership and general use in Zimbabwe. However, there is a problem with the low adoption and usage of mobile phone technologies for agricultural purposes in Zimbabwe. Low adoption was attributed to smallholder farmers' alleged lack of technical expertise and the exorbitant cost of mobile phone handsets and related agricultural applications and services, including data, which many people cannot afford. The focus group participants mentioned that some farmers have mobile phone SIM cards but no handsets, suggesting that the situation in the study location (Gokwe South District) may differ from that in other parts of the nation. Hence, the inability to utilise a mobile device without owning one affects using mobile phones. The results suggest that smallholder farmers' aspirations to become more productive are affected by the high cost of mobile phone technology and related services like mobile agricultural applications, cost of calling, data, level of

education attained, their age and gender, as well as the complexity of mobile phone technology applications. These findings tally with findings by Masuka et al. (2016), Weigel et al. (2014), Masimba et al. (2019), Mwantimwa (2019), Kabbiri et al. (2018), and Batchelor et al. (2014) among others.

The study found that some of Gokwe South's smallholder farmers are frequently without smartphones and dependable internet access, which limits their exposure to digital technologies and makes them less confident when using mobile agricultural apps. As a result, their digital literacy is low. The intricacy of these applications and the perceived challenge in using them hold back farmers from making full use of these resources. This presents a major obstacle to the uptake and use of mobile agriculture apps like ESOKO, eMkambo, EcoFarmer, and Mubatsiri among others.

The study found that smallholder farmers may benefit from employing mobile phones in their farming operations. The results of this study suggest that older, uneducated female smallholder farmers who do not own mobile phones are prevented from adopting and using mobile phone technologies in their daily agricultural information-seeking and sharing. In contrast, younger, educated male smallholder farmers who own mobile phone technologies are better equipped to adopt and use them in agricultural information-seeking and sharing. The research is qualitative and a small sample with deeper nuances was used, hence the findings may need to be investigated further using the quantitative approach for generalisability to other contexts.

7.2 Proposed solutions to increase adoption

Historically, agricultural extension service officers in Zimbabwe provided all agricultural information and solutions. However, these officers are now handicapped by the unavailability of resources like motorbikes for use in their daily operations; hence, they face challenges when disseminating agricultural information to smallholder farmers in their areas of supervision. Participants cited an array of uses for the mobile phone, such as a fundamental communication tool, a tool for learning, a banking tool, and a payment system, among other things. These uses suggest that the mobile phone is an asset that can reduce agricultural information collection costs and ease information disparity among smallholder farmers if it is effectively used. These findings corroborate with research by researchers such as Misaki et al. (2018) and Chikuni and Kilima (2019), that pointed out challenges confronting smallholder farmers in finding agriculture information and the usefulness of mobile phones. Therefore, the sustained usage of mobile phones for agricultural information dissemination purposes has the potential to lessen agriculture production losses and accelerate information transfer. It may result in the improvement of smallholder farmers' agriculture outcomes in Zimbabwe.

The results suggest the need to work with the agricultural extension services department as they are vital in the agriculture value chain to ensure that farmers use their mobile phones productively for agricultural reasons. The government could also help farmers get the training they need to use their mobile phones in a way that would benefit them. Effective use can be

achieved by providing agricultural extension service officers with the tools and authority to guarantee that smallholder farmers are informed about using agricultural mobile phone applications. The above recommendations align with findings by Van Loon et al. (2020), which established the role played by the key stakeholders in adopting, using and scaling new technology in agriculture across three continents. The results suggest that agricultural extension service officers are naturally interested in this project because they stand to gain from it. This research has previously shown that mobile phones can enhance their work. This tallies with research by Masuka et al. (2016), Musungwini (2016), and Misaki et al. (2018), which established that smallholder farmers have the potential to become more productive and contribute to the development and growth of their economies if their conditions are improved, especially agricultural information access.

The findings also suggest that it would be necessary to categorise these farmers according to their socioeconomic situation and demographic factors and create purposeful training programs aimed at encouraging these smallholder farmers in Zimbabwe to accept and use mobile phone technologies. The findings imply that the government or its agents should educate and train all farmers in using mobile phone applications in their agricultural activities, including information about crops, inputs, pests, diseases and meteorological information delivered via mobile phone technologies. Since most rural areas require the construction of base stations, private sector engagement may be necessary. In most countries, the private sector usually deals with this issue. According to Simuka and Chinakidzwa (2022), the government of Zimbabwe has mandated that the country's Postal and Telecommunications Regulatory Authority of Zimbabwe (POTRAZ) levies a 5% tax on telecommunication companies' profits through the Ministry of Finance and Economic Development to finance the construction of telecommunication infrastructure in rural and other areas where the companies deem it to be uneconomic to set up such infrastructure. If the Zimbabwean government is serious about achieving its national development strategy [Vision 2030], it should ensure that the revenue collected through this levy is used responsibly for setting up telecommunication and other infrastructure in rural areas where smallholder farmers are situated.

Additionally, the results suggest that POTRAZ should monitor the prices of mobile phone technology services to ensure that they are affordable for a wide range of individuals, particularly the disadvantaged, such as smallholder farmers in the Zimbabwean context. Prohibitive costs seriously hamper mobile technology's acceptance, adoption and continuous use. The research's conclusions are important because they can directly affect the achievement of SDGs 1, 2, and 3 and indirectly affect other SDGs in the development framework if the challenges presented are resolved. As was previously noted, attaining the SDGs also means meeting the Agenda 2063 objectives of the African Union and goal 1: "*A High Standard of Living, Quality of Life and Well Being for All Citizens*", goal 3: "*Healthy and Well-nourished Citizens*", goal 4: "*Transformed Economies*" and goal 5: "*Modern Agriculture for Increased Productivity and Production*". On the local front, the research findings have direct implications for the National Development Strategy 1 (NDS1), which seeks to increase Zimbabwe's level of food security. The macroeconomic measures developed by this plan also aim to improve smallholder farmers'

agricultural output and productivity to, among other things, ensure that their families have access to a sufficient supply of food and nourishment, and addressing the issues identified in this research is one way of ensuring the attainment of Vision 2030.

Other issues found The study also established that smallholder farmers in Zimbabwe, like their counterparts in other countries in SSA, engage in various agricultural activities, including field crop production, market gardening, poultry and livestock keeping. The research also established that farmers face multiple challenges ranging from drought, new and constantly evolving pests, bugs and diseases, low market prices for agricultural produce, and inconsistent government policies. Smallholder farmers in Zimbabwe are involved in many farming initiatives to boost their living standards but face inherent and manufactured obstacles that endanger their way of life. The research participants made recommendations that, if heeded, could help lessen the challenges smallholder farmers face practically every day. The farmers proposed that the Zimbabwean government publish feasible crop producer prices quickly and include farmer representatives in crafting agricultural policies, such as debates on the publication of crop producer prices. These findings tally with the literature carried out by Musungwini (2018), Dube (2020), Khan et al. (2019), and Mittal and Mehar (2016), among others.

Practical implications This research has practical implications for policy and practice. The government of Zimbabwe may craft legislation promoting the proliferation of mobile phone handsets, which may reduce their prices and increase affordability for smallholder farmers and other marginalised groups in Zimbabwe. The government can incentivise telecommunication operators by subsidising mobile services for development-oriented activities like agriculture, health and other productive service areas. The government may also make it mandatory for all agricultural extension officers to be trained and equipped with knowledge on how to use mobile technologies effectively to impart the knowledge to smallholder farmers as they work directly with them. The initiatives above enable the attainment of the country's Vision 2030, The United Nations SDG goals 1, 2 and 3, and The African Union Agenda 2063 goals 1, 3 and 5.

