

Article

Intelligent Wearable Technologies for Workforce Safety in Built Environment Projects in South Africa

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Abstract: In a quest for the safe and sustainable delivery of built environment projects in South Africa, this study explored intelligent wearable technologies (IWTs). A post-positivism philosophical stance was adopted by surveying 165 built environment experts. The technology–organisation–environment (T–O–E) framework was also employed in understanding the critical factors influencing the use of IWTs in the study area. Data analyses used mean scores, the Kruskal–Wallis H-test, confirmatory factor analysis, and structural equation modelling (SEM) with appropriate model fit indices. It was found that, albeit at a slow pace, IWTs such as smart safety vests embedded with indoor GPS/sensors, smartwatches, and smart safety helmets are gradually gaining popularity within the South African built environment. SEM revealed that while all the assessed T–O–E factors are important to the increased use of IWTs within the study area, the environment- and technology-related factors will significantly impact how individuals and organisations use these beneficial wearable technologies. This study contributes to the existing discourse on intelligent technologies for the safety of the built environment workforce from the South African perspective, where such studies have received less attention.



Citation: Aghimien, L.; Ngcobo, N.; Aghimien, D. Intelligent Wearable Technologies for Workforce Safety in Built Environment Projects in South Africa. *Sustainability* **2024**, *16*, 3498. <https://doi.org/10.3390/su16083498>

Academic Editors: Zufen Wang, Wei Zhang and Wentao Wu

Received: 5 March 2024

Revised: 17 April 2024

Accepted: 19 April 2024

Published: 22 April 2024



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Keywords: construction workforce safety; intelligent technologies; occupational health and safety; smart wearables; SEM; T–O–E

1. Introduction

The built environment, which comprises the Architecture, Engineering, and Construction (AEC) industry, has been pivotal to infrastructure delivery and socio-economic development in developed and developing countries worldwide [1]. Adding over USD three trillion to the global gross domestic product and providing millions of jobs to people worldwide, the AEC industry is highly valuable to the growth of diverse countries [2]. The AEC industry is labour-intensive [3], so ensuring workers' safety is essential for a sustainably developed built environment [4]. The importance of safely delivering built environment projects has received significant attention in many industry and academic discourses. This is because the AEC industry, while providing structures that meet individuals' needs, heavily depends on people to successfully deliver these projects [5]. This high dependence on people, coupled with the dangerous nature of the industry, implies the need to prioritise the safety of the workforce. Unfortunately, despite the continued attention garnered by safety within the built environment domain, injuries and fatalities still trail the industry around the world [6–8].

Reports of unsafe delivery of AEC projects and unsafe behaviour of site workers have continued to emerge over the years. With over 2.78 million deaths occurring due to

occupational accidents, the AEC industry is said to be responsible for one out of every six deaths recorded [7,9]. The case is worse in developing countries like South Africa, where safety is not prioritised due to several issues, including poor incentives to ensure safety on projects [10]. Several approaches have been proposed to ensure the safety of workers on built environment projects, including the development of safety models and practices, safety training, and the use of technological innovations [11]. From the technology perspective, studies have explored the use of emerging digital technologies such as drones, robotics, and augmented and virtual realities to address issues of general construction safety and improve the health conditions of workers [12–14]. Further advancements in technology have seen the development and deployment of intelligent wearable technologies (IWTs) in the quest for the safe delivery of projects. Also known as smart wearable technologies, these IWTs are worn by workers to monitor their health or alert them of any impending danger that might hamper their safety [15,16]. These IWTs are in the form of smart clothing, watches and wristbands, boots, and helmets, among others, which are fitted with electronic components and worn closer to the skin to detect, analyse and transmit information regarding the health and safety of the wearer [17]. Based on the importance of wearable technologies, Ahn et al. [18] noted that several studies have employed them to identify possible construction site hazards and continuously monitor construction workers' health.

The benefit of IWTs in providing safe and healthy working conditions for AEC workers has been acknowledged in past studies. For instance, using chest wearable sensors, Lee et al. [19] monitored construction workers' physiological status and activities. It was found that these wearable devices can significantly determine varying patterns in construction workers' physical responses, health statuses, and safety behaviours. Also, Shakerian et al. [20] assessed the occupational risk of heat stress among construction workers through an experimental approach involving wristband-type biosensors. It was found that physiological signals acquired through the wearable device can help predict on-site workers' heat strain. Awolusi et al. [6] noted that IWTs have the potential to deliver real-time safety information that could help manage the health and safety of AEC workers. Concurring with this submission, Ahn et al. [18] stated that wearable sensing technologies can produce momentous opportunities to gather near real-time data on workers' health and safety. It has been noted that IWTs can be used for physiological monitoring, environmental sensing, proximity detection and location traction within the AEC industry [6]. Also, these technologies are applicable in preventing musculoskeletal disorders among site workers. They can also be applied to prevent falls, assess physical workload and fatigue, evaluate workers' ability to recognise hazards and monitor workers' mental health [18].

