The impact of fourth industrial revolution technology innovation on STEM higher education students through flipped classrooms

George Iroha

Wits Business School, University of the Witwatersrand, Johannesburg, South Africa
george.iroha@wits.ac.za
https://orcid.org/0000-0002-5685-0018

Moleboheng Mokhele-Ramulumo

Department of Science and Technology Education, Faculty of Education, University of South Africa, Pretoria, South Africa
Moleboheng.Ramulumo@nwu.ac.za
https://orcid.org/0000-0002-5134-954X2

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Abstract

Our study explores the integration of Fourth Industrial Revolution technological innovations into the flipped classroom model in STEM higher education contexts. Using a mixed-methods sequential explanatory design, the research draws from quantitative survey data of 362 first-year engineering students and qualitative semi-structured interviews with 24 participants. The study is anchored in the Unified Theory of Acceptance and Use of Technology, examining constructs such as Effort Expectancy, Performance Expectancy, Facilitating Conditions, and Social Influence. Quantitative findings revealed high internal consistency in scales measuring technology innovation and perceptions of the flipped classroom approach, yet no significant relationship was found between technological innovation and academic outcomes. Qualitative insights highlighted both benefits, such as enhanced time management, self-directed learning, and collaborative engagement and challenges, including technical failures, inequities in resource access, and the impersonality of online interactions. Therefore, by critically addressing both affordances and limitations, the study advances a nuanced understanding of technology integration's impact on student experiences. It concludes with practical recommendations for fostering more equitable, resilient, and learner-centred flipped classrooms in the digital era.

Keywords: flipped classroom, fourth industrial revolution (4IR), STEM education, technology integration, UTAUT, self-directed learning

Introduction

The flipped classroom has gained prominence in modern higher education, especially in STEM fields, departing from traditional teaching methods (Cilliers & Pylman, 2022; Van Niekerk & Delport, 2022). Leveraging online platforms like Moodle LMS, this approach utilises technology, notably online video media, to foster self-paced learning, optimise classroom time, and encourage collaborative learning experiences (Motaung & Makhasane, 2020). Secker et al. (2022) emphasised that providing students with access to pre-recorded lectures and resources enhances their participation and understanding before face-to-face sessions.

While the effectiveness of the flipped classroom in improving student engagement and learning outcomes is well-established, ongoing discussions centre on the need for further technological innovation. Studies highlight the positive impact of technology, such as interactive quizzes and multimedia resources in Moodle LMS, on student learning (Cilliers & Pylman, 2022; Motaung & Makhasane, 2020; Van Niekerk & Delport, 2022). To clarify the role of technology, we explore detailed examples of how Moodle LMS and similar platforms are integrated in the flipped classroom, encompassing various components like pre-recorded lectures, interactive quizzes, discussion forums, and multimedia resources, as noted by Aljaber et al. (2023).

Despite the benefits, challenges including access barriers, digital literacy gaps, and resistance to change hinder the widespread adoption of technology in the flipped classroom (Gardner, 2017). Moreover, the rapid evolution of educational technology presents opportunities and challenges, requiring careful consideration of pedagogical objectives, student needs, and institutional contexts (Mshayisa & Basitere, 2021). Lin et al. (2019) highlighted the effectiveness of a cyber-flipped course, specifically successful implementation and the correlation between higher engagement with pre-recorded lectures and improved academic performance.

In our study, we aim to address specific challenges related to technology integration in the flipped classroom, including digital accessibility, student technological proficiency, and effective pedagogical design using technology. We explore and propose potential strategies for overcoming these obstacles. Additionally, we contextualise the use of technology in broader trends in educational innovation, offering insights into future directions for technology integration in higher education. Ultimately, we seek to fill a gap in the existing literature by investigating the impact of technology integration, particularly through platforms such as Moodle LMS, on the effectiveness of the flipped classroom approach in enhancing student engagement, improving learning outcomes, and enriching the overall educational experience in STEM domains.

To guide the research and achieve these objectives, we explored students' perceptions of the role of technology integration, particularly through Moodle LMS, in supporting their learning experiences in the flipped classroom model. We investigated the specific challenges related to digital accessibility that students encountered, technological proficiency, and the design of technology-enhanced flipped learning environments. Furthermore, we determined which technological features and practices students perceived as most beneficial for fostering self-directed learning, time management, and engagement. Finally, we explored how students' experiences with technology integration aligned with constructs from the Unified Theory of Acceptance and Use of Technology (UTAUT), including Effort Expectancy, Facilitating Conditions, Performance Expectancy, and Social Influence. Through addressing these key areas, we provide empirically grounded insights into the complex dynamics of technology integration in flipped classrooms and offer practical recommendations for optimising technology-enhanced teaching and learning practices in higher education.

