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Integrating Digital Twins, Mathematical Modelling and Embodied AI to Bridge Simulation–Reality Gaps in Robotics Education: A Qualitative Case Study in South African HEIs

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Abstract. Robotic manipulation research in higher education institutions (HEIs) often faces the challenge of bridging the gap between simulation outcomes and real-world performance. This study, grounded in embodied intelligence theory and mathematical modelling, explored how digital twins and embodied AI can be integrated to enhance robotic manipulation in academic contexts. The research objectives were: (1) To investigate how digital twins and embodied artificial intelligence can be integrated to enhance robotic manipulation in higher education contexts. (2) To examine the contribution of mathematical modelling to improving the transfer of skills from simulation environments to physical robotic systems. The study adopted an interpretivist paradigm and a qualitative case study design. Data were collected over a six-month period in 2024 through semi-structured interviews and laboratory observations involving 15 participants, including lecturers, postgraduate students and technical staff from three HEIs with established robotics laboratories. Findings revealed that digital twins, supported by mathematical models, significantly enhance the transfer of manipulation skills from virtual simulations to physical robots. Meanwhile, embodied AI improves adaptability in unstructured environments and fosters effective human–robot collaboration. The study may contribute to policy and practice by recommending broader integration of digital twin platforms, incorporation of embodied AI into robotics curricula, and strengthened institutional collaboration to address resource disparities and promote inclusive robotics education across HEIs.

Keywords: Simulation; Reality; Digital Twins; Mathematical Modelling; Robotic Manipulation; Artificial Intelligence

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1. Introduction

The combination of digital twins, mathematical modelling and embodied artificial intelligence is increasingly influencing the future of robotic manipulation in higher education enabling seamless transitions from simulated environments to real-world applications (da Silva, 2024; Kuts et al., 2022). Digital twins allow robotic systems to be simulated virtually for modelling, testing and optimisation before deployment, while mathematical modelling provides the analytical basis for predicting system behaviour and enhancing performance. Embodied AI enhances this process by enabling adaptive, environment-responsive learning, thereby providing graduates with skills and competencies aligned with those demanded by the Fourth Industrial Revolution (4IR). Nevertheless, uptake of these technologies in the South African setting remains inequitable due to stubborn structural and digital disparities (Maleka & Maidi, 2024).

Although a minority of adequately resourced universities have sophisticated robotics laboratories, many historically marginalised and rural institutions suffer from infrastructure limitations, poor connectivity and limited access to simulation and automation facilities (DBE, 2024; Department of Basic Education, 2023; Sangwa et al., 2025; Schmidt et al., 2024). These disparities inhibit fair access to robotics education and hinder the development of the pedagogy required to implement cutting-edge equipment essential for innovation and skills acquisition (Nkosi, 2021; Sarkar, 2025). This divide has profound implications, as students in under-resourced HEIs are less prepared for robotics-driven industries, thereby perpetuating socioeconomic inequalities and undermining national innovation capacity (Aderibigbe et al., 2023; Soni & Kaur, 2023). Overcoming this challenge necessitates more than technological availability; it requires inclusive, context-relevant pedagogical strategies guided by strong theoretical frameworks.

Drawing upon a sociotechnical lens that builds on elements of constructivist learning theory and activity theory, this study conceives digital twins and embodied AI as mediational artefacts operating within wider systems of pedagogy, institutional resources, and socio-cultural frameworks (Schmidt et al., 2024; Trist & Emery, 2015). Constructivism emphasises learners' active capacity to construct knowledge through modelling and simulation-based activity, whereas activity theory places learning in interacting systems of tools, rules and community. While global research shows that these technologies are effective in well-resourced settings (Li & Yang, 2025), South African studies also illuminate infrastructural disparities that limit their uptake (Maleka & Maidi, 2024).

This study addresses a gap in current discourse by fusing digital twins with embodied AI and mathematical modelling at the level of a sociotechnical perspective with the goal of simultaneously deepening simulation-to-reality experiences as a learner and addressing institutional inequities in the South African higher education system (Alam & Mohanty, 2024; Kayyali, 2025; Kumar, 2025). Together, these perspectives support an analysis of both learning processes and the structural conditions that influence technology integration in higher education.

To guide this investigation, the study was directed by the following research questions:

1. How can digital twins and embodied AI be integrated to enhance robotic manipulation within higher education environments?
2. In what ways does mathematical modelling contribute to improving the transfer of skills from simulation environments to real-world robotic applications?
3. How can these technologies be leveraged, and what institutional strategies can be adopted, to promote equitable, inclusive and sustainable robotics education across South African higher education institutions?