Theoretical contributions This research developed and used an eclectic model with nine (9) constructs, namely Perceived Expressiveness (PE), Perceived Mobility (PM), Perceived Support of Service Provider (PSoSP), Perceived Compatibility (PComp), Perceived Ease of Use (PEOU), Perceived Costs (PC), Perceived Usefulness (PU), Perceived Subjective Norms (PSN) and Perceived Behavioural Control (PBC) – see [Figure 1](#). The findings suggest that smallholder farmers in Gokwe South are wary of the perceived lack of support from service providers in addressing their unique challenges, such as addressing network outages, providing affordable data plans, or offering specialized agricultural services and content. This perceived lack of support can create a sense of uncertainty and distrust, further discouraging the adoption of mobile phones in their agricultural activities.

The research also established that, for most smallholder farmers, the cost of mobile phones and their associated services is a significant obstacle to their adoption and use of mobile phones in their agricultural activities. Because the cost price is a fundamental feature of an artefact (such as a mobile phone) or a service (such as voice calling, SMS messaging or WhatsApp) and cost perception is a secondary characteristic, the research aligns with Moore and Benbasat (1991) who contends that a person's impression of cost differs from the actual cost of a good or service. In terms of perceived cost, adopters (smallholder farmers in this case) consider the price of mobile phones and their associated services relative to their disposable income; as a result, perceived cost is contingent upon the disposable income of the individual smallholder farmer. Therefore, transparency (such as tariff models and cost per minute) and monetary expenses (such as acquisition and usage charges) are two aspects of perceived costs.

This research found that their perception of costs significantly predicted smallholder farmers' propensity to use mobile devices. The paper explains the factors causing non-adoption and a prediction of the non-adoption of mobile phone technologies for agricultural purposes in the Zimbabwean context. The intricate interplay of the eclectic model constructs, namely Perceived Costs, Perceived Mobility, Perceived Ease of Use, Perceived Usefulness, Perceived Compatibility, Perceived Support of Service Provider, Perceived Subjective Norms, and Perceived Behavioural Control helps to explain the non-adoption of mobile phones by smallholder farmers in developing regions. Understanding and addressing these factors is crucial for promoting the effective integration of mobile technology in agricultural development initiatives. The research makes a theoretical contribution to the body of literature. From a Zimbabwean perspective, it offers a better understanding of smallholder farmers' non-adoption of mobile phones for agricultural purposes. The findings can be generalisable to other contexts where they may be needed for a deeper understanding of analysing and explaining (non-)adoption.

This research concurs with findings by Etwire et al. (2017), Merriam and Grenier (2019) and Krueger and Casey (2014), who established the importance of socioeconomic factors as espoused in technology adoption models like TAM (Yousafzai et al., 2007), TRA (Loken, 1983), TPB (Weigel et al., 2014) and DOI (Rogers et al., 2019) among others. The findings suggest that most smallholder farmers in Zimbabwe own mobile phones and competently use them. However, the research established that most farmers were not using their mobile phones for agricultural purposes due to various dynamics and primarily because of a lack of support from telecommunication service providers. These factors provide a novel explanation of smallholder farmers' non-adoption of mobile phones in Zimbabwe.

Limitations of the research Smallholder farmers in Zimbabwe are scattered across multiple areas like small-scale farms, resettlement sites and tribal trust grounds known as 'reserves'. Gokwe South District is merely one district with a substantial farming population; hence, the experiences of Gokwe farmers, agricultural extension service officers, other FGD participants, and the 16 interviewees do not necessarily reflect the views of all smallholder farmers in Zimbabwe. Furthermore, while interviews and FGDs are helpful techniques for gathering qualitative research data, they have flaws that may influence the research findings. Some

focus group contributors may overshadow the conversation, and the interviews are costly in resources and time-consuming; hence, only a small sample was used.

8 CONCLUSION AND RECOMMENDATIONS

The research was undertaken because there is a lack of acceptance, adoption and sustained usage of mobile phones for agricultural purposes by smallholder farmers in Zimbabwe but the reasons for the low adoption had not been explored satisfactorily. Understanding the reasons for the disappointing adoption of agricultural applications (such as ESOKO, eMkambo, EcoFarmer, Mubatsiri and others) may help researchers, developers and software companies to improve their app designs and ways to roll out new software in rural areas. A naturalistic methodology, within an abductive approach, was used in the study to help elucidate some important intricacies about the adoption dynamics among smallholder farmers.

The research found that smallholder farmers in Zimbabwe face several impediments to adopting and using mobile technologies, including limited access to mobile phone services, lack of technical knowledge, high cost of mobile phones and inadequate infrastructure. Farmers are essential for economic growth and eradication of poverty in rural families and the country in general. However, farmers face numerous obstacles that limit their output, including timely agricultural information when it is most needed. Additionally, crop and animal diseases are constantly changing, and while there are mobile agricultural applications to assist in such circumstances there are many challenges that need to be addressed for adoption by smallholder farmers to be realised. Hence, there is no readily available solution at the moment, leaving smallholder farmers exposed to real time actionable information challenges.

The research makes a theoretical contribution to better understanding the critical factors that inhibit the adoption of mobile technology in marginalised settings. The eclectic model with nine constructs, developed and used to guide the empirical work, proved to be a useful framework to study an environment with a high mobile penetration but disappointing use in agricultural settings. The model could be useful in other environments showing similar discrepancies.

An improvement in smallholder farmers' awareness of mobile technologies and adequate training to enable them to utilise their mobile phones efficiently in their agricultural activities, coupled with favourable policies that encourage the development of user-friendly and affordable applications, may enhance uptake. In addition, many of the above difficulties may be significantly reduced by promptly providing smallholder farmers with crucial information. The research recommends possible avenues for future researchers to explore, for example, analysing the effect of mobile technologies on smallholder farmers' productivity and income or assessing the impact of mobile phone technologies on the gender dynamics of smallholder farming households. There is a need to develop strategies, models or frameworks to increase smallholder farmers' access to mobile technologies, improve affordability and network availability and equip them with digital skills, which may lead to improved usage. Future researchers may carry out quantitative studies using a larger sample size to evaluate our findings.

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A THE INTERVIEW GUIDE

Dear respondent,

This interview guide was prepared to collect data regarding the current state of mobile phone availability, accessibility, adoption level and mobile phone user ability of smallholder farmers in Zimbabwe. You are free to provide your responses to the questions. Your responses will be confidential.

General Information

Ward Village of Origin

Section A: Respondent' Characteristics

DEMOGRAPHIC CHARACTERISTICS *STATUS*

- A1 Sex of respondent.
- A2 What is your age?
- A3 What's your marital status?
- A4 How many family members do you have in your family?
- A5 Are you able to read and write?
- A6 What level of education did you acquire?

Section B: Interview Questions Regarding Agricultural Activities

- B1.** How big is your farming land?
- B2.** Which crops are you producing on your farmland?
- B3.** Do you have livestock?
- B4.** What are the major challenges that you face in your agricultural activities?
- B5.** What do you think should be done to overcome these challenges?
- B6.** Do you depend on agriculture only for income for your family?
- B7.** How much money do you get from your agricultural activities per month/year?

Section C: Interview Questions regarding Mobile Phone Availability, Accessibility, Level of Adoption and Usability of Smallholder Farmers.

- C1.** Do you own a mobile phone?

- C2.** How long have you had a mobile phone?
- C3.** Which type of phone do you use and are there any reasons?
- C4.** Which mobile network do you subscribe to?
- C5.** How much did you spend on acquiring your mobile phone?
- C6.** How much money do you usually spend on your mobile phone for airtime top-up and data per month?
- C7.** Are there any challenges that you face regarding the acquisition of mobile phones and airtime and their prices?
- C8.** Do you think you are capable of effectively and efficiently using the mobile phone?
- C9.** Can you state the agricultural activities you use your mobile phone for?
- C10.** In your opinion, do you think the mobile phone and its agricultural applications and services are affordable to farmers?
- C11.** Is the mobile phone compatible with many everyday agricultural activities of farmers?
- C12.** Do you think the adoption of mobile phones can help farmers overcome the challenges of accessing agriculture-related information?
- C13.** In your opinion, what role should be played by mobile telecommunication companies and other agricultural mobile application companies to assist farmers to realise their full potential?
- C14.** What role should the government /government officials play to enable more farmers to use their mobile phones when communicating agriculture-related information?