Literature review

In contemporary education, the Fourth Industrial Revolution (4IR) has sparked transformative changes, propelled by innovations such as artificial intelligence (AI), Big Data, and the Internet of Things (IoT) (Coetzee et al., 2021; Rossouw & Goldman, 2023). This literature review aims to explore comprehensively the dynamic interplay between 4IR technological innovations and the flipped classroom approach, emphasising their profound impact on teaching and learning processes.

We explore the transformative impact of 4IR technological innovations on higher education with particular emphasis on how machine learning facilitates autonomous learning experiences (Mhlanga, 2022). Specifically, machine learning algorithms analyse student data to discern individual learning patterns, facilitating personalised learning experiences tailored to diverse student needs and preferences (Kotsiantis, 2012). Additionally, they explore the immersive potential of augmented reality for heightened engagement (Nyagadza, 2021). Augmented reality applications offer interactive and hands-on learning experiences that enable students to visualise intricate concepts and participate in simulated environments, thus fostering deeper understanding and retention of information (AlGerafi et al., 2023). Furthermore, the secure credentialing capabilities of blockchain technology (Brown, 2022; Lee, 2022), emphasise how blockchain-based credentialing systems uphold the integrity and authenticity of academic credentials, bolstering trust and transparency in the credentialing process (Li et al., 2023).

We evaluate the flipped classroom approach, a pedagogical model that challenges conventional teaching methods by prioritising pre-class engagement and collaborative in-class activities (Nugraheni et al., 2022). We use a historical perspective to consider the evolutionary trajectory of the flipped classroom and how the integration of technology has expanded its engagement possibilities in aligning with evolving educational philosophies (Clark-Wilson et al., 2020).

We acknowledge the positive impact of 4IR technological innovations and the flipped classroom approach on student outcomes, particularly in STEM subjects (Ryan & Reid, 2016) and consider the strengths and weaknesses of existing research, highlighting areas where further investigation is warranted. For instance, while integrated technologies contribute to dynamic educational experiences, persistent challenges such as variability in student readiness, uneven access to technology, and faculty resistance continue to impede progress (Hao, 2016; McGrath et al., 2017; Park & Howell, 2015).

Furthermore, research provides insights into potential strategies for addressing challenges, such as targeted professional development initiatives and supportive institutional cultures (Al-Hamad et al., 2023). It emphasises the importance of providing educators with the necessary training and resources to integrate technology effectively into their teaching practices and foster a culture of innovation and collaboration in educational institutions (Diano et al., 2023).

The intricate interplay between 4IR technological innovations and the flipped classroom approach in modern education is explored through a synthesis of diverse empirical studies, theoretical frameworks, and practitioner insights. This synthesis highlights the transformative potential of technology integration in teaching and learning processes by enhancing autonomous learning, fostering greater student engagement, and promoting innovative pedagogical practices. To further enrich the discussion, attention is given to emerging trends, unresolved questions, and detailed strategies for addressing persistent challenges in technology-enhanced education. These insights are intended to support educators, policymakers, and researchers in harnessing the full potential of digital innovations for teaching and learning. Building on this foundation, we seek to address a critical gap in the literature by investigating how technology integration, particularly through platforms like Moodle LMS, can optimise the flipped classroom approach to enhance student engagement, learning outcomes, and the overall educational experience in STEM higher education contexts.

Theoretical framework

We explored theories of technology adoption and acceptance with a specific focus on integrating the flipped classroom approach in higher education, particularly in STEM disciplines. The research problem centred on the incorporation of 4IR technological innovations into modern educational practices. 4IR refers to the current era of technological advancement characterised by the fusion of digital, biological, and physical innovations, significantly transforming industries and education (Schwab, 2017).

The Unified Theory of Acceptance and Use of Technology (UTAUT), developed by Venkatesh et al. (2003), served as the foundational framework. UTAUT explains how individuals come to accept and use new technologies, based on four key constructs: Performance Expectancy, Effort Expectancy, Social Influence, and Facilitating Conditions. These constructs influence individuals' intentions collectively to adopt and use technology effectively (Abdullah et al., 2023; Alyoussef, 2022; Bakheet & Gravell, 2020; Gautam, 2023).