By engaging these questions, the study not only contributes to theoretical debates on embodied intelligence and simulation–reality integration but also provides an empirical lens on how robotics education can be reimagined to address systemic inequities in South Africa. Ultimately, it seeks to generate actionable insights for policymakers, educators and researchers aiming to align robotics education with both national development priorities and global trends in the 4IR era.

2. Literature Review

To illustrate the conceptual alignment of this study, a thematic framework was developed to map how digital twins, mathematical modelling and embodied AI interact to bridge the simulation–reality divide, while accounting for structural inequalities within South African HEIs.

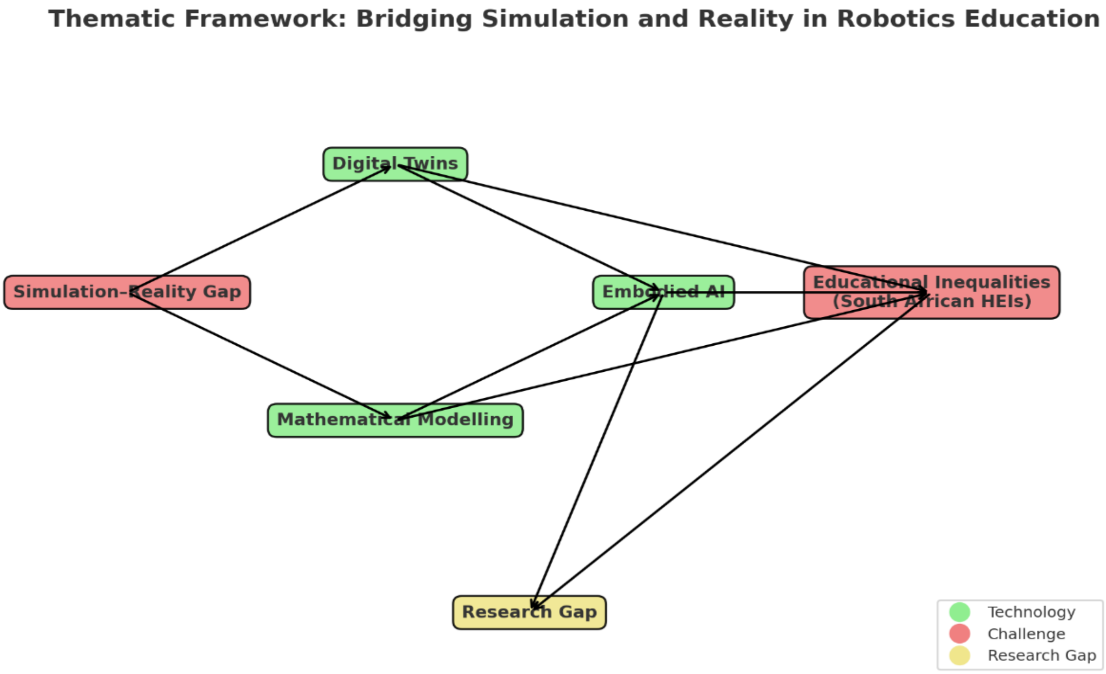

Figure 1: Thematic Framework for Bridging Simulation and Reality in Robotics

The framework highlights two key gaps: the limited integration of digital twins, mathematical modelling, and embodied AI to address simulation-to-reality challenges, and the lack of attention to the systemic educational inequalities that shape technology use in South African higher education.

Based on previous research documenting how digital twins, mathematical modelling and embodied AI can enhance robotics learning, this framework is further developed. It also recognises South African literature that shows continuing digital divides and infrastructure gaps in higher education. By linking these technological developments with the social and educational problems identified in the literature, the framework explains why this research is interested in the potential application of these technologies to reduce inequalities and facilitate robotics education in South Africa.

2.1 Digital Twins and Mathematical Modelling in Robotic Manipulation

Digital twins are increasingly used in robotics education to link simulation with physical experimentation, offering virtual models of robotic systems that enable iterative testing, optimisation and predictive analysis (Li et al., 2025). When combined with mathematical modelling, which underpins the analysis of kinematics, dynamics and control systems (Sajadieh & Noh, 2025), these tools enhance both theoretical and practical learning, effectively bridging the gap between simulation and real-world application (Mazumder, 2023). However, digital twins require significant computational resources and specialised expertise, making them costly to develop and maintain (Fuller et al., 2020). There exists limited evidence of their implementation in African and South African HEIs, highlighting the need for context-specific research.