B THE FOCUS GROUP DISCUSSION GUIDE







Section A

1. What are the agricultural practices that farmers in the Gokwe South District area are involved in?
2. What are the challenges faced by farmers in carrying out their agricultural activities in the Gokwe South District?
3. In your view, how can these challenges be addressed?
4. What are the sources of agricultural information for farmers in the Gokwe South District?

Section B

1. What is the general level of mobile phone ownership in Gokwe South District?
2. What do farmers use their mobile phones for?
3. Do farmers by any chance use mobile phones in carrying out their agricultural activities?
4. How useful is the mobile phone in the everyday life of a farmer?
5. What challenges do farmers in Gokwe South District face as far as using the mobile phone for agricultural activities is concerned?
6. What do you think should be done to address the challenges of using mobile phones for agricultural purposes faced by farmers in the Gokwe South District?

Integrating the TOE framework and DOI theory to dissect and understand the key elements of AI adoption in sociotechnical systems

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ABSTRACT

This study is interested in increasing the likelihood of achieving the organisational adoption of artificial intelligence that has a positive outcome. We argue that the technological-organisational-environmental framework provides a sound theoretical lens for analysing how an organisation's context influences the adoption and integration of artificial intelligence solutions. Furthermore, the diffusion of innovation theory is proposed to identify enablers for transforming organisations. Together with the combination of technological-organisational-environmental and diffusion of innovation, the stages of diffusion are proposed as an evaluation paradigm to evaluate the effectiveness of the enabling factors. Furthermore, the elements and objectives of artificial intelligence adoption in the context of data-driven organisations are included. From this, the research develops a comprehensive framework for studying the technical and social AI adoption elements in an organisational environment where complex symbiotic relationships prevail. This study uses generative artificial intelligence as a novel approach to exploring the framework's usability. The evidence from our research indicates that the developed framework can advance our comprehension of what drives the success or failure of artificial intelligence adoption in organisations. Theoretically, it provides a tool for dissecting and understanding the key elements influencing this process.

Keywords Adoption, Organisation, Sociotechnical, Design Science Research, Artificial Intelligence, Generative Artificial Intelligence, ChatGPT

Categories • Information systems ~ Information systems applications • Computing methodologies ~ Artificial intelligence

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1 INTRODUCTION

Herbert Simon, a pioneer in artificial intelligence (AI), in his landmark study, “The science of the artificial”, explained the difference between understanding the natural and the artificial world (Simon, 2019). Factual sciences explore, describe, explain, and predict phenomena in

Smit, D., Eybers, S., van der Merwe, A., Wies, R., Human, N., and Pielmeier, J. (2024). Integrating the TOE framework and DOI theory to dissect and understand the key elements of AI adoption in sociotechnical systems. *South African Computer Journal* 36(2), 159–176. <https://doi.org/10.18489/sacj.v36i2.17679>

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the natural world. Factual sciences can be categorised into natural and social sciences (Dresch et al., 2015). In natural and social sciences, a positivist paradigm can be applied where quantitative research methods are used (Myers, 2020). A disadvantage of quantitative methods is that they treat many social and cultural aspects of organisations as superficial. The context is seen as noise (Myers, 2020). This specific study is not concerned with natural phenomena; it is interested in investigating the suitability of combining two main theoretical underpinnings, technology-organisational-environment framework (TOE) and the diffusion of innovation theory (DOI), with the aim of gaining insights into AI adoption in an organisational setting, when using a qualitative approach. This is important as the context – often referred to as sociotechnical systems - within which AI systems exist cannot be ignored. Also, the challenges companies face regarding AI adoption include workforce and social (Hyder et al., 2018), which can only be fully explored using a qualitative approach. There have been many publications concerning the adoption of technology, which led to the development of many models, theories and frameworks. Examples of such theories are the technology acceptance model (TAM) (Davis et al., 1989), diffusion of innovation theory (DOI) (Rogers, 1995) and the technology-organisational environment (TOE) (Tornatzky & Fleischer, 1990). AI adoption is at the forefront of computational advancements and represents a “moving target” with its constantly evolving capabilities and leads to higher levels of uncertainty (Berente et al., 2021). These are all unique characteristics of AI adoption and add to the challenge of using existing technology adoption techniques. Therefore, adopting AI can be classified as a spectrum (Lacity & Willcocks, 2021). Adoption is complex and becomes even more so with different levels of adoption, individual or organisational, with organisational adoption being more complex (de Ven, 1991; Rogers, 1995).

Stephen Hawking is famously quoted: “AI could be the best or worst thing to ever happen to humanity. We cannot ignore it”¹. This study is interested in increasing the likelihood of achieving the organisational adoption of AI that has a positive outcome. Furthermore, organisations that fail to adopt AI, will lose out on new business opportunities or optimisation and efficiency potential. Considering the significance of AI adoption and the complex sociotechnical environment, the main research question this paper aims to address is: “*How can the combination of the TOE framework and DOI theory be leveraged to research and increase organisational AI adoption effectively?*”. This research question is in the context of data-driven organisations, where the organisation can be defined as one that acts on observed data rather than merely intuition to achieve financial or non-financial benefits (Anderson, 2015). They effectively use data to enable them to achieve their objectives. Data-driven organisations have the expertise, tools and culture to use data to make decisions (Anderson, 2015; Wixom & Someh, 2018). Furthermore, in corporate social responsibility (CSR), a responsible organisation is concerned about a positive relationship between global organisations and the local society in which they reside, including their employees (Crowther & Aras, 2008).

This study directly extends the paper “Exploring the suitability of the TOE framework and DOI theory towards understanding AI adoption as part of sociotechnical systems” presented at SAICSIT 2023 (Smit, Eybers, van der Merwe & Wies, 2023). It adds to the paper by developing a generative AI application to explore the usability of the proposed theoretical framework. The

¹ The best or worst thing to happen to humanity. Cambridge University – https://www.youtube.com/watch?v=_5XvDCjrdXs, [Accessed 18 April 2023].

TOE framework and the DOI theory are discussed. From this a comprehensive framework is designed. The framework can be used to study the technical and social AI adoption elements in an organisational environment. After that, the development of a generative AI application is explained, along with how it is used to explore and experiment with the usefulness of the proposed framework. In conclusion, the final section of this paper offers a summary and wraps up the discussion.

2 RESEARCH PARADIGM

In social sciences, qualitative methods offer in-depth insights into cultural and social phenomena, utilising tools like interviews and participant observation (Myers, 2020). Information systems research often adopts a positivist approach focused on identifying patterns and laws in organisational behaviour. However, creating and studying new artifacts expose the limitations of traditional quantitative and qualitative methods (Dresch et al., 2015). Pragmatism, as a philosophical alternative, acknowledges a dynamic reality shaped by human action (Goldkhul, 2012). It diverges from the realism of positivism and shares qualities with interpretivism, both commonly associated with qualitative research. Yet, unlike interpretivism's sole focus on subjective interpretation, pragmatism emphasises active engagement with the world. This is particularly relevant for research on transformational change, where positivism and interpretivism may fall short (Gioia & Pitre, 1990).