In higher education, particularly in STEM fields, the growing adoption of technological innovations promises transformative changes in teaching, learning, and research (Jones, 2023). However, persistent challenges remain, including disparities between technology availability and its effective utilisation, resistance to pedagogical change among faculty, and uncertainty regarding technology's actual impact on learning outcomes (Smith & Brown, 2021). Furthermore, issues related to accessibility, equity, and inclusivity must be addressed to ensure that technology-enhanced learning environments benefit all students equally (Garcia et al., 2022).

While the flipped classroom model offers significant pedagogical advantages, it is important to acknowledge its potential shortcomings to ensure a balanced understanding. One concern is that the success of the flipped model relies heavily on students' self-discipline and motivation to engage with preparatory materials, which may not be consistent across diverse learner populations (Abeysekera & Dawson, 2015). Without sufficient engagement before class, the intended benefits of deeper in-person learning activities may not materialise (Lo & Hew, 2017).

Additionally, disparities in access to reliable technology and stable internet connections can create barriers, particularly for students from under-resourced backgrounds (Bishop & Verleger, 2013). From an instructional perspective, preparing high-quality pre-class content and restructuring in-class activities can increase the workload for educators, potentially affecting the sustainability of the approach. Furthermore, there is a risk that students may engage superficially with preparatory content without adequate scaffolding or accountability mechanisms. Recognising these challenges is essential for refining flipped classroom strategies to maximise their effectiveness and inclusivity. We, therefore, examined critically not only the affordances but also the practical limitations of technology integration in the flipped classroom, particularly in a STEM education context.

Our findings explicitly align with the UTAUT constructs in several ways. In terms of Effort Expectancy, participants valued the user-friendliness and flexibility of technology platforms such as Moodle LMS, which enhanced their ability to manage learning independently and access materials at their own pace. Students' statements emphasising ease of access, the ability to revisit lectures, and the navigation of complex topics through recorded sessions strongly support UTAUT's prediction that the perceived ease of use promotes acceptance.

Regarding Performance Expectancy, participants consistently acknowledged that technology enhanced their understanding of difficult STEM concepts and improved their learning outcomes when tools such as interactive quizzes and instant feedback mechanisms were available. However, some participants indicated that while engagement increased, this did not always translate directly into higher academic performance, thus reflecting a nuanced divergence from UTAUT's more linear assumption that perceived usefulness always leads to performance gains, as noted similarly by Lai et al. (2024).

Findings related to Social Influence were more complex. While some participants highlighted the value of peer collaboration facilitated by cloud-based tools, others expressed concern about the impersonality of online communication and a diminished sense of community. These concerns suggest that social influence in technology adoption may be moderated by the emotional and relational quality of the learning environment, partially aligning with UTAUT, but indicating the need for greater emphasis on fostering authentic social presence in digital spaces.

Finally, with regard to Facilitating Conditions, our data showed that equitable access to high-end devices, stable internet connections, and institutional support were critical factors that influenced students' ability to engage fully with the flipped classroom model. Disparities in access and technical failures significantly disrupted learning for some participants, reinforcing UTAUT's assertion that the availability of resources and support structures is crucial for successful technology adoption (Al-Samarraie et al., 2020).

Additionally, our findings resonate with prior research that integrates UTAUT with active learning strategies, such as the work of Ahmed and Indurkhya (2020), who connected the perceived usefulness and ease of use to the successful adoption of flipped classroom methods. Nonetheless, consistent with Kgasi (2021), our study highlights the limitations of assuming universal applicability of technology-enhanced models, particularly in contexts where external barriers such as infrastructure gaps and digital inequity persist.

In essence, by linking our findings explicitly to UTAUT's constructs, we provide a nuanced understanding of technology adoption in the flipped classroom, acknowledging both the alignments with theoretical predictions and the divergences arising from practical realities. These insights underscore the importance of designing technology-enhanced learning environments that are not only technically accessible and pedagogically sound but also socially and emotionally supportive.

Methodology

We employed Creswell's realism research paradigm (2014) with a mixed-methods approach, merging positivist and constructivist elements (Gorski, 2013), aligning well to explore comprehensively the interplay between 4IR technological innovations and the flipped classroom approach in modern education. Acknowledging the complexity of educational phenomena and emphasising the importance of understanding the social context, this paradigm, coupled with the mixed-methods approach, facilitated gathering both quantitative and qualitative data to provide a more comprehensive understanding.

Utilising a sequential explanatory research design, we aimed to explore research questions and provide descriptive information about observed phenomena (see Baskerville et al., 2016). This design, (following Nardi, 2018), chosen for its inherent strengths in providing a comprehensive understanding of complex phenomena, involved initially collecting quantitative data through a validated closed-ended questionnaire administered to 362 first-year engineering students enrolled across four STEM courses at a South African higher education institution.