2.2 Embodied AI and Learning in Robotics Education

Embodied artificial intelligence (AI) is reshaping robotics research and education by emphasising learning through physical interaction, a principle aligned with constructivist learning theory (Blackie & Luckett, 2025). In robotics education, embodied AI enhances adaptive learning and problem-solving, with studies showing its effectiveness in enabling robots to master complex manipulation tasks through reinforcement and imitation learning (Roy et al., 2021). However, despite its alignment with 4IR skills needs, integration into curricula remains limited due to high costs, technical demands and educator shortages, raising concerns that embodied AI may remain confined to privileged institutions unless localised strategies are developed (Zhou et al., 20221).

2.3 Educational Inequalities and Robotics in South African HEIs

There are substantial disparities across higher education institutions in South Africa regarding digital and technological access. Well-funded universities benefit from advanced robotics facilities, but rural and historically disadvantaged institutions tend to lack resources, funding and skilled personnel (Council on Higher Education, 2021; Mhlanga & Moloi, 2020). Equitable access to robotics education is crucial for national competitiveness in the Fourth Industrial Revolution (World Economic Forum, 2022). However, there is little local research on how digital twins and embodied artificial intelligence (AI) could help narrow the gaps (Mihai et al., 2022; Mugunzwa, 2024). Without additional research, the existing inequalities in graduate outcomes and innovation are expected to persist.

2.4 Synthesis and Research Gap

Research in a recent paper shows how digital twins, mathematical modelling and embodied artificial intelligence are essential for robotics education. These technologies provide realistic simulations, opportunities for repeated practice, an opportunity for deep understanding of concepts, and help transfer from virtual experiences to real life (Telukdarie et al., 2025). The literature has, however, mainly examined these tools in technology-rich environments, with little focus on their use in resource-limited settings, such as South Africa, or on their potential to address educational gaps (Mac Fadden et al., 2024).

3. Theoretical Framework

This research employs a framework grounded in embodied intelligence theory (Raza, 2025) and mathematical modelling (Berry & Houston, 1995). Embodied intelligence elucidates the learning process through the relationships among the robot, its physical form, and the surrounding environment while mathematical modelling offers formal representations of these relationships. Together, this framework integrates abstract mathematical reasoning with embodied experiences, promoting the application of digital twins and embodied AI in robotics education and seeking to address systemic inequalities within South African higher education institutions.

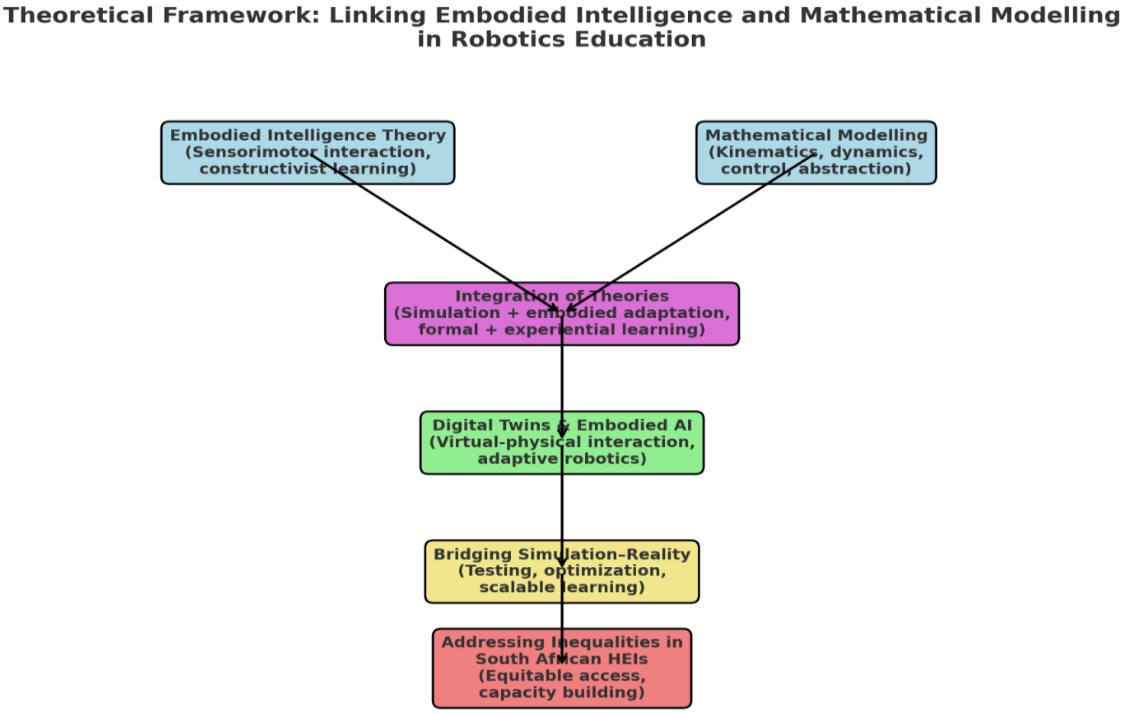

Figure 2: Theoretical Framework: Linking Embodied Intelligence and Mathematical Modelling in Robotics Education

Based on previous research documenting how digital twins, mathematical modelling and embodied AI can enhance robotics learning, this framework is further developed. It also recognises South African literature that shows continuing digital divides and infrastructure gaps in higher education. By linking these technological developments with the social and educational problems identified in the literature, the framework explains why this research is interested in the potential application of these technologies to reduce inequalities and facilitate robotics education in South Africa.