The pragmatic philosophical framework emphasises using empiricism for practical purposes while recognising the importance of both physical and social aspects of reality (Litchfield, 2009). In the context of AI adoption, this means that while technical considerations are important, the focus is on the organisational adoption process, which must also account for social factors like culture and human capabilities across the organisation. Pragmatism can be a valuable framework for information system (IS) research as it allows for a holistic approach which allows the researcher to deal with the rapidly changing IS environment (Litchfield, 2009) and focuses not only on what is but also on what might be (Goldkhul, 2012). Therefore, this study's philosophical underpinning is pragmatism.

As pragmatism is about being helpful and valuable, design science research (DSR) can be seen within the pragmatism realm (Goldkhul, 2012). It is appropriate to investigate the use in, for example, "organisational change (as in action research) or building of artifacts (as in design research)" (Goldkhul, 2012). This study aims to explore the suitability of theoretical constructs when considering organisational AI adoption. Future researchers could also consider and explore the appropriate methodology of DSR. In short, DSR is centred around the creation of artifacts (Hevner et al., 2004) and the method that is followed, as it offers practical significance (through its focus on creating functional tools) and scientific rigour (through the development of theoretical frameworks for design) (Baskerville et al., 2018, p. 358). DSR not only supports the development of artifacts but also allows for strengthening existing knowledge. A further, in-depth evaluation of the suitability of DSR for AI adoption, falls outside the scope of this paper. However, the philosophical paradigm and practical relevance of the DSR approach is an important background context to the approach of the research paper.

3 SOCIOTECHNICAL SYSTEMS

This study examines the organisational adoption of AI sociotechnical systems to ensure a holistic approach that considers technical and social aspects. Sociotechnical systems theories highlight that the construction and interpretation of these systems result from the interplay between their technical and social components (Wihlborg & Söderholm, 2013). A sociotechnical system has two subsystems: the technical system, which includes the hardware and software and also the actual tasks needed (Oosthuizen & Pretorius, 2016). Both the social and the technical interactions with each other play an important role (Smit, Eybers & Van der Merwe, 2023). The actual tasks might include topics such as operational processes or IT governance. The social system comprises typical soft issues such as organisational structure, people, reward systems, knowledge, skills and attitudes. Complex, unpredictable and unexpected relationships can come from human (socio) and technical interactions (Oosthuizen & Pretorius, 2016). Figure 1 provides a diagram of a sociotechnical system and its relationships. As seen in Figure 1, the sociotechnical system exists within a complex environment. Achieving human-AI symbiosis involves harmonising social and technical elements, working collaboratively to accomplish the intended objectives. For example, organisations can use AI to assist with quality checks in their production process. The objective function of the AI would be to minimise quality issues in the assembly, which would align with the production manager's objective. The production manager would, for example, support the AI solution by investing in more labelled data, providing more processing power or routinely maintaining the AI system by updating its algorithms to reflect any changes in production processes or quality standards. In return, the AI system will decrease rework costs and enable the organisation to achieve its production targets. In this example, the objective of the AI system and the humans involved are aligned.

As this study is focused on the suitability of two theoretical underpinnings in AI organisational adoption, a focus on sociotechnical aspects can assist change mediators in managing change between the actors such as firms, organisations and technology as well as the adoption as a whole. Gregor (2006) defines "how-to" theories as theories applicable to design and action. The theoretical "how-to" knowledge is required to assist the mediators of the adoption. For changes to sociotechnical systems, mediators are critical actors in promoting system changes, reducing risks, reducing uncertainties, and thereby improving system sustainability (Wihlborg & Söderholm, 2013). Wihlborg and Söderholm (2013) identify four reflective elements, in which mediators promote change while developing a system in its social context. They translate instead of transferring specific knowledge, function as a singular gateway to knowledge, support the selection process through their interpretive components, and connect knowledge in unexpected ways. Sociotechnical theory is employed as the guiding lens to achieve a holistic approach in investigating the fostering of human-AI symbiosis.

4 TOE FRAMEWORK

The TOE framework is an organisational-level theory which explains the technology context, the organisational context (Tornatzky & Fleischer, 1990), and the environmental context (see Figure 2) as the elements that influence a firm's technology innovation adoption

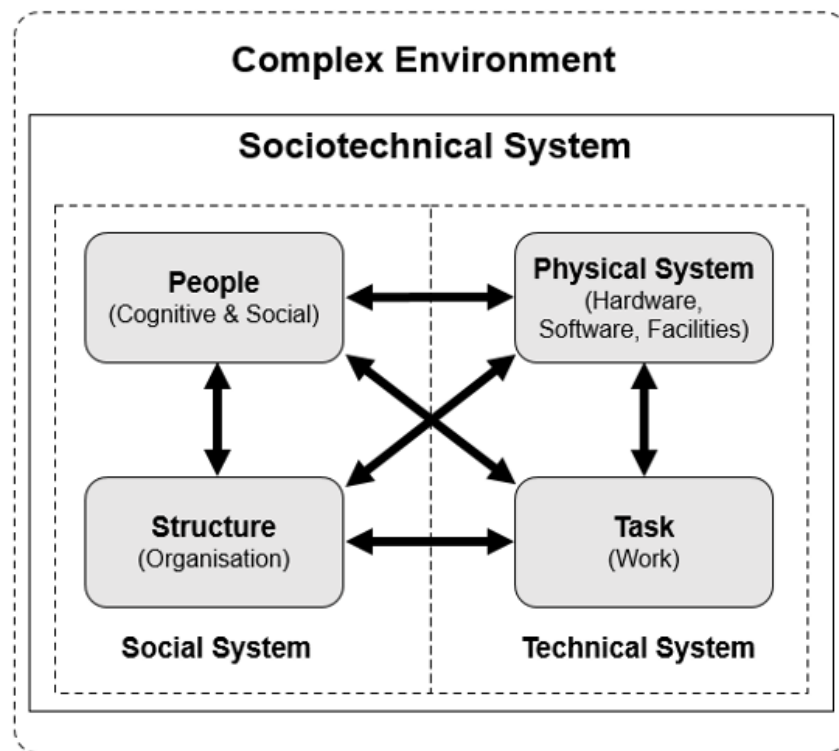


Figure 1: Sociotechnical systems (Oosthuizen & Pretorius, 2016)

decisions (Dwivedi et al., 2012). It provides a valuable theoretical perspective in examining the integration of information technologies, arguing that the adoption, implementation and assimilation systems in the organisation are influenced by elements associated with technology, the organisation itself, and the external environment (Xu et al., 2017).

The technology context refers to all the relevant technologies to the organisation. Both the technologies already in use and those not are included in the technology context and influence how organisations can use technology to evolve and adapt (Dwivedi et al., 2012). Technology innovations that are not presently in place in the organisation are categorised into; those that create incremental change, technologies that trigger synthetic change, and those that are radical and produce a discontinuous change (Dwivedi et al., 2012; Tushman & Nadler, 1986). The technology innovations that create incremental change require the smallest learning requirements. Technology innovations that produce a discontinuous change require a substantial learning requirement and, therefore, substantially and dramatically impact the organisation (Tushman & Nadler, 1986). An organisational context is the resources and characteristics of the organisation, including the firm size, internal company communication, structures between employees, and the resource availability level (Dwivedi et al., 2012). The organisational structure (centralised compared to decentralised) and communication processes (management leadership) must be understood to identify the relationship to the innovation adoption process. In the organisational context, the context involves the organisational component and the individual in it (Widyasari et al., 2018). The environmental context refers to the surrounding conditions and factors in which the organisation exists and includes aspects such as the structure of the industry, the service providers, the regulatory environment (Dwivedi