The participant pool included students aged between 18 and 23 years, with a relatively balanced gender distribution (58% male, 42% female). Participants represented a range of linguistic and socioeconomic backgrounds, reflective of the broader student demographics of the institution. Despite potential biases introduced by convenience sampling, efforts were made to ensure diversity within the sample to better capture varied student experiences with technology integration.

The questionnaire demonstrated strong content validity, and quantitative data was analysed using SPSS to identify patterns in students' technology adoption experiences in the flipped classroom environment. To enrich the findings, a subset of students from the quantitative phase, selected through purposive sampling based on their willingness to share more detailed perspectives, voluntarily participated in semi-structured interviews. In total, 24 students, representing a cross-section of the original survey group, participated in the qualitative interviews. The interview protocol was designed carefully, pilot-tested, and refined to ensure question clarity, content relevance, and overall reliability.

Beyond methodological rigor, the study also uncovered significant technological challenges that shaped students' learning experiences. Participants reported frequent disruptions during virtual laboratory sessions, with software crashes interrupting experimental tasks and undermining the flow of conceptual understanding. Internet instability, unequal access to high-performance devices, and limited technical support services further complicated engagement, thus highlighting persistent infrastructural barriers to equitable technology integration. Students often expressed frustration and diminished motivation after experiencing repeated technical failures, thus suggesting a tangible erosion of self-directed learning confidence over time.

Despite these obstacles, several successful implementations of technology were also reported. For instance, cloud-based collaboration platforms, such as shared design software for engineering projects, were praised for enabling effective teamwork even when some students faced temporary connectivity challenges. One participant noted, "When my internet was unstable, I could still contribute asynchronously to our project using the shared platform, and it kept the group moving forward." Similarly, interactive online quizzes embedded in Moodle LMS were cited as enhancing immediate feedback and self-paced learning, promoting a more autonomous study routine. These examples illustrate that when appropriate technological tools are selected and institutional support mechanisms are in place, technology integration can enhance both engagement and learning outcomes meaningfully in the flipped classroom.

While the sample provided valuable insights into first-year STEM students' experiences, it is important to recognise contextual limitations. The findings, though robust within the study setting, may not be fully generalisable to other populations, disciplines, or institutional contexts. Participants' perspectives were shaped by specific technological infrastructures, curriculum designs, and resource availability at the institution. These contextual factors highlight the need for future research across more diverse educational settings to validate, refine, or challenge the patterns identified.

Ethical integrity was prioritised throughout the research process to foster participant trust and enhance the credibility of the study. Informed consent was obtained from all participants, who were provided with detailed information sheets outlining the study's purpose, procedures, potential risks, and benefits. Participants' rights were protected through voluntary participation agreements and assurances of confidentiality. To ensure anonymity, unique participant codes were assigned during data management, with all identifying information removed prior to analysis and reporting. Data security protocols included encrypted, password-protected storage accessible only to the principal researchers. These measures were essential not only for ethical compliance but also for building the psychological safety necessary for participants to engage openly, especially when sharing potentially sensitive experiences with their use of technology.

Results

In this section, we present the research results and offer a thorough examination of students' perspectives and encounters concerning technology innovation and the flipped classroom model in higher education, concentrating on distinct STEM disciplines. Employing a combination of quantitative and qualitative approaches, we explore the intricate relationship between technology integration and educational outcomes. Quantitative analyses are enriched by qualitative insights from students, furnishing valuable context and illuminating the multifaceted landscape of technology integration in academia. Collectively, these findings provide a holistic comprehension of the intricate interplay among technology, teaching methods, and student learning experiences in STEM fields in higher education.

Table 1 presents the statistical analysis of students' perceptions of technology innovation. The scale, comprising nine items, evaluates attitudes and perceptions regarding various aspects of technology use in education.