Albeit the benefits evident in the use of these IWTs, their adoption within the AEC industry of many developing countries, particularly in Africa, is low, and this significantly impacts the health, safety and wellbeing of workers. Ibrahim et al. [11] noted that while wearable devices continue to gain recognition in developed countries with improved worker health and safety, the case is not the same for developing countries, where the use of these technologies is scant. To ensure the safe delivery of built environment projects, exploring the application of IWTs within the South African AEC industry becomes essential. South Africa is noted to be a leading country in Africa with the capability for rapid technological transformation when compared to other African countries [21]. However, like many other developing countries, the AEC industry in South Africa is still slow in its adoption of emerging technologies that could help improve its productivity [22,23]. Furthermore, a quick literature search using Google Scholar, Scopus, and Web of Science databases revealed the absence of studies exploring the use of IWTs within the South African context. This further underscores the timeliness of this study, designed to unearth the use of these beneficial wearable technologies and delineate the factors that could drive their widespread application in the quest for safer and sustainable built environment projects. This study contributes theoretically to the existing discourse on the use of wearable technologies for improved worker safety from the South African built environment perspective—an aspect

that has received less attention in the existing discourse on the use of wearable technologies in the AEC industry.

2. Intelligent Wearable Technology

The accident and injury-prone nature of the AEC industry has made the use of personal protective equipment (PPE) very important. This PPE comes in different forms and is designed to improve the health and safety of on-site personnel [24]. However, technological advancements have led to the development of IWTs that contain electronic devices designed to monitor the health and safety of workers [25–27]. Despite the slow adoption of IWTs globally, these technologies have been noted to have a substantial impact on the lives of site workers [28]. Based on this notion, Xu et al. [29] submitted that maximising the use of wearable technologies is essential to prevent or minimise workers' exposure to site risks. These IWTs are portable electronic devices that facilitate interaction between individuals and their environment [30]. They cut across activity trackers, pedometers, sleep monitors, and other medical and para-medical gadgets useful for tracking caloric intake, heart rate, and perspiration levels [25]. While many of these devices came from the health sector [27], studies have continued exploring them within the AEC industry to monitor health and safety while proffering measures to improve workers' wellbeing and productivity. To this end, studies have identified IWTs applicable to the AEC industry and how they can be used [15,31].

From the built environment perspective, several studies have explored IWTs for workers' effective health and safety. These IWTs are mostly worn directly (e.g., smart wristbands and watches) or are attached to wearable PPE like safety hardhats, vests, boots and glasses. Common among these IWTs are physiological sensors that could measure heart rate motion and track location. These wearable technologies can allow for the adequate monitoring of site workers' health and the early identification of potential risks. They also allow for timely feedback on potential risks within the environment and on the workers [32–34]. Choi et al. [33] explored the drivers for using a smart vest with an embedded indoor GPS for location tracking and a wristband with physiological sensors for on-site construction workers. It was concluded that perceived usefulness, social influence, and perceived privacy risk were associated with workers' intention to adopt these IWTs. To ensure effective safety management, Guo et al. [35] used the Basis Peak smartwatch to measure parameters such as heart rate, skin temperature, calories, and number of steps in determining the psychological status of on-site construction workers. Further studies have noted that smartwatches can be very useful in detecting falls and sending alerts from injured on-site workers, allowing them to receive help [36]. Similar to smartwatches, Hwang and Lee [37] measured on-site workers' safety demands using smart wristbands. In the same vein, Lee et al. [38] employed the use of smart wristband biosensors along with a machine learning algorithm to develop an automatic method for recognising on-site workers' perceived levels of risk. Jiang et al. [39] noted that mechanical bioelectronics and biosensors have become popular due to their simplicity in usage. There has also been the use of smart boots, which can monitor and track on-site workers' location, thus allowing for insights into how to keep them safe and notify them when they are in danger. This allows for workers' workflow transparency and provides a clear picture of the sequence of work to be carried out more efficiently and systematically [40]. Also, these smart boots offer safety by alerting on-site workers when they are in hazardous environments that might result in falling, slipping, or tripping [41].

Smart safety helmets are also gaining recognition within the AEC industry. Safety hardhats are fitted with sensors to track the level of fatigue of on-site workers and also detect collision or the risk thereof [24]. Al Naabi and Al Harthi [42] explored a wireless sensor network (WSN) in a smart safety helmet that could monitor workers' health conditions, safety, and location on construction sites. In case of falls or other site accidents, the smart safety helmet electronically sends a signal to the workers' supervisor to provide immediate assistance. In addition, a GPS was embedded to track on-site workers' location

by their supervisor. Also, advancements in augmented and virtual realities have led to the development of smart glasses fitted with sensors, integrated processors, and display screens to allow for effective visualisation and interaction between the actual and virtual worlds [43]. Moon and Seo [44] revealed that smart glasses can prove very useful in information exchange on construction sites. This information can be effectively used for safety management, especially for planning and coordination [45]. These studies exhibit the immense use of diverse IWTs for improving the safety and health of workers within the AEC industry.

3. Technology–Organisation–Environment Framework for Assessing the Factors Influencing the Use of Intelligent Wearable Technologies

The factors driving the use of IWTs were assessed using the technology–organisation–environment (T–O–E) framework developed by Tornatzky and Fleischer in the 1990s. The T–O–E framework hinges on the contingency theory to propose some general factors that could shape the use of innovations and technologies by individuals or organisations [46]. It is believed that factors relating to technology development, the conditions of an organisation, and the environment in which an organisation operates can impact the use of new technologies [47]. This framework was adopted to determine the factors influencing the use of IWTs due to its strength over other adoption models and frameworks. It has been noted that the T–O–E framework employs human and non-human factors, the combination of which is missing in other frameworks [46,48]. In exploring these T–O–E factors, due to the absence of specific IWT studies using this framework, this study relied on similar studies that have explored the adoption of diverse emerging technologies.