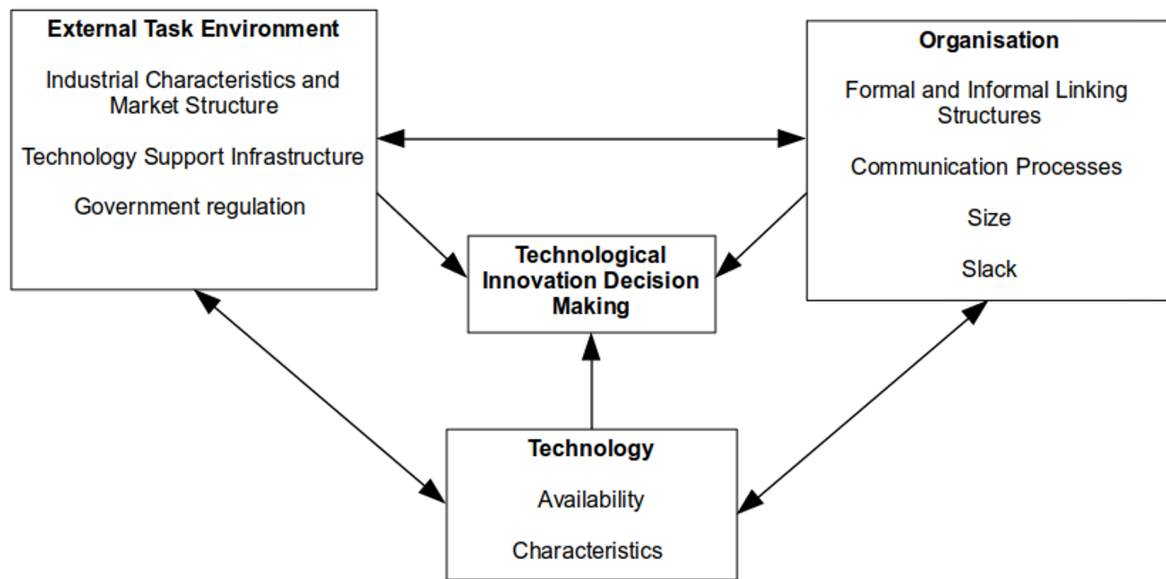


Figure 2: Technological-organisational-environmental (TOE) framework (Tornatzky & Fleischer, 1990)

et al., 2012), competitor pressures, customer pressures, partner pressures and government pressures (Chen et al., 2019).

Since the TOE contexts significantly impact adoption, including in the case of analytics (Maroufkhani et al., 2020), this study adopts the TOE framework as its conceptual foundation. The framework accounts for external factors directly influencing AI adoption and enables scholars to focus on broader AI adoption characteristics and attributes. Furthermore, the framework complements sociotechnical theory by considering the organisational context of AI adoption.

5 DOI THEORY

A theory often employed to understand and explain technology adoption within the realm of new innovative methods is the DOI theory (Lee et al., 2011; Nam et al., 2019; Rogers, 1995; Xu et al., 2017). Because AI is evolving and can be seen as a constantly changing entity, it remains an innovation. The DOI theory is well-suited for studies that emphasise the dissemination of innovation, as opposed to alternative theories such as the TAM (Davis et al., 1989) and the theory of planned behaviour (Taylor & Todd, 1995), which primarily concentrate on technology or behaviour in a broader sense. Also, because of the continuous evolution of AI technologies, the varying rates of adoption, and the complexity involved in adopting AI, AI adoption is a prime candidate for analysis using DOI (Almaiah et al., 2022; Handoko et al., 2023).

The definition of diffusion in the context of innovation theory is the mechanism through which, over time, innovation is communicated through specific channels among individuals within a social system (Rogers, 1995, p. 5). The concept is that an innovation achieved widespread adoption until it becomes self-sustained. The innovation-decision process is the mental

progression that an individual experiences. It includes stages such as knowledge, persuasion, decision-making, implementation and confirmation (Rogers, 1995). The innovation diffusion theory encompasses five attributes of an innovation: compatibility, relative advantage, trialability, complexity, and observability. These characteristics explain the adoption of innovations and the decision-making process. In innovation diffusion theory, the extent to which a person's (or unit's) adoption is relative to other members of the social system is classified as innovators, early adopters, early majority, late majority and laggards (Rogers, 1995). It should be noted that in technologies such as generative AI, issue observability could become a challenge. In many cases AI is seen as a black box to the end user (Asatiani et al., 2020).

This study aims to create a theoretical framework to assist researchers with “how-to” knowledge in terms of a theoretical approach to study the enablement of organisational AI adoption. Innovation diffusion theory has been extensively utilised to identify the enablers (variables) of information systems adoption in organisations (Nam et al., 2019; Ransbotham et al., 2019; Xu et al., 2017). When identifying the enablers, organisations need to consider that those focusing only on the technical enablers (variables) tend to neglect the transformational approaches required to obtain sustained business value with AI adoption (Ransbotham et al., 2019). DOI theory is a suitable mechanism for identifying enabling factors for adopting organisational AI.

6 A LENS FOR STUDYING THE ENABLEMENT OF AI ADOPTION

On an enterprise-level view, the most advanced level of data-drivenness and automation, an organisation can be viewed as a giant cybernetic collective (Yolles, 2006). This collective exists within an environment and will impact the people and the natural environment.

To study the enablement of organisational AI adoption, a comprehensive framework that integrates the sociotechnical nature of AI systems is proposed. This framework leverages the TOE framework to identify and analyse the various external and internal factors that influence the adoption of innovations within an organisation (Tornatzky & Fleischer, 1990). The DOI is included to study how knowledge about innovations spreads within social systems, focusing on communication channels and time (Rogers, 1995). The integration of DOI and the TOE offers distinct yet complementary epistemological, ontological, and axiological perspectives critical for understanding AI adoption. Although the focus is on pragmatism, epistemologically, this framework offers flexibility, accommodating various approaches, including positivism and interpretivism. Ontologically, in the context of knowledge representation, the DOI views innovations as entities that move through social networks, interacting with and being shaped by various actors (Rogers, 1995). In contrast, the TOE framework perceives innovations as complex phenomena influenced by the interplay of technological, organisational, and environmental factors (Tornatzky & Fleischer, 1990). Building on this understanding, the value-related considerations of these frameworks are explored. As introduced in Section 2, pragmatism embraces a particular ontological perspective, with actions and change as the essence, in this case, actions to increase AI adoption to bring value to the organisation. Axiologically, the DOI concerns itself with the societal value of innovations and how they are perceived across different adopter categories (Rogers, 1995). The TOE framework concerns how technological advancements, organisational readiness, and environmental pressures align with the organisation's goals, ethics, and strategic priorities. It focuses on the effectiveness

and ethical implications of adopting innovations, considering the internal and external consequences for the organisation and its stakeholders (Tornatzky & Fleischer, 1990).

The combination of DOI theory and a TOE framework is familiar to researchers as it offers both a macro (environmental and organisational) and micro (innovation characteristics and adoption process) perspective. DOI theory and the TOE framework have been successfully adopted in several studies (Wei et al., 2015; Wright et al., 2017; Xu et al., 2017; Zhu et al., 2006). “Business analytics adoption process: An innovation diffusion perspective” is one of the more recent studies. The study used DOI theory to understand organisations’ business analytics adoption (initiation, adoption, and assimilation) and TOE framework to identify its drivers (Nam et al., 2019). The TOE and DOI are also used in AI adoption studies. However, they do not fully allow organisational conclusions regarding causality (Alsheibani et al., 2020). To understand the causality of elements, we propose including the process steps toward adoption as an integral part of theories studying the organisational adoption of AI (See Figure 3). In DOI theory, the diffusion of innovation involves three main stages: initiation, adoption, and assimilation (Rogers, 1995). These phases are critical. The different phases will have different enablement elements and considerations. In the initiation process, the organisation becomes aware of the innovation, in this case, AI. The second process is the actual adoption process. During this process, AI is implemented and confirmed. The last process is the assimilation process. AI becomes an integral part of the organisation’s routines and practices during this process. The process is influenced by factors such as AI complexity, trialability, observability, relative advantage and compatibility with the organisation’s existing practices (Rogers, 1995).