Table 1
Summary of technology innovation scale analysis

Technology Innovation Items Total Statistics				
	Scale Mean if Item Deleted	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
I enjoy using technology.	30.04	37.761	0.642	0.848
I believe that using technology in class saves time.	30.03	37.242	0.668	0.845
I am aware that technology can assist me in learning a variety of new skills.	29.86	38.040	0.694	0.844
Using technology does not frighten or threaten me.	30.04	39.221	0.490	0.862
When it comes to working with tech technology in class, I am very confident.	30.02	37.940	0.634	0.849

Technology Innovation Items Total Statistics				
	Scale Mean if Item Deleted	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
I'd like to learn more about how to use technology in the classroom.	30.27	38.369	0.513	.861
I believe that technology can significantly improve my teaching practice.	30.24	37.358	0.673	.845
It is possible to modify the curriculum to incorporate technology.	30.09	38.204	0.606	.851
Technology breaks down too often to be reliable.	30.60	39.891	0.486	.862

The Technology Innovation scale exhibited strong internal consistency, with Cronbach's Alpha values ranging between 0.845 and 0.862 when considering the removal of individual items. The corrected item-total correlations were moderate to strong (ranging from 0.486 to 0.694), supporting the contribution of each item to the overall scale reliability. These results affirm the scale's robustness in measuring students' perceptions of technology innovation in educational settings.

Table 2 presents the statistical analysis of the Flipped Classroom Approach scale, which assesses students' perceptions in the context of the flipped classroom approach.

Table 2
Summary of Flipped Classroom Approach Scale Analysis

Flipped Classroom Approach Item-Total Statistics				
	Scale Mean if Item Deleted	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
Using the flipped classroom approach prevents me from becoming uninterested.	22.93	23.344	0.652	.819
My ability to learn on my own is enhanced by the flipped classroom approach, and I take pleasure in using that approach to further my education.	22.92	23.154	0.655	.818

Flipped Classroom Approach Item-Total Statistics				
	Scale Mean if Item Deleted	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
A live lecture in the classroom can provide me with more information than watching a video at home can.	22.75	23.671	0.696	.814
My anxiety level has increased as a result of using the flipped classroom approach of instruction.	22.93	24.359	0.508	.841
It is difficult for me to gain access to the internet and view the videos that have been assigned.	22.91	23.518	0.640	.821
The approach of instruction known as "flipping the classroom" is not one that I favour.	23.17	24.190	0.481	.846

The Flipped Classroom Approach scale demonstrated good internal consistency, with Cronbach's Alpha of item deleted values ranging from 0.814 to 0.846. Even with the potential removal of individual items, the scale maintained high internal consistency, as reflected by elevated scale means and strong corrected item-total correlations. These results confirm the reliability of the scale in effectively measuring students' perceptions of the flipped classroom approach in higher education contexts. Table 3 presents the results of an ANOVA test examining the effect of technological innovation on the flipped classroom approach.

Table 3
Test on the effect of technological innovation on the flipped classroom approach

ANOVA[a]						
Approach		**Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig.**
1	Regression	0.560	1	0.560	0.954	0.329[b]
	Residual	205.048	349	0.588		
	Total	205.609	350			
a. Dependent Variable: Technology Innovation						
b. Predictors: (Constant), Flipped Classroom						

The ANOVA results indicate that technological innovation does not contribute significantly to learning outcomes in the flipped classroom approach. This unexpected finding suggests that, within the study's parameters, incorporating technology in the flipped classroom does not yield a statistically significant improvement in technology innovation.

Further analysis into the qualitative data gives us subjective insights from students and provides valuable context to complement quantitative data, enriching the understanding of the student experience in the flipped classroom. Verbatim responses described vividly interactions with technology, shedding light on both challenges and positive aspects. These qualitative results serve as an explanatory tool for quantitative outcomes, offering a deeper exploration into the reasons behind specific trends. This integration of qualitative and quantitative data offers a comprehensive perspective on the intricate dynamics between technology and student learning in the flipped classroom setting.

Enhancement of learning through technology innovation

In the study, students emphasised the profound impact of technology on their learning experiences in the flipped classroom model. Simulation software was frequently highlighted for its effectiveness in enabling practical exploration, which is often difficult to achieve in traditional classroom settings. This sentiment was consistently echoed across participants, reflecting a strong consensus on the substantial enhancement that technology provides by offering hands-on learning opportunities that conventional lectures often lack.

The positive influence of technology extended notably to coding assignments, where students expressed particular appreciation for instant feedback mechanisms. One participant described the experience as similar to having a personal tutor, stating, "Interactive quizzes and instant feedback through online platforms reinforce concepts immediately, making it easier to understand and retain information." This observation underscores the perceived role of technology in guiding students through intricate algorithms and significantly improving their coding competencies.

Technology's collaborative potential also emerged as a key theme, particularly in relation to cloud-based Computer-Aided Design tools. As one student noted, "Collaborative projects using cloud-based tools have been excellent. We can work together in real-time, fostering teamwork even from different locations." This highlights the exceptional value students placed on technology in promoting collaboration, fostering teamwork, and managing complex design projects despite physical distance.