This study is anchored in a dual-theoretical framework that integrates embodied intelligence theory and mathematical modelling. More importantly, this framework enables a critical engagement with the structural inequalities facing South African higher education institutions (HEIs), particularly in rural and under-resourced contexts, thereby aligning the study with both global debates on robotics education and local imperatives of equity and access (Roy et al., 2021).

3.1 Embodied Intelligence Theory

According to embodied intelligence theory, cognition is the result of an agent's body and environment's real-time interaction, rather than simply the outcome of pure abstract calculation (Starzyk, 2008).

Application to Robotics Education: For robotics curricula, this view aligns with constructivism, which values active learning experiences. Embodied digital twins allow students to experiment, adapt and refine understanding through simulation, offering a viable pathway for meaningful robotics learning in resource-constrained South African HEIs (Vygotsky, 1978).

3.2 Mathematical Modelling

Mathematical modelling provides the formal and analytical foundation for robotics, encompassing the use of equations, algorithms and models to represent kinematics, dynamics, control systems and environmental interactions (Hazem et al., 2025). Through modelling, abstract principles are transformed into predictive systems that guide robotic design and manipulation.

3.2.1 Application to Robotics Education

In the academic context, mathematical modelling not only strengthens students' analytical skills but also bridges theory and application. Sathya et al. (2024) argued that by building and testing models, learners can predict how a robot will behave in a given scenario, optimise its performance, and understand the mathematical basis of adaptive systems. When embedded in digital twins, mathematical models enable safe, scalable and cost-effective experimentation, allowing students at underfunded HEIs to engage with robotics concepts without the need for expensive physical infrastructure. In the South African context, where only 37% of rural schools reported functional computer laboratories in 2023 (DBE, 2023), mathematical modelling serves as a crucial equaliser, enabling students to participate in robotics education through simulations and mathematical reasoning.

3.3 Integration of Theories: Towards Digital Twins and Embodied AI

The combination of embodied intelligence and mathematical modelling provides a synergistic framework for bridging simulation and reality in robotics education. While embodied intelligence emphasises the experiential, adaptive and context-driven aspects of learning, mathematical modelling ensures analytical precision, predictive capacity and formal validation (Zang et al., 2025). Together, they create a continuum in which:

- Digital twins act as the virtual embodiment of robotic systems, allowing mathematical models to simulate embodied interactions.
- Embodied AI provides adaptive learning capabilities, enabling robots and learners to co-evolve through trial, feedback and contextual adaptation.
- Pedagogical strategies leverage this integration to expose students to both formal abstraction (through models) and adaptive engagement (through simulation and practice).

This integration addresses a central tension in robotics education: the gap between simulation environments and real-world robotic behaviour. De Villiers (2023) emphasised that, by combining formal modelling with embodied adaptation, students can learn not only how to predict robotic performance but also how to design systems capable of learning and adapting in uncertain environments, a critical skill for the 4IR.

3.4 Implications for South African Higher Education

According to embodied intelligence theory, cognition is the result of real-time interaction between an agent, body and the environment, rather than simply the outcome of pure abstract calculation (Starzyk, 2008). In the context of a robotics curricula, this view is in keeping with constructivism, where active learning experience is valued. Embodied digital twins allow students to experiment, adapt, and refine understanding through simulation, offering a viable pathway for meaningful robotics learning in resource-constrained South African HEIs (Vygotsky, 1978).

4. Methodology

4.1 Research Paradigm: Interpretivism

This study adopted an interpretivist research paradigm, which posits that reality is socially constructed and best understood through the meaning's individuals attribute to their experiences (Pervin & Makhtar, 2022). Interpretivism is particularly suited to this study because it seeks to explore how students and lecturers in South African higher education institutions (HEIs) experience and interpret the use of digital twins, mathematical modelling and embodied AI to bridge simulation and reality in robotics education. Rather than striving for generalisability, the interpretivist approach emphasises depth of understanding, contextual meaning and the complexity of participants' lived realities, particularly within resource-diverse institutional environments (Jolly, 2025).

