Leveraging Industry 4.0 Technologies for Construction and Demolition Waste Management in South Africa

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Abstract
The construction industry generates significant construction and demolition waste (C&DW). This remains a growing challenge in South Africa. Conventional management approaches have proved inadequate, while Industry 4.0 (I4.0) technologies provide new opportunities to improve efficiency and sustainability. This study examines the adoption of I4.0 technologies for C&DW management in South Africa and their role in promoting digital transformation and resource efficiency. This study used a quantitative research approach. The study collected 102 responses from construction professionals in South Africa using a structured questionnaire. The responses were analysed using Percentages, Mean Item Score, Standard deviation, and a one-sample t-test. The findings show that GIS, GPS, IIoT, UAVs, and cloud computing are the most widely adopted technologies. This reflects their practical value in waste monitoring, data management, and process coordination. However, advanced technologies like blockchain, digital twins, robotics, and AI are still underutilised. These results highlight both progress and challenges in the industry's digital transformation. The study concludes that I4.0 technologies have the potential to reduce waste, optimise resources, and support sustainable construction practices. Thus, it recommends stronger policy support, targeted training, industry-wide collaboration, and pilot projects to accelerate adoption. These insights contribute to policy and practice by showing how digital tools can reshape waste management strategies in developing nations.

Keywords
Construction and demolition waste management, Industry 4.0 technologies, South Africa.

1. Introduction

The construction industry (CI) is one of the most significant contributors to global waste, generating about 40% of the world's total solid waste annually (van Stijn et al., 2020). According to Andrade et al. (2018), projections show that construction and demolition waste (C&DW) will increase from 12.7 billion tonnes in 2012 to 27 billion tonnes by 2050. A significant portion of this waste still ends up in low-capacity landfills. This leads to energy consumption, water pollution, environmental degradation, and harmful gas emissions (Abdullahi et al., 2023; Ding et al., 2016; Huang et al., 2018; Wang et al., 2020). These concerns highlight the urgency of adopting innovative and effective waste management practices in the construction sector. Industry 4.0 (I4.0), defined by digital transformation and interconnected technologies, presents opportunities to address these challenges. Unlike conventional C&DW management approaches, which often rely on manual processes and reactive strategies, I4.0 technologies provide proactive, data-driven solutions (Chong et al., 2017; Sagan & Sobotka, 2021; Mishra, 2024). These technologies support accurate forecasting of material flows, improve tracking of waste streams, and enable better recovery and reuse of materials. Thus, they align with global efforts to promote sustainable resource use and circular economy practices in construction.

The construction industry in South Africa is under growing pressure to reduce waste and transition towards sustainability. However, adoption of I4.0 technologies in the country remains limited. Existing studies on C&DW management in South Africa have focused mainly on recycling practices (Otasowie et. al., 2024a) and stakeholder behaviour (Otasowie et al., 2024b), with little emphasis on how emerging technologies could transform waste

management systems. This creates a gap in both academic knowledge and practical guidance. Hence, limited empirical research explores leveraging I4.0 technologies for C&DW management in South Africa. This study addresses this gap by investigating the I4.0 technologies that can be applied to improve C&DW management in the South African construction industry. The contribution of this study is threefold. First, it provides empirical evidence on the applicability of I4.0 technologies in C&DW management in South Africa, an area largely overlooked in current literature. Second, it highlights the relationship between digital transformation and sustainable construction practices. This provides insight into how advanced technologies can reduce waste and improve resource efficiency. Finally, it provides recommendations to guide policy and practice integrating I4.0 solutions into waste management strategies. This will support South Africa's broader sustainability agenda.

2. Methods

This study adopted a quantitative research design. This enabled the collection of numerical data from a large sample for statistical analysis. This approach was appropriate because the research explored leveraging I4.0 technologies for C&DW management in South Africa (Ishtiaq, 2014). The study focused on registered construction professionals, including architects, quantity surveyors, engineers, construction managers, and project managers working in different construction organisations. The sample frame was drawn from the Construction Industry Development Board (CIDB) register, with attention given to professionals in grade 7–9 organisations due to their higher experience levels. Using Yamane's (1967) formula, a sample size of 311 was determined from a population of 1,400 professionals. However, 102 valid responses were obtained and analysed, which is acceptable for statistical research in construction management. A simple random sampling technique was applied to ensure equal selection probability across the population (Etikan & Bala, 20170). Data were collected using a structured, closed-ended questionnaire developed from a literature review on I4.0 technologies. The questionnaire had two sections. The first section focused on the demographics of the respondents. The second section focused on the I4.0 technologies for C&DW management. The instrument employed a five-point Likert scale to capture respondents' level of agreement, as this method is widely used in construction management studies for its simplicity and suitability for statistical analysis (Alabi & Jelili, 2023). The collected data were analysed using descriptive statistics. Percentages were used to summarise demographic responses, while Mean Item Scores (MIS) identified the most significant I4.0 technologies for C&DW management in South Africa. Standard deviations assessed response variability (Field, 2005), and a one-sample t-test tested whether the mean scores significantly differed from the hypothesised midpoint. Cronbach's alpha was calculated to test reliability, and the result (0.94) exceeded the recommended threshold, confirming the instrument's internal consistency. Ethical research procedures were followed throughout. Participation was voluntary, respondents were informed about the purpose of the study, and anonymity and confidentiality were maintained. The data were used solely for academic purposes.