The technology dimension of the T–O–E framework relates to every technology relevant to the organisation. The ready availability of these technologies can determine the scope and pace of their adoption [49]. With the pace of rapid technological advancement, IWTs need to be readily available to promote their use. Also, their compatibility, complexity and perceived usefulness are equally important. Compatibility has been described as the extent to which a new technology aligns with an organisation or individual's values, practices, and potential needs [50,51]. When IWTs are considered compatible with the safety values of an organisation, there is the possibility of significant improvement in their usage. Choi et al. [33] noted that many IWTs are compatible with existing PPE (hardhats, safety vests, boots, and glasses). The South African AEC industry is no stranger to the use of PPE on construction sites [52]. Thus, it should be easier to introduce applicable electronic devices into this existing PPE for smarter and safer project delivery and an increase in the productivity of on-site workers. However, when these technologies are compatible but complex to use, organisations and individuals might be discouraged from investing in and adopting them. This complexity might overshadow the perceived benefits of these technologies and negatively influence their adoption, preventing them from increasing the safety of AEC projects [53]. Several other technology-related factors have been adopted in exploring technology adoption. For instance, security, technology readiness, and cost savings have effectively shaped how organisations and individuals adopt new technologies in Malaysia [54]. Also, in Portugal, technology readiness, cost, security, complexity, and compatibility were adopted [55]. Gupta et al. [56] used the ability to reduce cost, ease of use, security, and privacy as key technology adoption determinants. Based on these past submissions, this study employed the availability of IWTs, their compatibility with existing values, practice and potential needs, cost-effectiveness, ease of use, ability to ensure workers safety, perceived innovativeness, and their reliability in measuring the technology dimension of the factors influencing the use of IWTs for safe project delivery in the South African built environment.

The organisation dimension of the T–O–E framework entails the resources and the culture within an organisation. This dimension encompasses factors such as the organisation's size, people quality, and the managerial structure [49,50]. In exploring an integrated T–O–E taxonomy for the adoption of technology, Awa et al. [46] explored the organisa-

tional dimension from the perspective of support from management, as well as the size and scope of the business. It has been noted that adopting any new idea depends on top management's support. Low et al. [57] noted that this top management support comes in the form of a positive environment through their vision and commitment. By prioritising safety and supporting innovative approaches within AEC organisations, top management can improve the use of IWTs. Similarly, the importance of technology readiness within an organisation can significantly influence the use of new technologies [58]. This technological readiness cut across having the right mindset [58] and the financial, technological and manpower resources to promote these new technologies [59]. The AEC industry in developing countries like South Africa (where this current study was conducted) has been berated for its poor technology adoption culture due to the absence of technological and financial resources [21]. Based on these observations, this study employed support from management, available organisational resources, the organisation's digital culture, the organisation's readiness, organisation size, and available technical expertise in measuring the organisational dimension of the factors driving the use of IWTs for safe project delivery in the South African built environment.

The last dimension of the T-O-E is the environment, which entails factors relating to the industry in which an organisation operates. This environment in which an organisation operates can shape the adoption of emerging tools [60]. Gutierrez et al. [58] mentioned that these environmental factors, among others, include market forces and technology service providers. Moreover, it has been noted that the pressure from competitors, the supporting regulations and legislation are all crucial environmental factors that can promote the use of emerging tools [60–62]. With the availability of legislation and regulations that support the use of technologies to ensure safety, the use of IWTs can be improved within the AEC industry as organisations will be compelled to meet available regulations. Moreover, the government, being the biggest client of the AEC industry in most developed countries [63], can promote the use of IWTs on public projects through favourable legislation. Also, the use of these IWTs by competitors can serve as a yardstick for organisations to adopt these technologies [46,64]. Similarly, the availability of trusted suppliers to ensure easy access to these IWTs can be crucial to their usage. These suppliers must be reliable, available, and ready to support organisations through training workers on the use of these IWTs [58,65]. Based on these past studies, this study employed the availability of supporting industry regulations, the demand from construction clients, available legislation, competitors' pressure, and trust in suppliers in measuring the environmental dimension of the factors driving the use of IWTs for safe project delivery in the South African built environment.

4. Research Methodology

In exploring the use of IWTs for the safe delivery of built environment projects, particularly in South Africa, this study adopted a post-positivist philosophical stance wherein the research questions were explored objectively using a quantitative research design and a structured questionnaire as the instruments for data collection, with the interpretation of the results shaped by the experience of the researcher [66]. The questionnaire allowed for anonymity and wider participation [67]. The absence of studies from within the country necessitated an exploration of the use of these wearable technologies for the safe delivery of projects. Figure 1 shows the research framework adopted. The study gathered information from built environment professionals (architects, quantity surveyors, engineers, construction and project managers, and construction safety officers) actively involved in construction projects in the country who had at least five years of continuous working experience in the South African AEC industry. This threshold was important to ensure that the study's respondents understood the country's AEC industry safety dynamics. Based on this set threshold, it was difficult to determine the exact number of the target population (i.e., those with the set number of years of experience who were actively participating in project delivery in the country), thus making the calculation of a sample size impossible.

As such, the study relied on the snowball sampling approach, wherein a small group of participants were first identified and invited for the survey. Based on the referral of this initial group, other participants were identified for the survey.