4.2 Research Design

A qualitative case study design was employed to provide an in-depth exploration of robotics education practices within selected HEIs (Chou et al., 2023). The case study design facilitates the integration of multiple data sources, such as interviews, focus groups and field observations, to capture the dynamic interplay among pedagogy, infrastructure and student engagement (Mămăligă, 2024). This design aligns with the interpretivist stance by valuing participants' perspectives and prioritising contextual interpretation over experimental control (Monrouxe, 2023). It further enabled the researcher to examine how institutional inequalities shape the adoption of robotics technologies and pedagogical innovation in diverse settings.

4.3 Population and Sample

The study population consisted of lecturers and students enrolled in engineering, computer science and mathematics education programmes with exposure to robotics or AI-related coursework (Stratton, 2021). The final sample included:

4.3.1 Three HEIs: one urban, well-resourced university and two rural, historically disadvantaged HEIs.

4.3.2 Fifteen (15) lecturers teaching robotics, mathematics, or AI-related modules.

4.3.3 Twelve (12) students drawn from senior undergraduate and postgraduate cohorts.

This sample size (n = 27) was deemed sufficient based on the principle of information power following Malterud et al. (2016), who argued that sample adequacy in qualitative research depends on study aims, specificity and data richness rather than numerical quantity. Participants were selected through purposive sampling, focusing on individuals with direct experience in robotics education and digital technologies in higher education. Selection was guided by relevance to the study aims and the ability to provide rich, context-specific data, thereby ensuring sufficient information power.

4.3.1.1 Sample Size Justification and Data Saturation

A purposive sampling technique was used to select the 27 participants, ensuring they had relevant experience in robotics education and digital technologies while allowing for sufficient analytical depth. As a qualitative case study research, a sample of this size is adequate for identifying convergent and divergent patterns of experience while allowing for meaningful engagement with each participant's context. Data saturation was achieved after the fifteenth lecturer interview and the second focus group discussion, when no new themes, concepts, or perspectives emerged. Subsequent interviews and discussions confirmed thematic stability, ensuring that the findings reflected a comprehensive understanding of the phenomenon under investigation.

4.3.1.2 Sampling Strategy

A purposeful sampling strategy was adopted to select participants with relevant experience and direct engagement in robotics or AI education (Palinkas, 2015). Lecturers were selected based on their involvement in teaching robotics, AI, or applied mathematics, while students were identified through departmental nominations to ensure inclusion of those who had engaged with robotics laboratories, simulations, or digital learning platforms. This approach prioritised *information-rich cases* capable of providing detailed insights into the opportunities and constraints of integrating robotics technologies in South African HEIs.

4.4 Data Collection Methods

Table 1: Summary of Data Collection Methods

Data Source	Participants	Purpose	Duration	Data Output
Semi-structured interviews	Lecturers (n = 15)	To explore teaching strategies, perceptions of digital twins and embodied AI, and institutional barriers to robotics technology use	45–60 minutes per interview	Audio recordings and verbatim transcripts
Focus group discussions	Students (n = 12 across three HEIs)	To examine shared learning experiences, access to robotics technologies, and perceptions of simulation–reality integration	Approximately 90 minutes per session	Audio recordings and group transcripts

Table 2: Coding Framework and Theme Development Process

Coding Stage	Description of Process	Examples of Codes	Resulting themes
Open coding	Initial inductive coding through close reading of transcripts to identify recurring ideas, practices and challenges related to robotics education	Simulation accuracy; equipment availability; student engagement; technical support	
Axial coding	Grouping related codes to explore relationships between technological practices and institutional conditions	Simulation–reality mismatch; mathematical abstraction; control precision	Bridging simulation and real-world manipulation
Selective coding	Refinement of core themes aligned with the conceptual framework and research objectives	Embodied learning; adaptive behaviour; human–robot	Embodied AI for adaptive robotic manipulation

These methods were selected to capture the depth of participants' experiences while allowing flexibility for unanticipated insights to emerge, consistent with the principles of interpretivist inquiry.

4.4 Researcher Positionality and Reflexivity

The researcher adopted a reflexive stance throughout the study, acknowledging her dual role as both an academic within a South African HEI and a scholar investigating institutional inequalities in robotics education. It provides a dual lens, one adaptive and experiential, the other analytical and predictive, which is uniquely suited to bridging the divide between simulation and reality. More importantly, it situates robotics education within the realities of South African HEIs, highlighting how theory can be mobilised to address structural inequalities while preparing students for meaningful participation in 4IR.