3. Results

The background of the respondents supports the reliability of the study. Among the 102 participants, 19.61% held a bachelor's degree, 48.04% an honours degree, 28.42% a master's degree, and 3.92% a doctoral degree. This shows that most respondents had the academic capacity to understand I4.0 adoption for C&DW management (Bryman, 2016). For professional roles, engineers accounted for the highest proportion at 23.53%, followed by construction managers (18.63%), quantity surveyors (16.67%), project managers (16.7%), urban planners (12.75%), and architects (11.76%). This distribution indicates that the study captured perspectives of major stakeholders in the construction industry. The respondents also reflect a wide range of work experience. 12.8% had less than one year of experience, 37.3% had between one and five years, 28.4% had six to ten years, 11.8% had eleven to fifteen years, 6.9% had sixteen to twenty years, and 2.9% had more than twenty years. This mix of early-career and highly experienced professionals ensured balanced perspectives. Employment sectors were also well represented, with 55.5% of respondents from contracting organisations and 45.5% from consultancy organisations. This balance highlights that perceptions of I4.0 for C&DW management were examined across different industry segments. Hence, the participants' qualifications, roles, and experience strengthen the validity of the study findings.

In addition, to analyse I4.0 for C&DW management, the study used the mean, standard deviation, and one-sample t-test. These methods are widely recognised for evaluating perceptions in construction research (Field, 2005; Pallant, 2020). The mean provided the average rating of each technology on a five-point Likert scale, while the standard deviation measured the spread of responses. A lower standard deviation indicated stronger agreement among participants. The one-sample t-test assessed whether the mean scores significantly differed from the hypothesised

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midpoint of 3.5 at a 95% confidence level. This is consistent with statistical standards in social science and construction research (Hair, 2016). A technology was considered statistically significant if the p-value was ≤ 0.05. In cases where mean scores were equal, ranking was based on the lowest standard deviation (Bryman, 2016). Table 1 presents the study's I4.0 technologies and their mean values, standard deviations, and t-test results.

Table 1. One-Sample Statistics and Test of Technologies

I4.0 Technologies	T	Df	Sig. (1-tailed)	Mean	SD	Mean Diff.	95% Confidence Interval of the Diff. Lower	Upper
Geographical Information System (GIS)	7.576	101	<.001	4.29	1.189	.794	.59	1.00
Global Positioning System (GPS)	6.269	101	<.001	4.19	1.106	.686	.47	.90
Industrial Internet of Things (IIoT)	4.220	101	<.001	3.99	1.173	.490	.26	.72
Drones/Unmanned Aerial Vehicle (UAV)	3.405	101	<.001	3.87	1.105	.373	.16	.59
Cloud Computing	2.998	101	.002	3.85	1.059	.353	.12	.59
Big Data	2.553	101	.006	3.79	1.163	.294	.07	.52
Automation	2.463	101	.008	3.78	1.166	.284	.06	.51
Machine Learning/Deep Learning	2.228	101	.014	3.75	1.156	.255	.03	.48
Building Information Modelling (BIM)	2.053	101	.021	3.73	1.109	.225	.01	.44
Mixed Reality (Augmented/Virtual)	1.147	101	.127	3.64	1.209	.137	-.10	.37
Artificial Intelligence (AI)	.852	101	.198	3.60	1.163	.098	-.13	.33
Prefabrication	.648	101	.259	3.58	1.222	.078	-.16	.32
Blockchain Technology	.623	101	.267	3.57	1.113	.069	-.15	.29
Digital Twin	-1.138	101	.129	3.38	1.044	-.118	-.32	.09
Robotics	-3.501	101	<.001	3.08	1.216	-.422	-.66	-.18

SD: Standard deviation; DF: Degree of Freedom; T: T-test Value

4. Discussion

The findings reveal uneven adoption of Industry 4.0 technologies (I4.0Ts) for construction and demolition waste (C&DW) management in South Africa. It clearly distinguishes between mature technologies and those still at an emerging stage. The findings show that integrated tools such as Geographical Information Systems (GIS), Global Positioning Systems (GPS), the Industrial Internet of Things (IIoT), Unmanned Aerial Vehicles (UAVs), and cloud computing collectively explain a large share of adoption variance. This reflects their perceived practicality and immediate operational value. GIS emerged as the most widely adopted. This reinforces evidence that GIS provides critical capabilities for spatial mapping of waste streams, monitoring illegal dumping, and planning sustainable disposal routes (Li et al., 2025; AlZaghrini et al., 2019). The consistently high adoption rate among practitioners suggests that GIS is not only an accessible tool but also serves as an anchor for integrating more advanced technologies. It provides both a visual and analytical foundation for decision-making in C&DW management. Furthermore, GPS was the second most adopted technology. Its mainstreaming indicates a strong recognition of its role in improving transport logistics, reducing fuel consumption, and ensuring compliance with disposal regulations