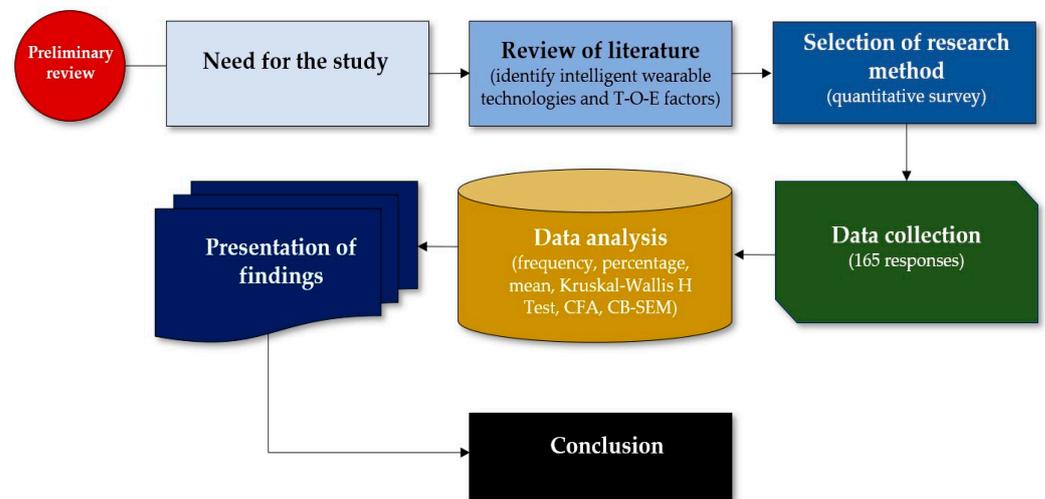


Figure 1. Research framework.

Data collection was performed electronically using a self-administered questionnaire designed in three sections. The first section identified the characteristics of the respondents to determine their suitability for the study. The second section assessed the use of IWTs. A description of IWTs was given to ensure general understanding, and the respondents were asked to rate their overall usage on a scale of 1 to 5, with 1 being “very low” and 5 being “very high”. Also, the respondents were presented with seven IWTs based on the literature reviewed. They were expected to rate these technologies on their usage level using a scale of 1 to 5, with 1 being “not used at all” and 5 being “very high usage”. Section three assessed the factors influencing the use of these IWTs using the T–O–E framework. Again, the respondents were expected to rate the significance level of 18 variables on a scale of 1 to 5, with 1 being “very low” and 5 being “very high”. The questionnaire included a cover letter that described the research, notified the respondents of their voluntary participation, and assured them of anonymity. The data collection period spanned a period of two months, giving the respondents adequate time to respond to the survey. Based on the snowball approach adopted, 165 responses were gathered from the respondents.

The respondents’ background information was analysed using frequency (f) and percentage (%). The reliability of the data from the second and third sections was tested using the Cronbach alpha (α) test in Equation (1) with a 0.7 cut-off for data reliability to be achieved.

$$\alpha = \frac{K \bar{r}}{1 + (K - 1)\bar{r}} \quad (1)$$

where K = items in the scale and \bar{r} = average of the inter-item correlation.

Also, since the data were gathered from diverse built environment professionals, determining the significant difference in the rating of the use of these IWTs and the T–O–E factors by the different professionals became apparent. As such, the Kruskal–Wallis H-test (K-W), which is a non-parametric test for determining the difference in the rating of three or more groups of respondents, was employed [68] using Equation (2).

$$H = \frac{12}{N(N - 1)} \sum_{i=1}^k \frac{R_i^2}{n_i} - 3(N + 1) \quad (2)$$

where N = total sample, k = total number of groups, R_i = sum of ranks of group i , and n_i = sample size of group i .

The mean item score (\bar{X}) was also calculated for the variables in Sections 2 and 3 using Equation (3).

$$\bar{X} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + 1n_1}{n_5 + n_4 + n_3 + n_2 + n_1} \quad (3)$$

where n = the frequency of each of the rankings.

The T–O–E variables were also confirmed using confirmatory factor analysis (CFA) in EQation (EQS) version 6.4, which offers fit statistics that accommodate the non-normality in questionnaire data [69]. Also, covariance-based structural equation modelling (CB-SEM) was used to determine the relationship between the T–O–E variables and the level of usage of IWTs. CB-SEM was adopted as it allows for testing existing theories [70]; it has become popular in many built environment studies due to its ability to integrate several multivariate techniques, such as regression, path analysis and CFA [71]. A popular argument around the use of CB-SEM has been around the ideal sample size. While different views have been submitted on this issue, most studies have suggested the use of a large sample for adequate model fit to be derived, depending on the complexity of the model. To this end, a sample size of between 100 and 200 has been noted as ideal for CB-SEM to be conducted [72–74]. Since the model in this current study is not complex, the derived sample of 165 was considered adequate for data analysis and to draw logical conclusions in the study.

5. Findings and Discussion

5.1. Background Information of Respondents

The analysis of the respondents' background information revealed that more engineers (civil, electrical and mechanical) participated in the survey ($f = 73$). The respondents also included construction and project managers ($f = 38$), architects ($f = 25$), quantity surveyors ($f = 16$), and construction safety officers ($f = 13$). The results also showed that most of the respondents have bachelor's degrees ($f = 132$), followed by diplomas ($f = 24$) and master's degrees ($f = 9$). In terms of years of experience, 97 of the respondents have 5 years, while 43 have between 6 and 10 years, 19 have between 11 and 15 years, and 6 have over 20 years working experience. This background result implies that the respondents are well equipped academically to understand the research questions and have adequate experience in the industry.