4.5 Data Analysis

Data were analysed thematically using Braun and Clarke's (2006) six-step process: familiarisation, coding, theme generation, reviewing, defining, and reporting (Braun & Clarke, 2006). A hybrid deductive–inductive approach was used. Initial codes were developed from the research questions, while additional themes emerged inductively from the data through iterative coding and constant comparison supported by NVivo software which supported the systematic coding of transcripts. Themes were guided by the research questions but remained open to emergent patterns (Elliott-Mainwaring, 2021). Key themes included:

1. Simulation as a scaffold for embodied learning.
2. Mathematical modelling as a bridge to reality.
3. Institutional inequalities shaping access to robotics.
4. Adaptive strategies for learning in constrained environments.

This process ensured that participants' voices were central, while also linking empirical findings back to the study's theoretical framework.

4.6 Trustworthiness

Credibility: Triangulation of lecturer interviews and student FGDs ensured multiple perspectives on the same phenomenon (Bang, 2024). Member checking was used by sharing summaries with participants to validate interpretations.

Transferability: Support was provided by including participants from diverse institutions and by documenting detailed contextual information, allowing readers to assess the applicability of the findings to similar settings.

Dependability and Confirmability: An audit trail (including interview guides, coding decisions and reflective notes) was maintained, ensuring transparency in methodological decisions (Carcary, 2020).

4.7 Ethical Considerations

The researcher adopted a reflexive stance throughout the study, acknowledging her dual role as both an academic within a South African HEI and a scholar investigating institutional inequalities in robotics education. To address concerns regarding data trustworthiness, the study applied established qualitative rigour strategies, including reflexive journaling to document analytic decisions, triangulation across data sources and institutional sites, and peer debriefing with independent colleagues to challenge interpretations. These measures strengthened the credibility and dependability of the findings and reduced the risk of researcher bias. These measures enhanced transparency, reflexivity, and analytical credibility.

5. Results

Data analysis yielded four key themes that reflect participants' experiences of integrating digital twins, mathematical modelling and embodied AI into robotics education in South African HEIs. Each theme was illustrated with verbatim quotations to foreground participants' voices.

5.1 Theme 1: Simulation as a Scaffold for Embodied Learning

The findings indicated that simulation and digital twin technologies are part of the teaching process for rural higher education, rather than adjuncts. Simulation provided students a secure space to practice, easing their concerns about operating expensive or delicate equipment, they said. This allowed them to build confidence and learn by experimenting rather than working with real robots. As one student put it, *"With the digital twin, I could test the robot's movements without worrying about breaking the machine. It gave me confidence before we touched the real robot"*.

Another student shared, *"Practising in the simulator helped me build confidence before using the physical hardware"*. These examples demonstrate that simulation is crucial for preparing students to work with real robots. The lecturers concurred, suggesting that simulation addressed the issue of constrained supplies on rural campuses. When there are insufficient physical robots for robotic education, simulation is often the primary means of instruction. One lecturer remarked, *"The simulator is like our robot"*, and another added, *"The virtual environment becomes our classroom"*. They pointed out, too, that, with digital twins, students can experiment safely in this kind of environment and learn from their mistakes: *"students can make mistakes, test their assumptions and improve their code without damaging fragile equipment"*.

In conclusion, this article shows how simulation supports safe, risk-free learning. Simulation means students can learn with confidence, feel secure and acquire skills. Digital twins also help more students engage in robotics education by making robotics less reliant on expensive equipment and easier to approach, particularly in rural areas with fewer resources.

5.2 Theme 2: Mathematical Modelling as a Bridge to Reality

According to my students, simulation environments allow students to connect abstract math theory to real robotics. For a long time, they viewed math formulas as separate from real-world use, but they became comprehensible when applied in the simulator. It could also show students how equations predict and control the robot's movement. Mathematical modelling combined with simulation improved their insights and demonstrated why mathematical reasoning is critical in robotics.

The findings show that simulation-based learning helps students connect abstract mathematical theory to real robotic behaviour, making equations meaningful and practical. Students reported that formulas became understandable when applied in simulators, where they could see how equations predict and control robot movement. As one student explained, *"At first, I thought the formulas were just theory, but when I applied the equations in the simulator, I saw how they predict what the robot will actually do"*, while another noted that simulations show *"how robots actually think and move"*. Students who previously struggled with mathematics indicated improved understanding once models were tested in simulations: *"Once we ran them on the simulator, I understood why they mattered"*. Lecturers reinforced this view, emphasising that mathematical modelling provides structure and meaning to robotics, especially in resource-constrained contexts. As one lecturer stated, *"Without equations, robotics is just trial and error"*, while others described modelling as *"the language that makes robotics possible"*. Overall, combining mathematical modelling with simulation enhanced conceptual understanding, demonstrated the value of mathematics in robotics, and supported more equitable access to robotics education in rural colleges.