As mentioned in the introduction, a data-driven organisation can be defined as an organisation that acts on observed data rather than merely gut feeling and does so to achieve financial or non-financial benefits (Anderson, 2015). AI can act autonomously. Therefore, AI should not be seen as merely a hyper-digital technology (Smit, Eybers & Van der Merwe, 2024). AI, by virtue of its decision-making capabilities and ethical implications (Crawford, 2021). Therefore, it should be considered as possessing a form of agency. This perspective would acknowledge the role of AI role as an active agent in organisational contexts.

Additionally, a data-driven organisation would require AI expertise, tools and a certain culture to adopt and embed AI in the organisation. They effectively use data to enable them to achieve their objectives. Furthermore, the impact of AI is recognised by including the environmental context. The impact can be extensive and includes AI technologies’ social, political, and environmental implications. It can go as far as examining the hidden costs of data extraction and labour exploitation (Crawford, 2021).

The proposed theoretical framework is similar to Alsheibani et al. (2020). However, it includes AI expertise, AI tools (including platforms), culture, execution, and benefits of AI. This is included, as a theory should not be limited to the “what”, but also includes the “how”, “when” or “why” (Bacharach, 1989), Answering research questions such as *how did the enabling factor contribute to the initiation of the use of AI tools in the organisation?* and *when does the enabling factor contribute to an adoption of a data-driven culture in the organisation?*, can assist in the evaluation of enabling factors and also be used as a step towards understanding of causality in AI adoption. In the first research question example, *how did the enabling factor contribute to the initiation of the use of AI tools in the organisation?*, an example of an enabling factor could be the hosting of technology days (Smit et al., 2022).

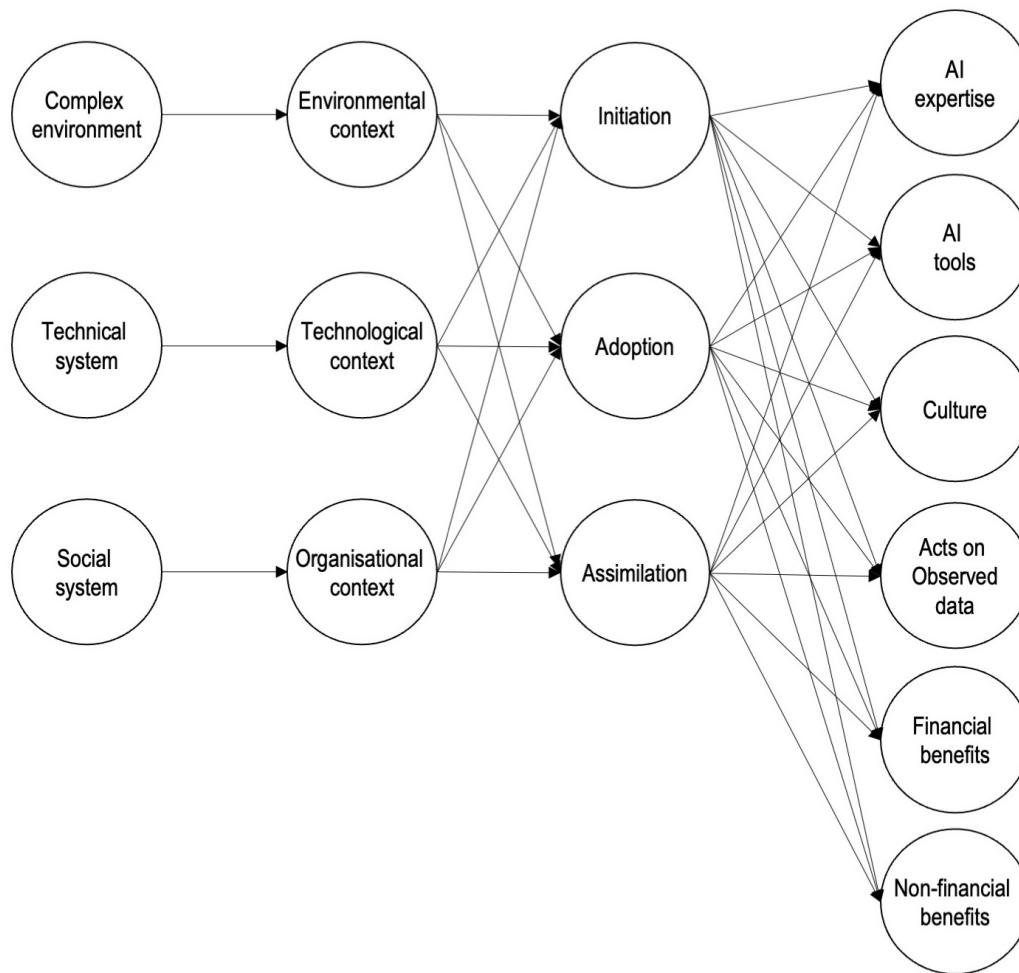


Figure 3: The proposed framework provides a theoretical lens for studying the enabling AI adoption

Framing these questions within a pragmatist paradigm encourages a focus on obtaining information that is of value to practice. We want to emphasise how important pragmatism is for this study as a philosophical foundation, especially in DSR. A pragmatic approach concentrates on the applications and implications of concepts, theories, and deeds in the real world. It emphasises how crucial it is to consider how valuable and applicable research findings are to solving real-world issues. Pragmatism has several significant benefits in the context of this article, which tries to identify and assess enablers for the successful adoption and application of AI within organisations:

Emphasis on practical results: By taking a pragmatic approach, the research will concentrate on producing information that can immediately be implemented to help organisations adopt AI. This strategy fits in well with the paper's objectives: to comprehend the elements that influence the adoption and implementation of AI successfully or unsuccessfully.

Flexibility and adaptability: Pragmatism promotes blending research approaches and meth-

odologies and various theoretical viewpoints (such as TOE and DOI). This adaptability fits in well with the paper's strategy, which mixes several theoretical frameworks to analyse and comprehend the adoption of AI in organisations.

Problem-focused approach: Pragmatism strongly emphasises tackling real-world issues and difficulties, making it especially appropriate for DSR. DSR attempts to develop and assess artefacts (such as models, frameworks, or tools) to address real-world issues. This study shows a clear commitment to solving the practical issues of AI adoption through the evaluation methodology for evaluating the efficacy of enabling variables and the focus on the complex sociotechnical systems within organisations.

Place an emphasis on context: Pragmatism recognises the significance of context in comprehending and solving problems. This is especially pertinent to this article because it is believed that the organisational context significantly impacts the adoption and use of AI. The research can better account for the various and complicated circumstances in organisations' functions by adopting a pragmatic approach, improving the findings' generalisability and application.

Pragmatism enriches the research by focusing on useful results, encouraging methodological flexibility, adhering to the problem-oriented methodology of DSR, and taking context into account. The goals of the article will be met by this philosophical position, which will ultimately contribute to a more thorough and practical understanding of the elements that affect the effective adoption and application of AI within organisations. To support the integration of AI in an organisation, the framework depicted in [Figure 3](#) was utilised in the form of a case study (Smit, Eybers & van der Merwe, 2024). It effectively links theoretical insights with practical applications. It drew upon the DSR methodology, particularly the cycle steps outlined by Vaishnavi et al., to construct an AI Adoption Framework (AIAF) (Vaishnavi et al., 2004). The theoretical foundation for the research was based on the theoretical framework as outlined in this paper. A case study at an IT Hub formed the basis of the empirical work, which was structured around a main DSR cycle and three supporting sub-cycles. These sub-cycles examined socio-enabling factors, technical-enabling factors for AI adoption, and a comparative analysis between AI and traditional data-driven technology adoption.

While evaluating the framework across multiple case studies is ideal, it may not always be feasible. The next section explores generative AI as a potential alternative for assessing the effectiveness of a theoretical framework.