5.2. Use of IWTs for the Effective Safety of Built Environment Projects

In determining the use of IWTs for the effective safety of built environment projects, the respondents were given a clear definition of IWTs, and they were asked to rate the overall usage level on a five-point scale. The result in Figure 2 reveals that overall, 54.5% noted that IWT usage is low, while 15.8% and 29.7% noted an average and high level of usage, respectively. This implies the need to promote these IWTs' usage further within the South African AEC industry.

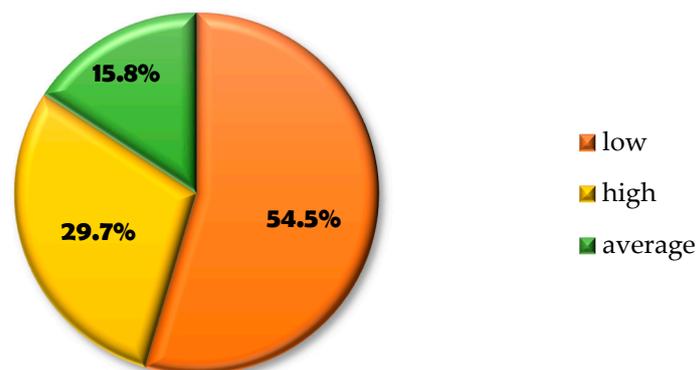


Figure 2. Overall adoption of IWTs in the South African AEC industry.

Further assessment of the individual IWTs' usage levels was conducted, and the result is presented in Table 1. The reliability of these IWTs was assessed using the Cronbach alpha (α) with a set threshold of 0.7. The result gave an α -value of 0.889, which implies the reliability of the variables in this section. The K-W test was employed to further determine the significance of the rating of the use of these IWTs. The K-W test revealed that the respondents had a convergent view for five out of the seven IWTs. These five IWTs had a p -value of above 0.05. However, the use of smart safety helmets and boots revealed a significant p -value of 0.010 and 0.047, thus implying a divergent view in rating these IWTs. Smart safety vests embedded with indoor GPS/sensors, smartwatch and wristband biosensors, and smart safety helmets were rated as the three most used IWTs with a \bar{X} of 3.21, 3.13 and 3.10, respectively. The least used IWTs are chest wearable sensors ($\bar{X} = 2.96$) and smart gloves ($\bar{X} = 2.84$). Overall, the use of all IWTs is rated at 3.05, which is the average based on the Likert scale adopted. This result further affirms the need for an improved use of IWTs for effective safety in the delivery of South African built environment projects.

Table 1. Use of IWTs for safe built environment projects.

Intelligent Wearable Technologies	\bar{X}	Rank	K-W	
			χ^2	p -Value
Smart safety vest embedded with indoor GPS/sensors	3.21	1	9.469	0.051
Smartwatch and wristband biosensors	3.13	2	1.806	0.771
Smart safety helmet	3.10	3	13.340	0.010 **
Smart boots	3.08	4	9.620	0.047 **
Smart glasses	3.01	5	3.777	0.437
Chest wearable sensors	2.96	6	2.923	0.571
Smart gloves	2.84	7	5.429	0.246
Overall	3.05			

Note: ** significant at $p < 0.05$, \bar{X} = Mean Score, K-W = Kruskal–Wallis H-test, χ^2 = Chi-square.

5.3. Factors Influencing the Use of IWTs for Effective Safety of Built Environment Project Delivery

Table 2 shows the result of the assessment of the factors that could influence the increased uptake of IWTs for the effective safety of built environment project delivery in South Africa based on the T–O–E framework adopted. Initial analysis revealed that the data met the data-reliability threshold, with α -values of 0.938, 0.945 and 0.921 for the technology, organisation, and environment dimensions. Also, the K-W test revealed no disparity in the rating of the variables in these groups as all assessed variables had a p -value above 0.05. A cursory look at the \bar{X} derived for all the assessed variables revealed that they all have an above average of 3.0, thus implying that they can considerably drive the use of IWTs and ensure safe delivery of built environment projects. In the technology group, the ability of devices to ensure workers' safety was considered the most crucial driver. This is followed by the cost-effectiveness, reliability, and compatibility of these wearable technologies. From the organisational perspective, the support from top management and the available resources within the organisation are germane to the use of IWTs. Also, the availability of favourable regulations that support the use of wearable technologies and the demand from clients for the use of IWTs by workers on their projects were considered crucial environmental factors needed to drive the uptake of IWTs for the safe delivery of built environment projects.

Table 2. Factors influencing the use of IWTs.

T–O–E Factors	\bar{X}	Rank	K-W	
			χ^2	<i>p</i> -Value
Technology				
Ability of devices to ensure workers safety (Tech 6)	3.60	1	5.971	0.201
Cost-effectiveness (Tech 4)	3.49	2	8.005	0.091
Reliability of wearables technologies (Tech 2)	3.47	3	4.055	0.399
Compatibility with existing technologies (Tech 7)	3.45	4	1.641	0.801
Availability of wearables devices (Tech 1)	3.42	5	8.227	0.084
Ease of use (Tech 5)	3.42	5	2.431	0.657
Perceived innovativeness (Tech 3)	3.28	7	3.348	0.501
Organisation				
Support from management (Org 2)	3.47	1	2.739	0.602
Available organisational resources (Org 6)	3.45	2	3.585	0.465
Organisation’s digital culture (Org 3)	3.38	3	5.145	0.273
Organisation’s readiness (Org 1)	3.34	4	3.652	0.455
Organisation size (Org 4)	3.33	5	6.886	0.142
Available technical expertise (Org 5)	3.27	6	5.250	0.263
Environment				
Supporting industry regulations (ENV 2)	3.47	1	1.357	0.852
Demand from construction clients (ENV 3)	3.43	2	3.872	0.424
Available legislation (ENV 1)	3.38	3	3.392	0.494
Competitors pressure (ENV 4)	3.29	4	4.085	0.395
Trust in suppliers (ENV 5)	3.19	5	1.375	0.849