5.3 Theme 3: Institutional Inequalities Shaping Access to Robotics

Results showed that institutional inequities prevent both students and lecturers from fully engaging in robotics education. According to students, schools with fewer resources, especially in rural areas, often lack robotics labs, hindering hands-on learning. *"Our university does not have a robotics lab"*, said one student, adding *"I only did coding on my laptop, and I felt I was behind compared to peers in bigger universities"*. These differences produce disparities in learning opportunities.

As one student noted, *"The first time I compared notes with my friends from other universities, I noticed just how behind we were in our own learning. They had labs, projects, and internships we could only dream of"*. Many students consider these differences to be unfair, particularly as regard to future employment opportunities: *"Sometimes it feels unfair, we are supposed to compete for the same jobs, but we don't have the same preparation"*. Lecturers addressed many of these concerns, underscoring the tangible and emotional toll of educational inequality. They are frustrated that having fewer resources prevents them from leveraging their skill sets to the fullest.

As a lecturer said, *"I can use robotics to motivate my students to want to excel as an example, but we're unable to even buy the same basic kits because our school cannot afford them"*. These gaps are most apparent at conferences where this inequality occurs: *"I see colleagues from urban universities presenting projects built with advanced robotics… I return to my campus and feel the gap widening"*. The comments by the students reflected those by the professors, saying that this inequality shapes their prospects: *"Urban students get internships in robotics labs, while our students rely mostly on simulations and sometimes don't see a real robot until their senior year of college"*.

In short, these comments reveal how structural disparities in students' access to resources and in students' self-belief in educational opportunities for hands-on experience and future employment are constricted when systemic injustices in educational robotics are exposed as the problem under analysis. Although simulations can promote learning where materials are limited, their dependence on them can contribute to a better understanding of higher education. These findings emphasise the need for equitable solutions that leverage digital tools and address the root causes of such disparities.

5.4 Theme 4: Adaptive Strategies for Learning in Constrained Environments

The results unveil institutional inequities in maintaining participation in robotics education under South African universities, especially in rural areas. Students described unequal access to resources and equipment: One student said, *"Our university is missing a robotics lab… I only had access to coding on my laptop and felt inferior compared to my peers in larger schools"*. The sense of marginalisation, in particular, was also evident. However, students and faculty engaged in flexible and cooperative ways to sustain the learning process. Social interactions among peers—such as device sharing and mutual teaching—were the norm for students, as reflected in statements like *"We started sharing laptops in groups of three," and "explaining it to another just got us to learn it more"*.

Lecturers, too, adapted pedagogy, using open-source and offline tools, as one said, *"I taught students to leverage free AI platforms without any online access"*. Digital twins, simulations and mathematical modelling facilitated hands-on learning opportunities and connected them to the theoretical and practical integration; however, the study participants recognised that such tactics did not address the structural injustices at the core. Nonetheless, the results imply that site-specific, tailored interventions can improve student engagement in robotics education, although broader institutional interventions remain needed.

6. Discussion of Findings

6.1 Integration of digital twins, embodied AI and robotics learning (RQ1): The results for the first research question suggest that digital twins, as well as embodied AI, are particularly relevant for connecting simulation with the real-world manipulation of robots, particularly in rural and resource-limited South African HEIs. Consistent with other international literature (e.g., Choi et al., 2021; Weinhandl & Lavicza, 2021), simulations are not merely preparatory tools but critical learning environments that enable experimentation, mitigate equipment risk and foster learner confidence prior to physical engagement. The study also shows that, in rural South African contexts, simulations typically replace physical laboratories rather than augmenting them.

This finding, from a sociotechnical perspective, reveals how institutional constraints and technological tools together reconfigure teaching practices. Where earlier work on well-resourced settings has described digital twins as an improvement of hands-on experience, this work highlights a turn: in such contexts, digital twins constitute foundational instructional infrastructure. This is consistent with constructivist and embodied learning theories, which emphasise learning through interaction, feedback and iterative experimentation, even when the hands-on experience is digitally mediated.

6.1.1 Mathematical Modelling and Simulation–Reality Transfer (RQ2)

The results of the study suggest that mathematical modelling facilitates students' use of abstract theory in practical operations within a robotic environment. In simulation contexts, equations pertaining to kinematics, control and motion became more meaningful to students as they could see how mathematics provides predictions and uses this knowledge to control robotic movements. This aligns with Brown et al. (2024), explaining that students can use modelling to relate symbols to system operations to achieve a better grasp of concepts. Notably, this work demonstrates that mathematical modelling is also a pedagogical leveller when advanced hardware is not widely available. Lecturers explained that even low-tech methods for teaching modelling can be taught conceptually. They also noted that it enabled meaningful manipulation of robotics principles through simulation. This fills an existing gap in the literature by situating mathematical reasoning as a cognitive tool and an opportunity to advance equity through its inclusion in robotics education, provided it is not infrastructure-based.