The challenges and frustrations of technology integration

Our study on technological integration in the flipped classroom revealed both positive impacts and notable challenges. Technical glitches during virtual lab sessions frustrated students and disrupted the natural flow of experiments, ultimately impeding their conceptual understanding. As one participant explained, "Software crashes disrupt experiments and affect our understanding." Such interruptions not only hinder the immediate learning experience but may also erode students' confidence in their ability to complete tasks independently, undermining the goal of promoting self-directed learning in STEM education. To mitigate these challenges, it is recommended that backup plans such as offering alternative offline simulation activities or pre-recorded walkthroughs be incorporated into lesson designs to ensure continuity when technical failures occur.

Disparities in access to technological resources further complicated students' experiences. Access to specialised, high-end engineering software often depends on owning powerful devices and this can create inequities among students. One participant captured this concern in stating, "Accessing complex software requires high-end devices, creating disparities among students." To address this issue, institutions could provide remote access to virtual desktops or cloud-based versions of specialised software, thereby reducing dependence on personal hardware. Establishing loan programs for laptops or offering subsidised hardware upgrades could also help bridge the technology gap among students.

Connectivity issues compounded these challenges. Internet access, device compatibility, and synchronisation problems emerged as persistent barriers to smooth participation. A student said, "Reliable internet access is crucial for streaming engineering lectures, posing challenges for students in remote areas who resort to time-consuming lecture downloads." To counter these barriers, institutions should prioritise providing downloadable content for offline access, support asynchronous participation options, and partner with service providers to offer subsidised data packages for students in underserved areas. Ensuring that learning platforms are optimised for low-bandwidth environments would further enhance accessibility.

These verbatim responses offer a nuanced perspective on the complexities of integrating technology into educational practices. They illustrate that while technology holds great promise in enhancing learning experiences, it also risks deepening existing inequalities and introducing new obstacles when technical infrastructure is insufficient. Addressing these challenges through proactive strategies, such as robust backup systems, equitable access initiatives, and offline learning options, is essential to ensure that all students can benefit fully and fairly from innovations in teaching and learning.

The nature of technology in self-directed learning

In our study on technology's impact on self-directed learning among engineering students, verbatim responses revealed a range of nuanced perspectives. Participants appreciated the empowering nature of technology, in particular expressing gratitude for the ease of accessing research materials, digital libraries, and online tutorials. Learning management systems such as Moodle and Blackboard were frequently mentioned as pivotal platforms that enable students to access lecture notes, supplementary readings, and self-assessment quizzes at their own pace, thereby fostering autonomy. However, concerns about online distractions were voiced, emphasising the need for a delicate balance between flexibility and focus. As one participant noted, "While technology provides access to valuable resources, it's easy to get distracted during online study sessions."

The flexibility of accessing course materials at any time was widely acknowledged as a key factor in promoting self-paced learning. Features such as recorded lectures, modular content delivery, and mobile accessibility were highlighted as crucial supports for students managing their own learning schedules. Nevertheless, some students expressed nostalgia for the structured routine of traditional classrooms, indicating that while technology facilitates flexibility, it can sometimes blur boundaries between learning and leisure. One participant reflected, "I do miss the structured routine of traditional classrooms, as it provided a sense of order and consistency."

These findings highlight the complex and dual-edged impact of technology on self-directed learning. On the one hand, digital platforms and features such as immediate feedback mechanisms, personalised learning paths, and on-demand resources significantly enhance students' capacity for independent learning. On the other, the freedom afforded by technology requires strong self-regulation skills to avoid distractions and maintain consistent progress. Recognising and addressing this balance is essential if we are to maximise the benefits of technology-driven education while mitigating its potential drawbacks.

Students' concerns and reservations regarding technology integration

In exploring concerns about technology in education, participants' verbatim responses provided rich insights into several nuanced challenges. Worries about potential disruptions caused by technical issues were prominent, with one student noting, "Technical issues can be frustrating and disrupt the flow of learning, making it harder to focus and learn effectively." Such disruptions were seen not only as barriers to cognitive engagement but also as factors that could diminish students' motivation over time, particularly when repeated technical frustrations led to feelings of helplessness or discouragement.

Privacy concerns also emerged as a significant issue, particularly regarding the security of personal data and intellectual work on online platforms. One participant emphasised, "Security of our work is a concern. How safe is our data on these platforms?" These apprehensions suggest that uncertainties about data protection can undermine students' trust in digital learning environments, leading to reduced willingness to engage fully with online tools and platforms. When students feel unsure about the safety of their work, this may inhibit open participation in collaborative tasks, uploading assignments, or sharing ideas freely, all of which are crucial components of a vibrant, self-directed learning experience.