Note: \bar{X} = Mean Score, K-W = Kruskal–Wallis H-test, χ^2 = Chi-square

5.3.1. Confirmatory Factor Analysis

CFA was conducted to confirm the significance of these identified T–O–E factors influencing the use of IWTs for the safe delivery of built environment projects in South Africa. Robust maximum likelihood (RML) estimation in EQS 6.4 was used as it provides more robust fit indices through its Satorra–Bentler scaled chi-square ($S-B\chi^2$), which is a more robust χ^2 [69,75]. Table 3 shows the standardised coefficient (λ) for each measurement variable under the three different groups. This λ depicts the construct validity of these variables. Past studies have proposed several thresholds for an acceptable λ . This has ranged from 0.4 to 0.7 in many studies [74,76]. The result in Table 3 shows that all the variables have a λ ranging from 0.75 to 0.900, thus confirming that they all met the construct validity threshold. Also, Table 3 shows the result of the internal consistency of these variables using the α and Rho alpha (ρ_A) tests, as suggested in past studies [77]. Past studies have noted a threshold of above 0.7 for internal consistency to be deemed achieved [72,78]. The result revealed an α -value of 0.967 and a ρ_A -value of 0.975, which are higher than the set cut-off, thus confirming internal consistency. The result in Table 3 further shows the significance of each variable along with their Z-statistics. It has been suggested to make at least one variable a fixed parameter [73], and as such, no Z-value is assigned to the first variable of each dimension in the table. All the assessed variables were significant to the use of IWTs for the safe delivery of built environment projects, as their Z-statistics revealed a value of well above 1.96 ($p < 0.05$). The significance of these variables was further confirmed through the coefficient of determination (R^2). Past studies have noted that R^2 of 0.75, 0.50 and 0.25 are considered substantial, moderate, and weak [78]. The result in

Table 3 shows that all the assessed variables have between moderate and substantial power to determine the use of IWTs within the country. The derived R^2 values ranged from 0.57 to 0.84, implying that these variables have the power to impact the use of IWTs.

Table 3. Factor loading, Z-statistics and internal consistency of the hypothesised model.

Groups	Variable	Standardised λ	Z	Significant at 5% Level?	R^2	Group R^2	α	ρA
Technology	TECH1	0.79		Yes	0.62	0.69	0.967	0.975
	TECH 2	0.84	12.366	Yes	0.71			
	TECH 3	0.86	12.617	Yes	0.73			
	TECH 4	0.75	10.642	Yes	0.57			
	TECH 5	0.87	12.922	Yes	0.76			
	TECH 6	0.82	11.812	Yes	0.67			
	TECH 7	0.87	12.926	Yes	0.76			
Organisation	ORG1	0.87		Yes	0.77	0.75		
	ORG2	0.79	13.071	Yes	0.62			
	ORG3	0.85	15.077	Yes	0.73			
	ORG4	0.85	15.053	Yes	0.73			
	ORG5	0.90	17.038	Yes	0.82			
	ORG6	0.90	16.923		0.82			
Environment	ENV1	0.82		Yes	0.67	0.69		
	ENV2	0.92	14.933	Yes	0.84			
	ENV3	0.77	11.359	Yes	0.59			
	ENV4	0.82	12.563	Yes	0.68			
	ENV5	0.85	13.291	Yes	0.73			
Use of IWTs	USE	0.77		Yes	0.60			

Note: Robust statistical significance at a 95% confidence level.

5.3.2. Model Fitness

The fitness of these group of factors and the attributed variables were measured using standardised root-mean-square (SRMR) along with any supplemental fit index, such as the Tucker–Lewis Index (TLI), Comparative Fit Index (CFI), Bentler–Bonnet Non-Normed Fit Index (NNFI), Gamma Hat, McDonald’s Centrality Index (Mc), goodness-of-fit index (GFI), Bollen’s incremental fit index (IFI), or root-mean-square error of approximation (RMSEA), as suggested in [79]. Past studies have suggested the cut-off for an acceptable SRMR to be ≤ 0.08 [79]. Table 4 shows that this fit index was achieved as a good fit of 0.045 was attained for the SRMR. Further analyses using other fit indices were conducted in line with past suggestions. The $S-B\chi^2/Df$ derived from RML with a cut-off of < 3.0 for a good fit [79] was conducted, with a derived value of 2.02. Also, the NNFI revealed a value of 0.914, which is within the acceptable threshold of 0.60 to 1.00 [79,80]. GFI, CFI and IFI all revealed good fits of 0.786, 0.926 and 0.927, respectively. The result for the RMSEA also revealed a good fit with a value of 0.073, which is within the acceptable threshold of ≤ 0.08 [81]. Based on these results, it is evident that the T–O–E factors assessed in this study are valid, reliable, and fit to determine the use of IWTs for the safe delivery of built environment projects in South Africa.

Table 4. Model fit indices.