7 GENERATIVE AI AND RESEARCH

True to the pragmatism approach described in [Section 6](#), a flexible problem-oriented way to explore the framework's usefulness is required. Generative AI can be a powerful tool for brainstorming research ideas (Al-Ahmadi, 2023). Therefore, to assess the framework's effectiveness, this research utilises generative AI to generate and explore research ideas based on the proposed framework (See [Figure 3](#)).

7.1 Generative pre-trained transformers

In the domain of generative AI, the recent advances in large language models (LLMs) like ChatGPT², Google's Bard³ and X's Grok⁴ are taking the world by storm. OpenAI's ChatGPT is one of the most popular LLMs. It is trained on many books, press articles, Wikipedia, and other web content (Teubner et al., 2023). ChatGPT accesses GPT-4, which is a language model based on the generative pre-trained transformer architecture and has been enhanced through a training method known as reinforcement learning from human feedback (Thorp, 2023). GPT-4 allows for new business opportunities and efficiency potential (Teubner et al., 2023). One example is its use by writers to suggest corrections, alternative phrasing or even to write stories (Teubner et al., 2023). GPT-4 can be used to support empirical research (Liang et al., 2024). However, it is also known to make mistakes, for example, referencing scientific studies that do not exist (Thorp, 2023). While fully acknowledging the limitations of LLMs (Al-Ahmadi, 2023; Thorp, 2023); this research utilises LLMs' capabilities to generate text based on prompts, which allows the researchers to apply the theoretical framework experimentally.

7.2 Generative AI prototype that applies the framework

A generative AI application was developed to experiment with the usefulness of the proposed framework (Figure 3). Like a human applying the framework, the generative AI application uses the framework as a lens to study how to enable AI adoption. This application uses the framework as the theoretical basis from which GPT-4 will be called. The user is then allowed to select focus areas from the framework. In the example in Figure 4, the **Technical system**, **Technological context**, **Assimilation** and **Analytical tools** were selected.

The selection is then used as input to the prompt engineering process. Prompts are instructions given to an LLM to ensure specific qualities of the generated output. It can be seen as a form of programming that can customise the outputs and interactions with an LLM (White et al., 2023). The first step of the prompt engineering process was to set the context as "You are an information systems researcher and interested in the adoption of artificial intelligence in organisations". After that, the selected framework elements are used to define the prompt. A prompt pattern was created from the framework to provide re-usability (White et al., 2023). The code can be seen in Figure 5. As the LLM's ability to generate relevant and accurate responses is directly correlated to the clarity and precision of the prompt provided (Zhou et al., 2023), an iterative process was used to define the prompt's code.

After the prompt engineering process, the application calls a GPT-4 API and requests GPT-4 to create a possible problem statement and related research questions. The context, prompt and result are displayed to the user for review. An example of how the application presents the results can be seen in Figure 6. As can be seen by the following prompts, the generated results by GPT-4 are relevant.

Example 1 prompt: "Propose a problem statement and relevant problem research questions about the environmental aspects to increase the adoption of tools in the context of organisational artificial intelligence adoption".

² OpenAI's ChatGPT – <https://openai.com>, [Accessed, November 17 August 2023].

³ Google's Bart – <https://bard.google.com>, [Accessed, November 17 August 2023].

⁴ xAI's Grok. <https://x.ai>, [Accessed, November 17 August 2023].

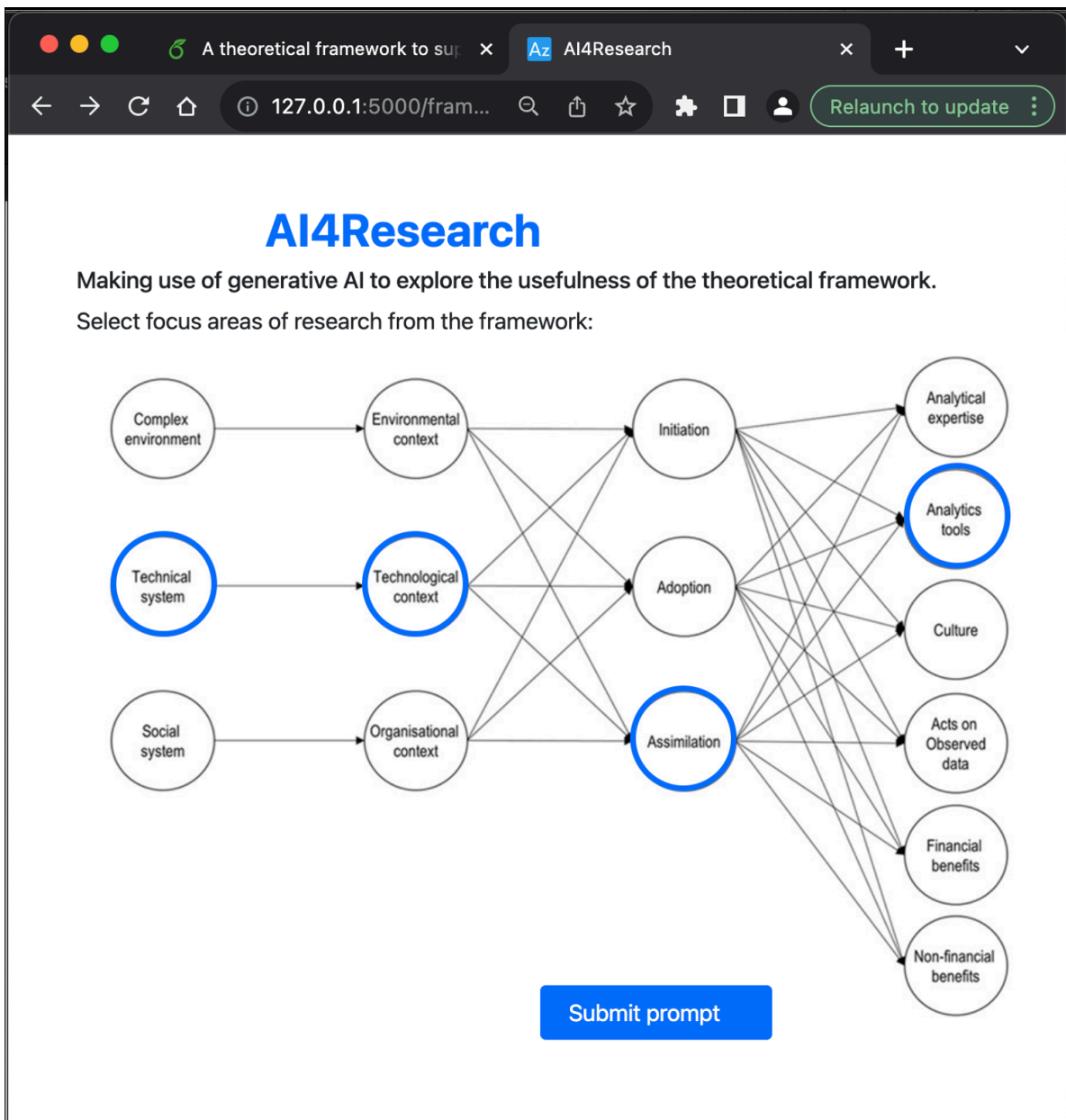


Figure 4: Generative AI application allowing a user to select elements from the framework

Example 1 output: *“Research Question: What are the key environmental factors that either promote or inhibit the adoption of AI tools in organisations? Problem Statement: Despite the rapid advancements in artificial intelligence (AI), its adoption in organisations remains relatively low. The problem seems to lie in the environmental factors that influence the decision-making process of AI adoption in an organisation. These factors include competitive pressure, technological infrastructure, regulatory climate, and socio-cultural norms within the organisation. The understanding of these environmental aspects and their impact on AI adoption is crucial to increase the utilisation of AI tools in organisations”.*

```
# create prompt
context = ('You are an information systems researcher and interested in the adoption of artificial intelligence ' +
          'in organisations. ' +
          'You use the Technological-organisational-environmental framework and the diffusion of innovation ' +
          'theory as theoretical lens for your research.')

prompt = ('Propose a problem statement and a relevant problem research questions about the ' + toe_text +
          ' aspects to increase the ' + doi_text +
          ' of ' + ddo_text +
          ' in the context of organisational artificial intelligence adoption.')
```