Participants further articulated strong reservations about the perceived impersonality of online communication and evaluation methods, expressing a sense of disconnection from their learning community. As one student stated poignantly, "Online communication lacks the personal touch of face-to-face interactions. It feels impersonal, and sometimes, you miss that connection with your peers and instructors." This perceived emotional distance can impact students' intrinsic motivation negatively since social presence, the feeling of being *seen* and *heard* is a key driver of engagement and persistence in learning. When communication feels transactional or distant, students may feel less valued, less supported, and ultimately less motivated to invest effort in their learning journey.

These direct perspectives provide an authentic understanding of the multifaceted concerns surrounding technological reliance in the flipped classroom. They reveal that beyond technical proficiency, educational technologies must also address psychological and relational dimensions to maintain high levels of student engagement and motivation. Designing more secure user-friendly platforms and fostering opportunities for meaningful, personalised interactions will be critical to overcoming these barriers and ensuring that technology integration enhances, rather than diminishes, the human experience of learning.

Time management and efficiency in the flipped classroom

Participants valued highly the flexibility afforded by technology to access lectures at any time, thus emphasising its critical role in enhancing time management skills—a key aspect of self-directed learning among engineering students. One participant stated, "Having the flexibility to access lectures whenever suits me best has been a game-changer for managing my time effectively." Similarly, the ability to revisit recorded lectures was frequently praised for supporting independent learning, with another student noting, "Being able to revisit lectures is a great feature. It helps me navigate through complex topics at my own pace, ensuring a deeper understanding and making my learning experience more efficient." These findings align closely with the Effort Expectancy construct of the UTAUT, which emphasises the perceived ease of technology use (Venkatesh et al., 2003). As Testa and Tawfik (2017) have argued, understanding students' real interactions with digital tools, beyond theoretical expectations, is crucial. Our study similarly highlights that when technology is perceived as easy to navigate and flexible, it enhances engagement and promotes autonomous learning significantly.

However, despite these benefits, challenges related to the Facilitating Conditions construct also emerged. Participants reported difficulties in coordinating group work across different time zones, with one student expressing, "Coordinating group work can be tricky when everyone is in different time zones. It requires careful planning to ensure effective collaboration." These logistical barriers underscore UTAUT's assertion that external conditions, such as access to resources, institutional support, and infrastructure, directly influence successful technology integration (Al-Samarraie et al., 2020; Venkatesh et al., 2003). Inadequate support for managing asynchronous collaboration can diminish the perceived usefulness and ease of technology, ultimately impacting adoption and sustained use.

Our findings further resonate with broader literature on technology adoption and self-directed learning. For instance, Rashid and Asghar (2016) and Shadiev et al. (2024) found that technology use positively correlates with greater student autonomy and engagement. Similarly, our participants' experiences suggest that technology supports independent learning behaviours. However, as noted by Lai et al. (2024), increased engagement does not necessarily guarantee improved academic outcomes. This complexity mirrors UTAUT's recognition that Performance Expectancy, the belief that using technology will improve academic performance, can be influenced by many mediating factors, including learning design and student motivation.

In addition to performance-related perceptions, participants raised important concerns about the social dimensions of technology use. Privacy concerns and the impersonality of online interactions, as expressed by students, reflect the influence of both Social Influence and Effort Expectancy in UTAUT. As students grappled with the perceived lack of personal connection and risks to data security, their willingness to engage fully with online platforms was affected. As noted by Brewer and Movahedazarhouligh (2018), addressing these emotional and relational dimensions is vital to supporting technology acceptance. Therefore, ensuring data security and creating opportunities for meaningful interaction are essential for strengthening students' trust and the perceived value of technology-enhanced education.

Further emphasising external influences, our study aligns with those of Al-Samarraie et al. (2020) and Arora and Arora (2021), thus highlighting the importance of Facilitating Conditions such as the availability of reliable infrastructure, accessible platforms, and strong institutional support for flexible learning. By identifying time management benefits alongside collaboration barriers and emotional disconnects, our findings offer a comprehensive perspective that complements and extends UTAUT's applicability to modern, digitally mediated education contexts.

Ultimately, by aligning our findings with UTAUT (Venkatesh et al., 2003) and related research, we provide deeper insights into the multifaceted factors shaping technology adoption and integration in the flipped classroom model. These insights suggest that for technology to realise fully its potential in enhancing self-directed learning and student engagement, educators and institutions must not only ensure ease of use and robust technical infrastructure but must also address the emotional, social, and collaborative dimensions of the learning experience (Cheung et al., 2021). Our study thus contributes to the growing body of knowledge advocating for a holistic, learner-centred approach to technology integration in higher education.