Fit Indices	Cut-Offs	Value	Remarks
$S-B\chi^2$	-	295.44	-
Df	-	146	-
$S-B\chi^2/Df$	<3—good fit	2.02	Good
GFI	0 to 1 (0 = no fit; 1—perfect fit)	0.786	Good
CFI	0 to 1 (0 = no fit; 1—perfect fit)	0.926	Good
NNFI	0.60 to 1.00—acceptable fit	0.914	Good
IFI	0.90 to 1.00—acceptable fit	0.927	Good
RMSEA	0.05 to 0.10—acceptable fit	0.079	Good
SRMR	≤0.08—acceptable fit	0.045	Good

Threshold Sources: [74,76,77,79–81].

5.3.3. Structural Model Assessment

Based on the attainment of appropriate model fits, the structural relationship between the T–O–E framework and the usage level of IWTs was assessed. The path coefficient (β), which shows the relationship between the T–O–E dimensions and the usage level, was evaluated in assessing the structural relationship. As seen in Figure 3, the technology has a significant β -value of 0.77 with a p -value of 2.887, thus implying that this dimension will have a 77% impact on the use of IWTs in the study area. The same applies to the environment, with a significant β -value of 0.9 and a p -value of 3.049. However, the organisation revealed a β -value of 0.44 with a p -value of 1.436—less than the 1.96 cut-off (i.e., at $p < 0.05$). This implies that while organisational factors might exert a 44% impact on using IWTs, their impact is not as significant as those from the environmental and technology dimensions. Having established the significance of the paths in the model, the predictive power was measured using the overall derived R^2 . The result revealed a moderate predictive power of 0.460.

5.4. Discussion and Implication of Findings

This study found that the use of IWTs in the South African AEC industry is slow-paced. This finding is consistent with past studies that have noted that the AEC industry is a slow adopter of emerging technologies, and the use of IWTs is still slow despite them offering significant benefits for safer project delivery [33,82]. An emergent implication of this finding is the need for improved awareness of IWTs for monitoring and tracking workers' health and safety on construction sites. Industry regulatory bodies like the Construction Industry Development Board (CIDB), which regulates the activities of construction organisations in South Africa and those regulating the built environment professions, can help promote the use of these wearable technologies. This can be done by revising the industry's safety regulations to support emerging technologies and providing workshops, seminars, and conferences designed to further promote IWTs. Similarly, the government has been noted to be a key player in the activities of the built environment [63]. As such, they can champion the course for a safe and sustainable built environment by creating and enforcing favourable policies and legislation that promote the use of IWTs in all public projects. This can serve as an example that private clients will follow to request these wearable technologies on their projects. The required level of improvement in the use of IWTs cannot be achieved without the help of IWT suppliers/vendors. IWT suppliers need to promote their technologies by showcasing their advantages to organisations and workers while ensuring training on how to use these devices is provided to encourage adoption [65]. Through this showcase, the fear of many workers, which has caused resistance to the use of wearable technologies [6], can be alienated, and by offering training, organisational resistance to investing in technologies due to the associated cost of training workers to use them [11,83] can be addressed.

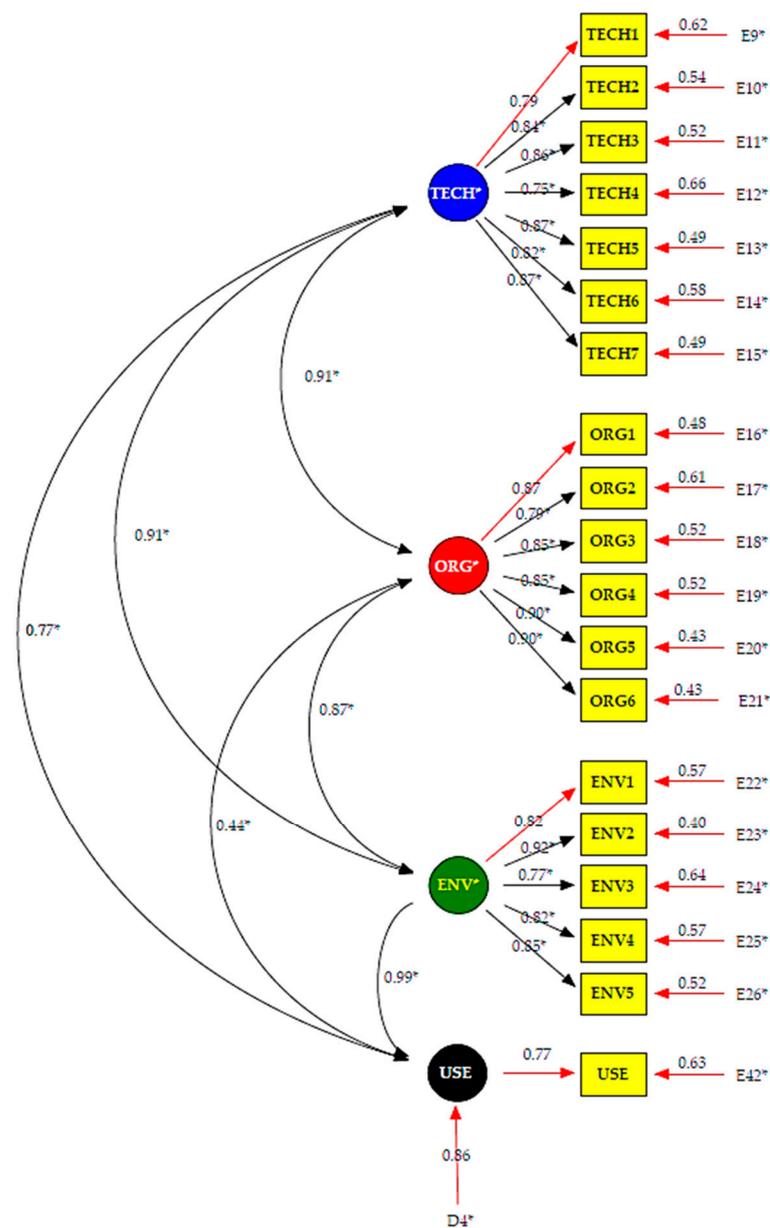


Figure 3. Structural assessment of the factors influencing the use of IWTs. * = significant at $p < 0.05$.