Figure 5: Prompt engineering setting the context and question

Example 2 prompt: *“Propose a problem statement and relevant problem research questions about the organisational aspects to increase the initiation of financial benefits in the context of organisational artificial intelligence adoption”.*

Example 2 output: *“Research Question: How can organisations strategically align their AI initiatives with their business objectives to maximise financial benefits? Problem Statement: Despite the increasing interest and investment in artificial intelligence (AI) technologies, many organisations are yet to realise significant financial benefits from their AI initiatives. This underperformance may be due to a variety of factors, including technological complexities, organisational readiness, and environmental dynamics. Understanding these factors can provide valuable insights into the initiation of financial benefits from AI adoption in organisations”.*

A clear and well-defined problem statement and supporting research questions set up a good starting point for a concise and convincing argument for a thesis. Research questions support the problem statement to pinpoint what the study is addressing (Hofstee, 2006). Both examples from the generative AI application provide well-defined and topic-specific problem statements and research questions, which can facilitate a researcher in the first step to a thesis with a compelling argument.

In addition to the examples, all permutations of the section of the framework were submitted via the application. Proposed research questions included a wide range of “how”, “when” and “why” questions. Similar to the results found by Sandkuhl et al. 2023, this application illustrates that GPT, in this case, GPT-4, can coexist with domain experts (Sandkuhl et al., 2023). The use of generative AI to support research is still a contentious topic. Still, this small prototype showed that generative AI can be used to explore the validity of proposed frameworks. Generative AI can play an important role in supporting researchers and as tools for the people posing the hypotheses (Thorp, 2023). Even if generative AI is just used in the ideation phase of research, the potential and impact of such tools warrants future research (Stokel-Walker, 2023).

8 CONCLUSION

The paper’s main objective was to explore the suitability of the technological-organisational-environmental (TOE) framework and diffusion of innovation (DOI) theory towards comprehending AI adoption as part of sociotechnical systems. This paper explained the requirement

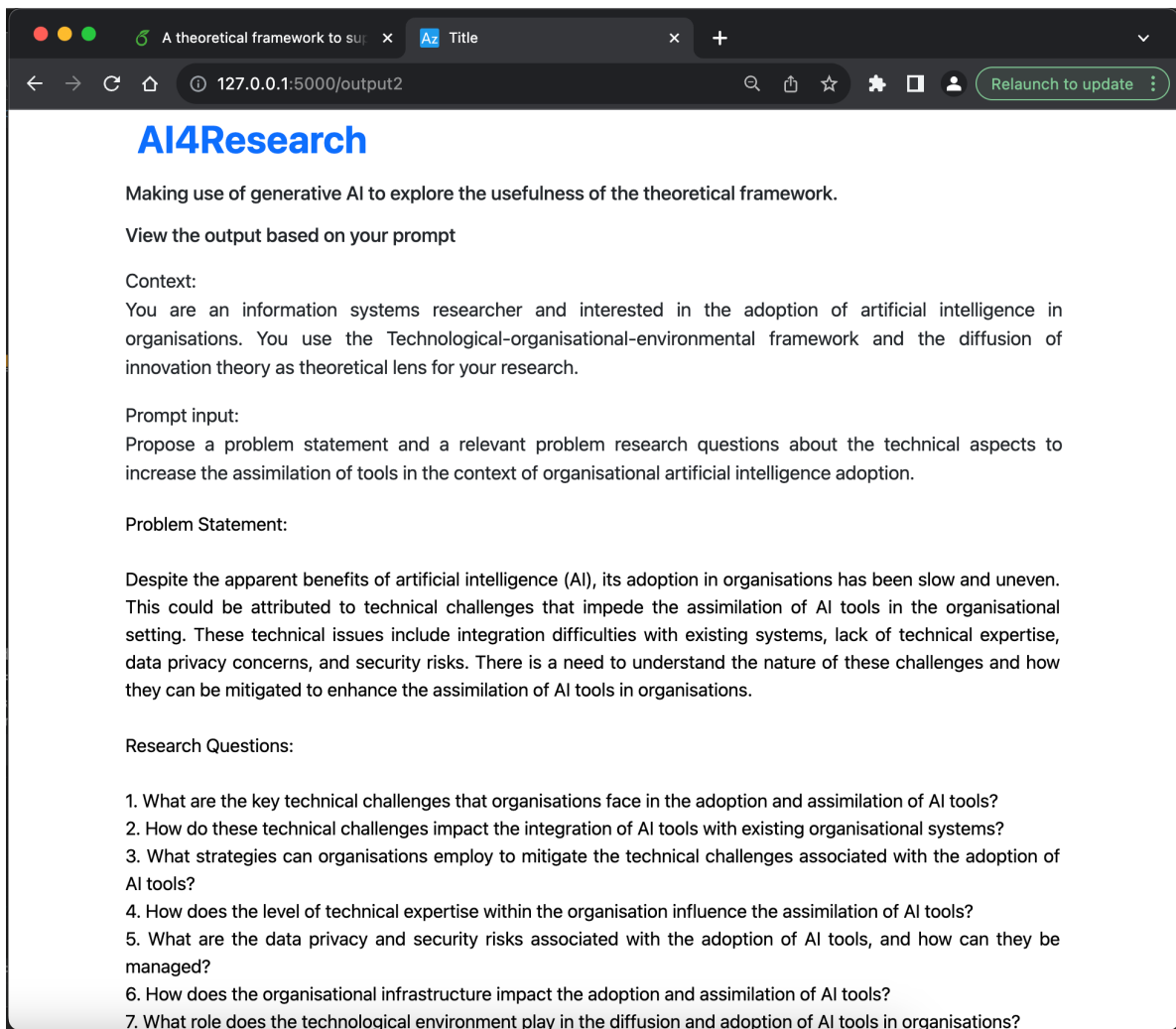


Figure 6: Based on the proposed theoretical lens, GPT-4 generated results

of an appropriate theory to assist in identifying enablers for transformations and be useful to support and help the change management and adoption process while having a holistic perspective. Firstly, sociotechnical theory is introduced as a high-level lens for this study to allow for a holistic perspective with the target of human-AI symbiosis. In sociotechnical theory, the TOE framework is proposed to identify elements that influence an organisation's adoption decisions regarding technology innovation. Secondly, DOI theory is suggested to identify the enablers of AI adoption.

The TOE framework, the DOI diffusion processes (initiation, adoption and assimilation) and the elements of data-driven organisations are combined into one framework. This paper contributes on a theoretical level by providing a framework to evaluate the possible impact of the enabling factors and, therefore, contribute to causality knowledge. It can, therefore, be used to identify research questions related to the "how", "when" and "why". However, like all studies, this paper has limitations. The researchers are fully aware that the proposed theoretical model is not close to a grand theory on organisational AI adoption. However, our

approach includes the use of the diffusion processes to evaluate the “how”, “when” and “why” the enabling factors can contribute to causality knowledge in the field of AI research in Information Systems. Future studies will focus on applying the theoretical framework to support understanding the causality and effectiveness of different enabling factors. The Technology-Organisation-Environment (TOE) framework can be harnessed to enhance AI prompt generation, contrasting it with the Diffusion of Innovations (DOI) theory to produce a coherent contribution to future research. Additionally, the application of generative AI in research remains a relatively novel area. Future studies could further explore how recent advances in LLMs may influence academic research practices and outcomes.

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