6.1.2 Educational Disparities and Adaptive Practices (RQ3)

In terms of equity and inclusion, the findings confirm that institutional inequalities remain persistent limiting factors for robotics education (Choi et al., 2021) and, as in earlier studies, they inhibit access to robotics education. The students' sense of marginalisation and lecturers' frustration suggest wider systemic problems in South African higher education, which manifest in uneven access and the lack of infrastructure, connectivity, and equipment to sustain progress. In contrast to research that primarily documents these inequalities, the current study draws attention to how students and lecturers work with these constraints by employing flexible learning strategies.

In line with De Silva and Peramunugamage (2023), participants demonstrated resilience in sharing devices, open-source software and learning together. These strategies illustrate how learning communities can mitigate structural disadvantages to some extent through social education and innovative pedagogy. From an activity theory perspective, these techniques are collective responses within an activity system that adjust tools, rules and the division of labour to maintain learning despite limitations.

6.1.3 Implications for Theory and Practice

The bottom line is that these data suggest that although digital twins, embodied AI and mathematical models may not have the potential to completely disrupt systemic inequality, they offer promising new forms of access to robotics education when used in context-specific ways. This study may contribute to the global literature by providing insights into the realities of rural HEIs and the ways sophisticated technologies are developed under constraints in rural contexts. Theoretically, the findings contribute to contemporary sociotechnical and constructivist perspectives that learn through the interaction among technology, pedagogy and institutional context. In a pragmatic sense, the results suggest that simulation as a 'supplementary' activity can enhance the inequality process, whilst deliberate modelling-led simulations may facilitate an inclusive approach to South Africa's digital transformation.

7. Recommendations

The study recommends a multifaceted strategy to promote equitable and innovative robotics education in South African higher education. It urges universities, particularly in rural areas, to invest in digital infrastructure, integrate simulation-based learning and mathematical modelling into curricula, and provide continuous professional development for lecturers. The use of open-source and low-cost software is highlighted as vital for affordability and sustainability. To reduce systemic disparities, the study recommends policies that support digital equity through targeted funding, institutional collaboration, and the establishment of shared innovation hubs. Partnerships with industry and government should align training with labour market needs, while rural institutions should develop context-specific, low-cost solutions. Ultimately, fostering resilience, creativity and research on digital pedagogy will ensure sustainable, inclusive and future-oriented robotics education.

8. Limitations of the Study

Several limitations should be noted when interpreting the findings of this study. Firstly, it employed a qualitative case study design with a small, purposively selected sample from three South African higher education institutions (HEIs). Thus, while this approach facilitated deep dives into participants' experiences, it limits the generalisability of our findings to other institutional or national contexts. Secondly, reliance on self-reported qualitative data may introduce subjectivity, including participants' perceptions, recall bias and socially desirable responses. Third, the study focused on resource-constrained HEIs, which may not fully capture how digital twins, mathematical modelling and embodied AI function in well-resourced environments. Finally, the cross-sectional approach of the data does not encompass long-term learning outcomes or sustained pedagogical impact.

9. Future Research

The results suggest that future research should utilise mixed-methods, longitudinal and (quasi-)experimental designs to strengthen evidence on the effectiveness of digital twins, mathematical modelling and embodied AI in robotics education. Mixed methods could integrate quantitative measurement of learning outcomes with a qualitative understanding of how and for whom such improvements occur across the diverse segments of South African HEIs. Longitudinal investigations are required to assess sustained conceptual understanding, computational thinking, retention in the programme and transfer from simulation to reality, especially in rural and historically disadvantaged areas.

Using experimental and quasi-experimental methods to investigate causal associations, comparative analysis of digital twin-enriched, blended and traditional forms of instruction can be supported. Future work could beneficially validate transfer from simulation to reality via parallel virtual–physical task performance and investigate design attributes which would support effective real-world experience. Research on equity and multi-site implementation is needed to understand how infrastructure, access and low-cost configurations shape impact, and help to inform research on professional development, institutional support and cost-effectiveness. Lastly, participatory and design-based research can yield contextually relevant, scalable and equitable intervention models adapted to low-resource settings.

Conflict of Interest

The author confirms that there are no known financial, personal, or professional conflicts of interest that could have appeared to influence the work reported in this manuscript.

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