In summary, our study's findings revealed nuanced alignments and divergences with the UTAUT constructs. Effort Expectancy was strongly supported since participants emphasised the ease of using technology platforms to enhance time management, flexibility, and independent learning. The ability to access and revisit recorded lectures contributed significantly to their engagement and autonomy. Facilitating Conditions, however, showed partial alignment since, while students benefited from institutional technology provisions, challenges such as coordinating group work across time zones and infrastructural limitations highlighted gaps in external support systems.

Regarding Performance Expectancy, participants acknowledged that technology enhanced their engagement and understanding of complex STEM content but noted that improved learning experiences did not always translate directly into higher academic outcomes, thus suggesting that technology's perceived usefulness is influenced by additional mediating factors like motivation and instructional design. Finally, findings related to Social Influence indicated divergence from UTAUT expectations: while technology enabled collaboration, concerns about data privacy and the impersonality of online interactions weakened students' emotional engagement and trust in digital platforms. Together, these patterns suggest that although technology integration facilitates many aspects of the flipped classroom model, success depends not only on usability and resource availability but also on fostering strong social presence and addressing relational and emotional needs in digital learning environments.

Limitations of the study

While this study provides valuable insights into the integration of technology in the flipped classroom model, several limitations must be acknowledged. First, the reliance on convenience sampling and voluntary participation may introduce self-selection bias since students who were more motivated or technologically confident may have been more likely to participate, thus at least potentially limiting the representativeness of the sample. Second, the study's focus on engineering students in a single South African higher education institution constrains the generalisability of the findings to broader populations, particularly across different disciplines, educational levels, or cultural contexts. Additionally, the mixed-methods approach, while strengthening the depth of the findings, also presents inherent challenges, including the potential for inconsistencies between self-reported perceptions and actual learning behaviours. Furthermore, the study was conducted during a period of rapid digital adaptation in education, which may have temporarily influenced students' perceptions and experiences with technology in ways that might differ under more stable circumstances. Acknowledging these limitations demonstrates a critical understanding of the study's scope and provides important context for interpreting the findings. Future research is encouraged to address these constraints through larger, more diverse samples, cross-institutional comparisons, and longitudinal designs that capture evolving student experiences over time.

Conclusion

Our study challenges assumptions regarding the transformative impact of technology in the flipped classroom, advocating for a more nuanced understanding that prioritises practical insights over theoretical expectations. The findings highlight the complexity of the relationship between technology integration and learning effectiveness, emphasising the need for educators to reassess their strategies critically when implementing educational technology in flipped learning environments. A key implication is the importance of adopting active learning approaches that prioritise hands-on, participatory experiences to foster deeper cognitive engagement and promote self-directed learning. Furthermore, clear and structured instructional design must be emphasised to help students navigate flexible content effectively, reducing cognitive overload, and supporting time management skills critical to success in self-paced environments.

Technological challenges identified by participants, including software reliability, equitable access to specialised resources, and the impersonality of online communication, point to areas in which educators and institutions must intervene proactively. Developing contingency plans for technical disruptions, such as offering offline simulations, downloadable materials, and robust technical support, can help mitigate disruptions to learning. Equitable access initiatives, including device loan programs, subsidised data packages, and cloud-based access to high-end software are essential to prevent digital disparities from undermining student success. In addition, fostering a stronger sense of social presence in online environments, through strategies such as virtual office hours, real-time discussion opportunities, and personalised instructor feedback, is crucial to maintaining motivation and engagement in the flipped classroom.

For future research, longitudinal studies are recommended to investigate how students' technology use, engagement, and learning outcomes evolve over time in flipped classroom settings. Further research should also explore which specific pedagogical designs, support structures, and technological interventions most effectively mediate the relationship between and among flexibility, motivation, and academic success. Comparative studies across different disciplines, institutional contexts, and cultural backgrounds would offer valuable insights into how technology integration strategies must be adapted to meet the needs of diverse learner populations.

Therefore, by shifting the focus from broad theoretical claims to practically grounded, student-centred approaches, educators and policymakers can better meet the complex and evolving needs of learners in technology-enhanced educational environments. Our study contributes to the ongoing refinement of the flipped classroom model, emphasising the importance of practical insights, continuous adaptation, and targeted interventions to optimise learning experiences and outcomes in the digital age.

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