The findings from the SEM also revealed that the use of the IWTs for safe built environment projects can be influenced significantly by some technological and environmental factors of the T–O–E framework adopted. From the results, in terms of the technology dimension, it is evident that for organisations and individuals within the AEC industry to improve their use of IWTs, an understanding of the ability of the chosen wearable technology to ensure safety is critical. Choi et al. [33] noted that the slow adoption of many IWTs within the built environment results from a lack of evidence of the benefits of these technologies. Therefore, for these wearable technologies to be adopted within the South African built environment, there is a need to showcase their benefits through continuous promotion and investment in forward-looking research and development in the country. The results also show the importance of these technologies being cost-effective to acquire and maintain. Earlier, Goodrum et al. [83] noted this to be a critical issue deterring the use of these wearable technologies. Moreover, reliability, compatibility, availability, and ease of use were all observed as key factors that deserve adequate attention. This finding is consistent with past submissions on the factors influencing the use of emerging

technologies [54–56]. An emergent implication of this finding is the need for IWT providers to ensure the ready availability of these tools and the reduction in their complexity to encourage their adoption. More so, AEC organisations must carefully assess their values and resources to ensure the compatibility of adopted IWTs with what is obtainable within the organisation.

From the environmental perspective, this study found that support from the industry through favourable regulations, available legislation, client demand, trust in suppliers, and pressure from competitors are all germane to the use of IWTs for safe built environment project delivery in South Africa. Earlier studies have noted that issues relating to regulations and legislation can deter the use of wearable technologies within the built environment [11,84]. As noted earlier, the government and other regulatory bodies in the South African AEC industry have a critical role to play in promoting the use of IWTs to attain a safe and sustainable built environment in the country. By creating favourable policies, legislation, and regulations, the use of IWTs on public and private projects can be encouraged. Although organisational factors revealed a non-significant relationship with the level of usage, we revealed they had a 44% impact, which is worthy of attention. As such, organisations seeking to ensure the safe delivery of their projects must consider the identified organisational factors in this study, specifically their available resources and technical expertise, as both had high standardised coefficients.

6. Conclusions

Technological advancements have created the emergence of ubiquitous technologies that offer solutions to age-long problems of the AEC industry, including the poor health and safety of on-site workers. Emerging IWTs offer momentous benefits in attaining safe and sustainable built environment projects. However, like its counterparts worldwide, the AEC industry in South Africa is a slow adopter of these beneficial wearable technologies. Also, studies assessing the use of these technologies and possible bases for improved adoption are absent within the context of the South African AEC industry. To address this knowledge gap, this study explored the use of IWTs to deliver built environment projects in the country safely. Using a survey, the study concludes that, despite the slow pace of adoption, IWTs such as smart safety vests embedded with indoor GPS/sensors, smartwatches, and smart safety helmets are gradually gaining popularity within the South African built environment. There is a need to further promote the benefits inherent in the use of these technologies, including smart boots, glasses, smart chest wearable sensors, and gloves. This study further concludes that the use of these IWTs can be influenced significantly by technology- and environment-related factors such as the ability of devices to ensure workers' safety, cost-effectiveness, reliability, supporting regulations, legislation, and client demand, among others. However, while the organisation dimension did not prove significant to the use of the IWTs, its possible impact is worth acknowledging, particularly in terms of the organisation's available resources and technical expertise.

These findings offer practical implications for the AEC industry by providing directions for improving the use of IWTs in South Africa to attain a safe and sustainable built environment. Theoretically, the findings offer an excellent platform for future studies seeking to explore the use of wearable technologies in the AEC industry. This is because the study adds to the existing discourse on the use of smart wearable technologies from the South African built environment perspective—an aspect that has received less attention in the existing discourse on the use of wearable technologies in the AEC industry. Furthermore, the study's findings will engender a wider discussion on the implications of IWTs for the AEC industry in South Africa and other developing countries, where such a study is absent. It is important to note the limitations of this study to provide direction for future work. Most important is that this current study is exploratory due to the absence of studies focusing on IWTs in the study area. Further studies can adopt an experimental approach in testing the application and impact of selected IWTs on on-site workers' health, safety, and wellbeing. Unearthing the benefits of the identified IWTs to the reduction of

fatalities and injuries within built environment projects can go a long way in improving their adoption. Also, the study draws its conclusions from the responses of 165 built environment professionals who are actively involved in construction projects in South Africa. While this sample was adequate for the selected data analysis, there is the possibility of having a different perspective if more professionals participated in the study. As such, it is recommended that further studies consider a much larger sample to be able to generalise the results to the entire country.

Author Contributions: Conceptualisation, L.A. and D.A.; methodology, L.A., N.N. and D.A.; software, D.A.; formal analysis, D.A.; investigation, N.N. and D.A.; resources, N.N. and D.A.; writing—original draft preparation, L.A. and D.A.; writing—review and editing, L.A., N.N. and D.A.; visualisation, D.A.; supervision, N.N.; project administration, N.N. and D.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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