(Chong et al., 2017). Unlike many other I4.0Ts, GPS might have reached a phase of routine application. This signals that South Africa might have developed baseline competence in digital tracking. IIoT adoption, although significant, remains uneven. This might be due to infrastructure and cost constraints (Otasowie et al., 2023). However, its increasing use reflects a gradual shift toward predictive analytics and proactive waste management through sensor-based monitoring. UAVs also showed good adoption. This highlights their contribution to efficiency in site inspections and waste hotspot detection (Chen et al., 2025). Nonetheless, the response variability might indicate that regulatory and skills-related challenges restrict their scalability. Also, cloud computing has demonstrated stable adoption. This aligns with global trends. Cloud platforms enable collaboration, remote access, and integration across project stakeholders (Marques & Ferreira, 2020). Its diffusion in South Africa signals a readiness for collaborative project environments and data-driven circular practices.

Furthermore, big data and machine learning (ML/DL) recorded good adoption levels. This suggests growing interest in advanced analytics for forecasting waste generation and optimising recycling strategies (Otasowie et al., 2024c). However, the unevenness reflected in confidence intervals underscores the shortage of local expertise in data science. Similarly, the adoption of Building Information Modelling (BIM) remains moderate. However, BIM has been widely recognised for its ability to minimise waste through improved design and planning (Ajayi et al., 2015; Chong et al., 2017). Nevertheless, barriers such as upfront investment and training have slowed its diffusion. In addition, technologies such as mixed reality (MR), artificial intelligence (AI), prefabrication, blockchain, and digital twins have not been adopted significantly. Their uncertain status might reflect systemic barriers such as high capital costs, lack of supportive infrastructure, and limited policy incentives. Despite blockchain's potential to enhance transparency in waste transactions (Wang et al., 2020), it remains underexplored in South Africa. Similarly, although digital twins show promise for real-time simulation of material flows, the results suggest they might be primarily confined to conceptual discussions rather than field deployment. In addition, robotics adoption showed a significantly low adoption level. This reinforces concerns around affordability, technical capacity, and the absence of enabling ecosystems (Pan & Zhang, 2021).

Hence, these findings point to a tiered adoption landscape. The findings suggest that GIS, GPS, and cloud computing might have been institutionalised in South Africa. Other technologies, such as IIoT, UAVs, big data/ML, and BIM, seem to be growing in terms of adoption for C&DW management in the country. This is because they face barriers such as cost and skills-related constraints. In addition, cutting-edge tools such as AI, MR, blockchain, digital twins, and robotics remain experimental. This suggests they require targeted interventions to transition from the pilot stage to the mainstream. This hierarchy might mirror adoption pathways reported in other emerging economies, where technologies with immediate and tangible benefits are adopted earlier than those requiring systemic change. The theoretical implication of these findings reinforces the adoption of a life-cycle model by technology. It shows that relative advantage, trialability, and complexity shape diffusion rates in resource-constrained economies. Practically, the findings suggest that South Africa's C&DW sector should prioritise leveraging existing competencies in GIS, GPS, and cloud platforms as gateways for scaling up more advanced systems. Furthermore, addressing uneven adoption will require multi-level strategies such as government-led demonstration projects to de-risk new technologies, fiscal incentives to support capital-intensive tools, and workforce development programmes to close digital skills gaps. Also, collaborative pilot schemes between industry, municipalities, and academia can create feedback loops demonstrating tangible value and accelerating mainstreaming.

5. Conclusions

This study highlights the link between digital transformation and sustainable construction practices in South Africa. The findings show that I4.0 technologies such as GIS, GPS, IIoT, UAVs, and cloud computing already contribute to improved monitoring, coordination, and data-driven decision-making in C&DW management. These technologies demonstrate how digital tools can drive waste reduction and resource efficiency by enhancing transparency, optimising material flows, and supporting collaborative planning. However, emerging technologies such as blockchain, AI, digital twins, and robotics remain underutilised, reflecting cost, skills, and infrastructure barriers. This uneven adoption suggests that while the sector is moving toward digital transformation, more substantial support is required to unlock the full potential of advanced technologies. The study provides practical insights for policymakers, construction organisations, and industry stakeholders. Policies should create incentives for digital adoption, while training programs can build the skills needed to use I4.0 solutions effectively. Also, construction organisations should consider pilot projects and partnerships to test innovative technologies before scaling them across projects. The construction industry can advance sustainability and efficiency, contributing to a more circular and resource-conscious industry by integrating digital solutions into C&DW management strategies.

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